SAND2017-2583PE

Development of an Optically Pumped Magnetometer Array for Magnetoencephalography

Peter D. D. Schwindt
Sandia National Laboratories

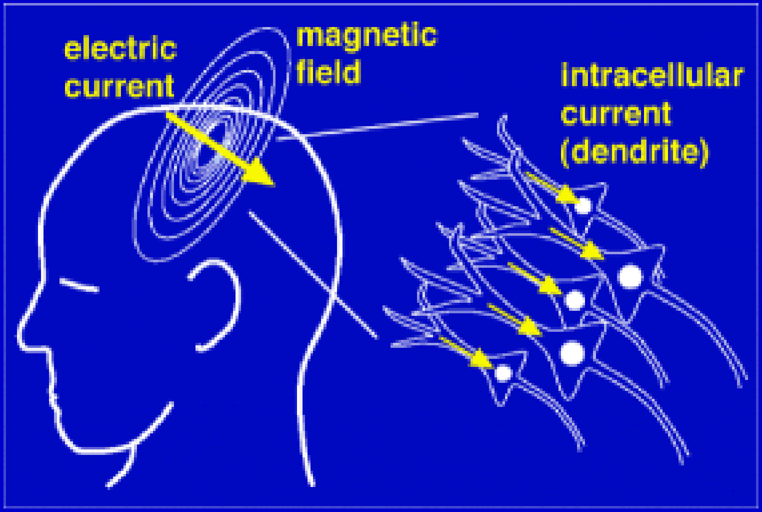
March 9th, 2017

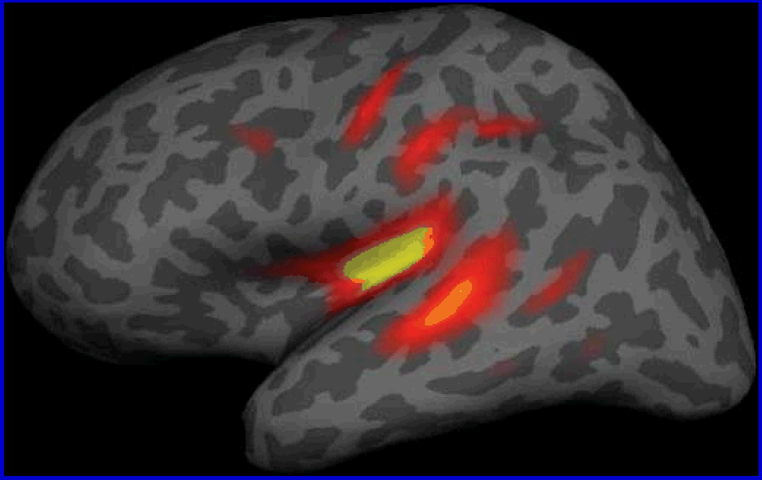
Outline

- Introduction
  - What is MEG?
  - Why optically pumped magnetometers?
  - Our first MEG measurements
- A complete MEG system
  - Sensor design
  - Magnetic shield design
  - Array construction and issues
  - First MEG results with the array
- Conclusion

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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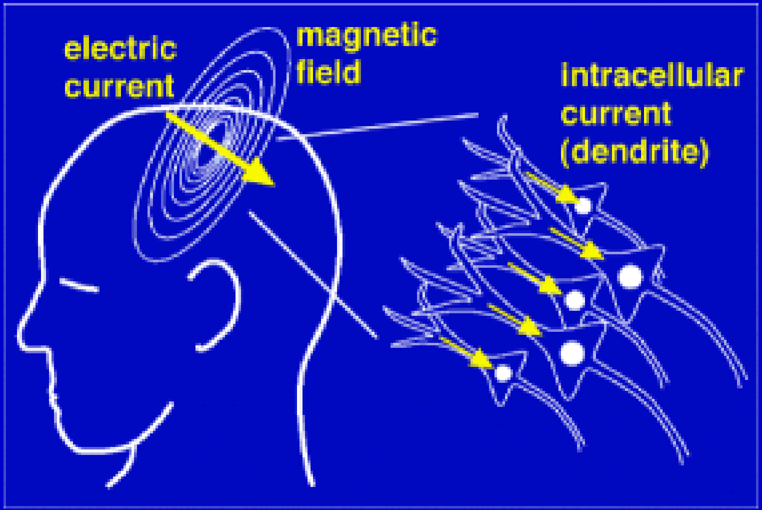
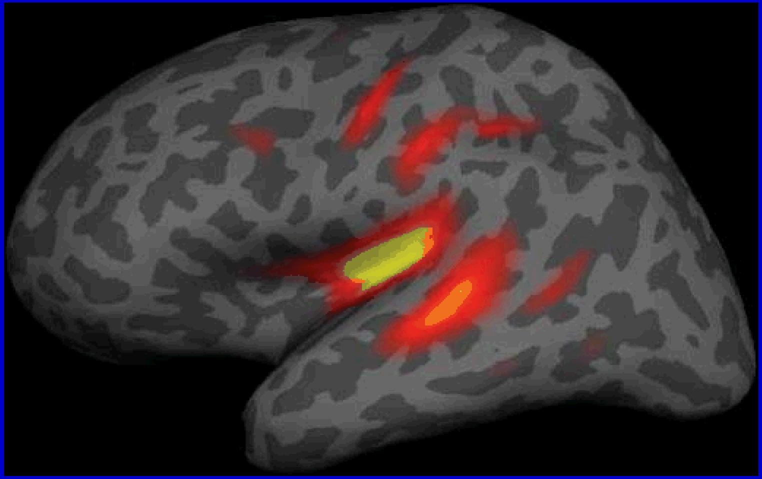
What is MEG?

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





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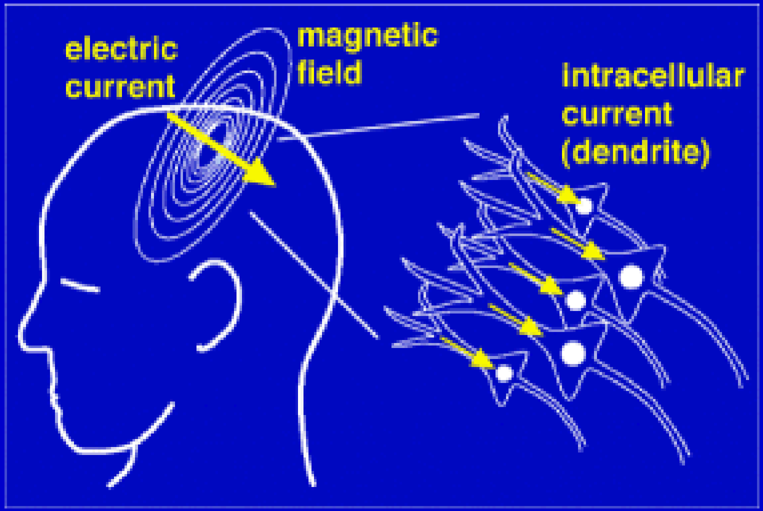
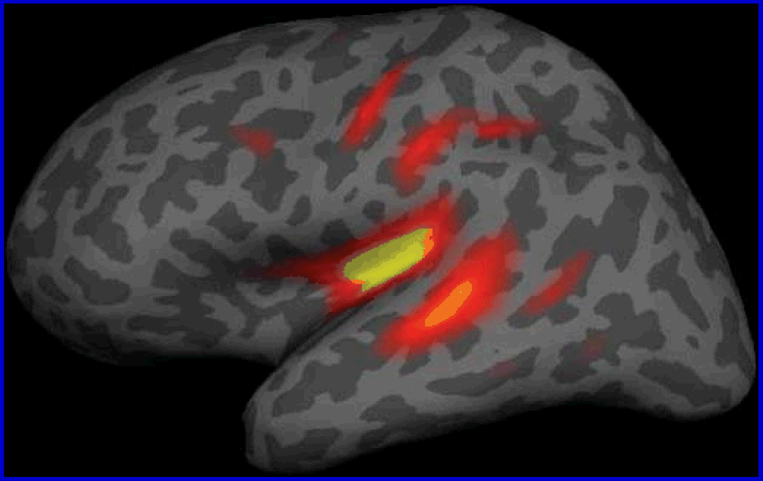
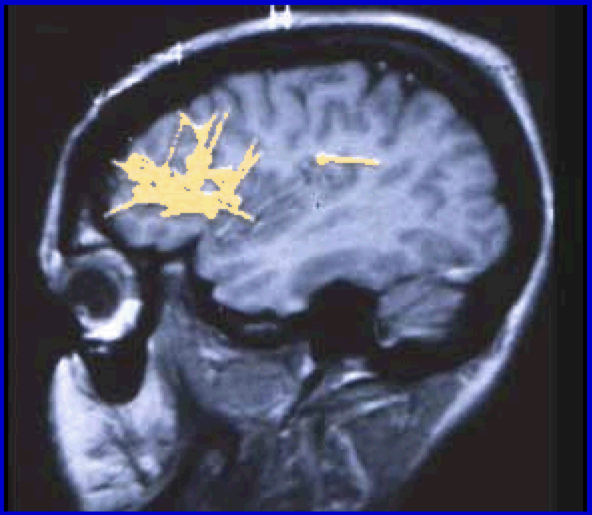
MEG is inherently hard.

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







Current Technology

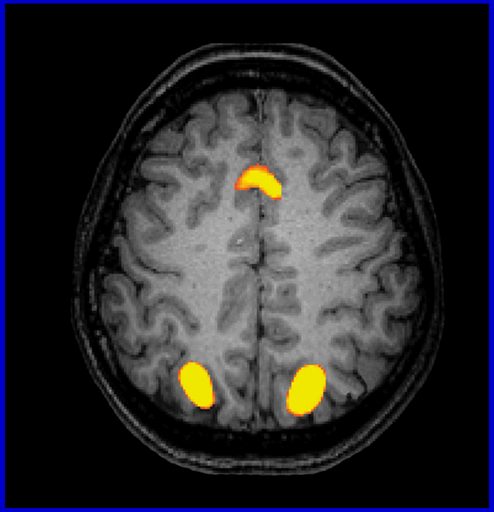
Superconducting Quantum Interference Devices (SQUIDs)

- 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 room
  - Helmet size is fixed to accommodate largest head size.
    - Sensor to head distance is not optimized.

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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The potential of MEG has not been fully realized.

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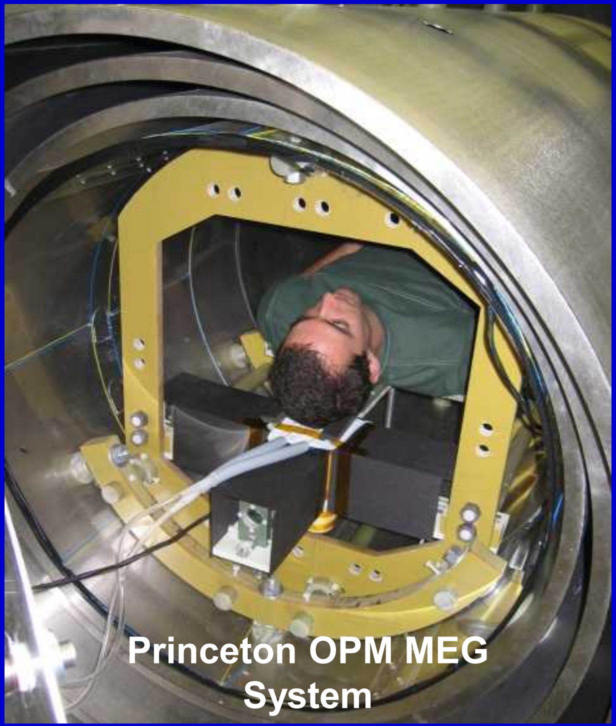
Groups Working on OPM MEG

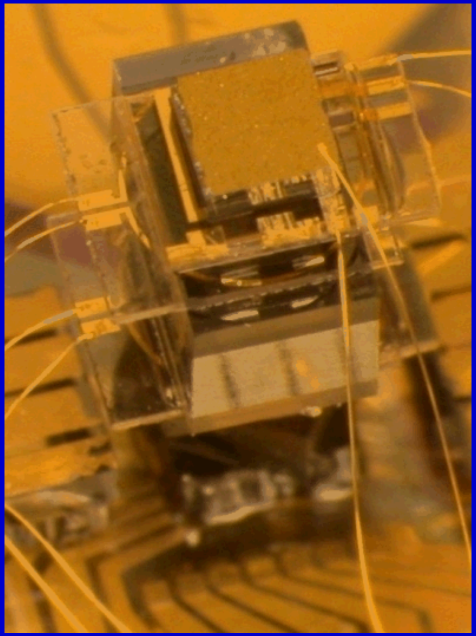


Also
Twinleaf LLC

Optically Pumped Magnetometers for MEG

Potential Improvements for MEG

- No cryogenic cooling
  - OPM needs to be heated
- Much smaller MEG system 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 are 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

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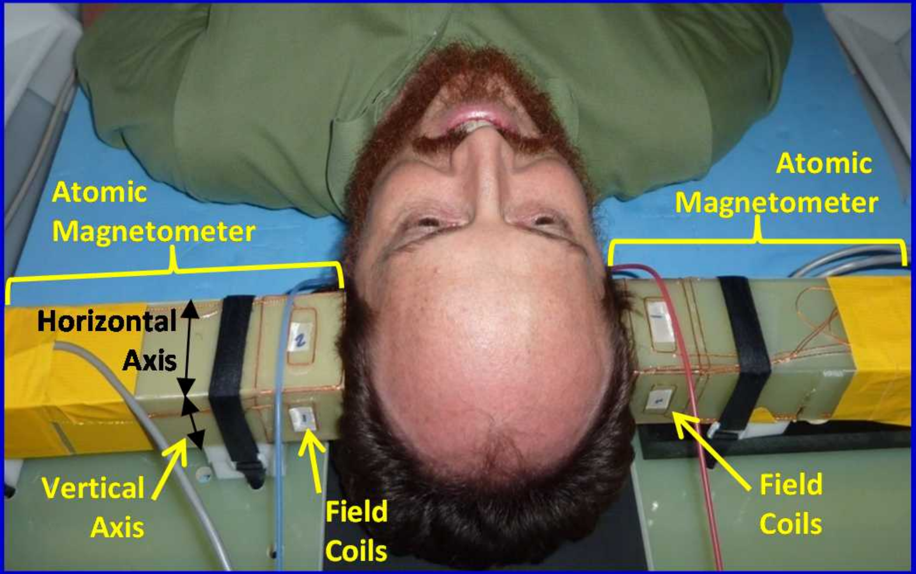
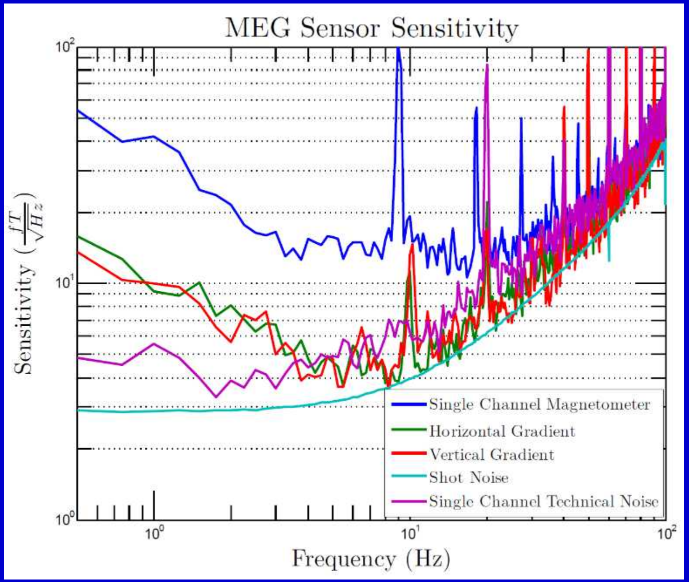
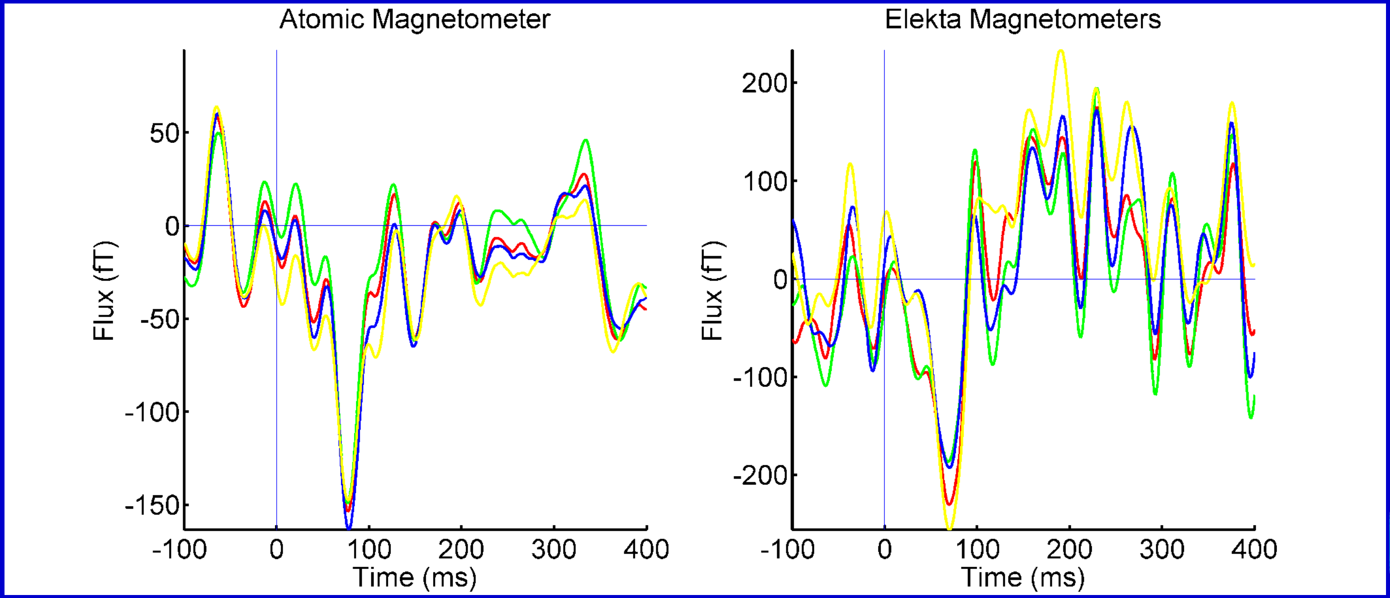
Our First OPM MEG Project (2007-2010)





Auditory Stimulation



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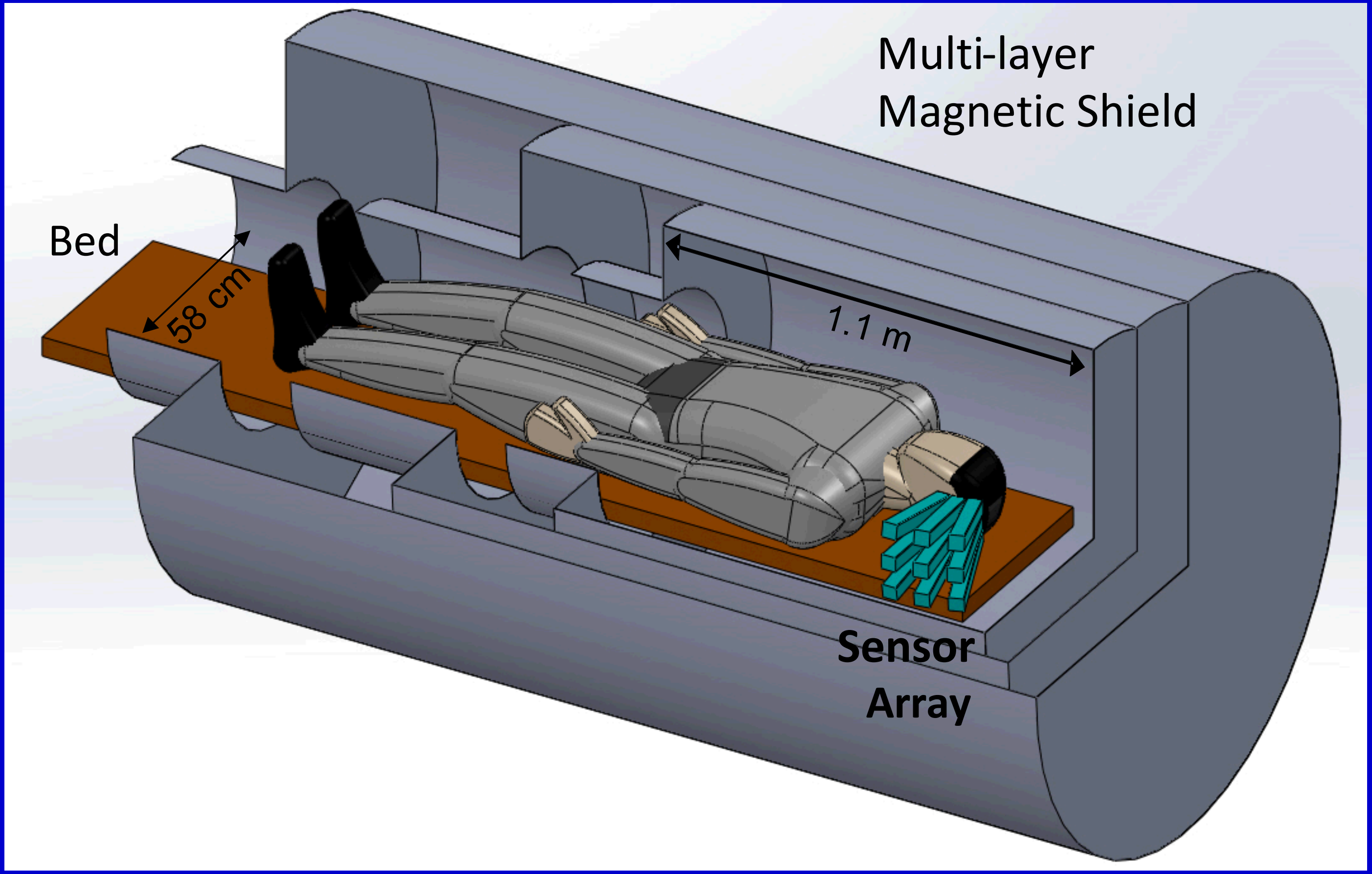
Complete MEG System (2012 to present)

- 36 channel OPM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation
- Compare OPM and SQUID magnetic source localization in human subjects: auditory and somatosensory



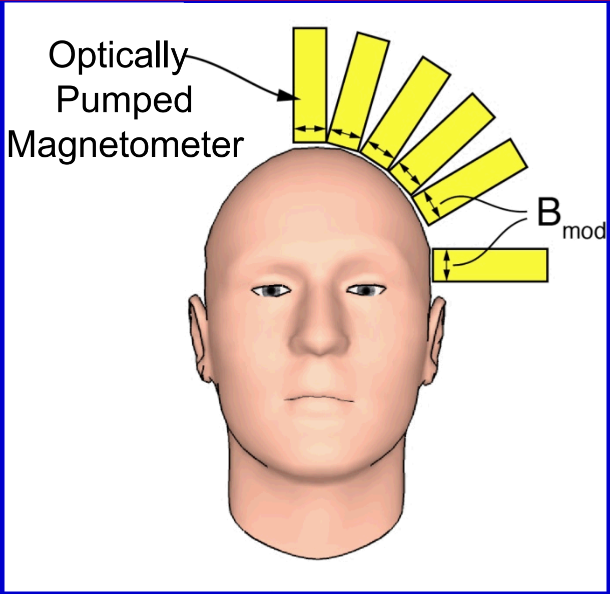
Collaboration: The Mind Research Network, Cleveland Clinic, University of New Mexico

- Design input from neuroscientists
- Strengthen ties to ultimate user community

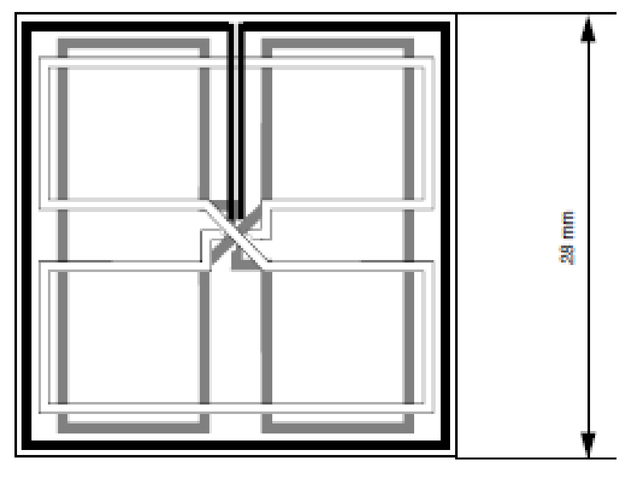
Our OPM Sensor Goals for MEG

Mimic SQUID MEG sensor

- Whole-head coverage: tailor sensor design for arrays
- Adequate sensitivity/bandwidth (<10 fT/Hz$^{1/2}$/100 Hz)
- Small footprint ~ 40 mm square
- Eliminate free space beams (fiber coupled sensors)
- Gradiometric 2D output



Elekta Triple Sensor Chip

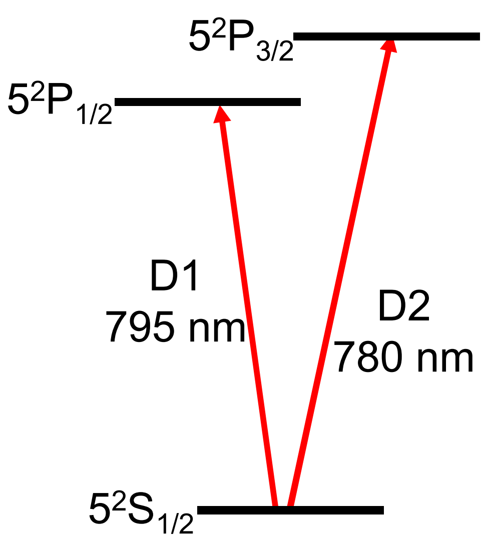


Two-color pump/probe scheme

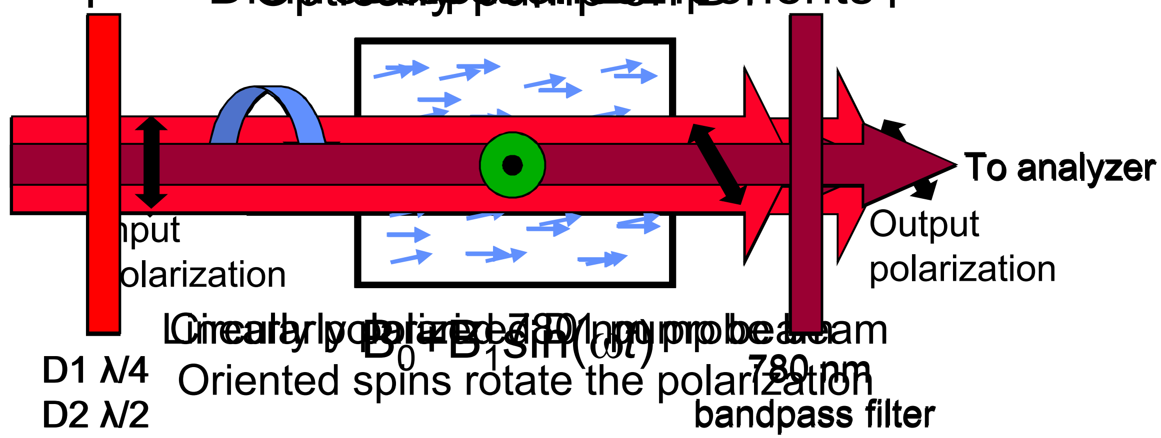
Single axis, elliptically polarized pump/probe scheme

- Circular component pumps, linear component probes
- 7 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

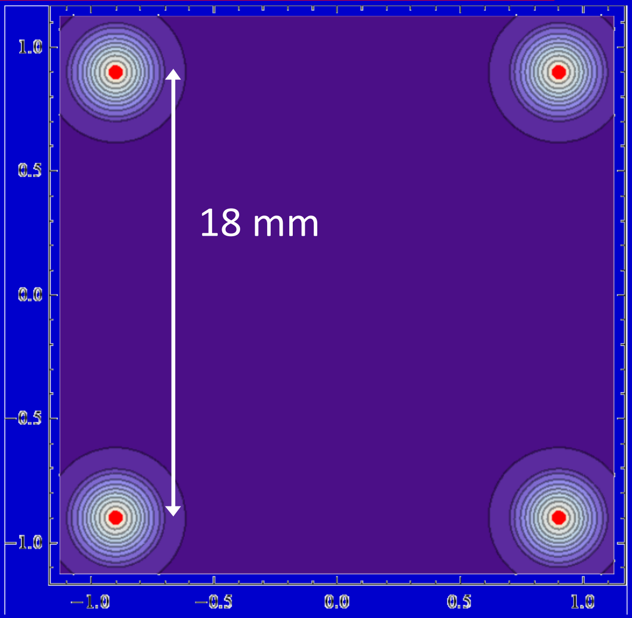


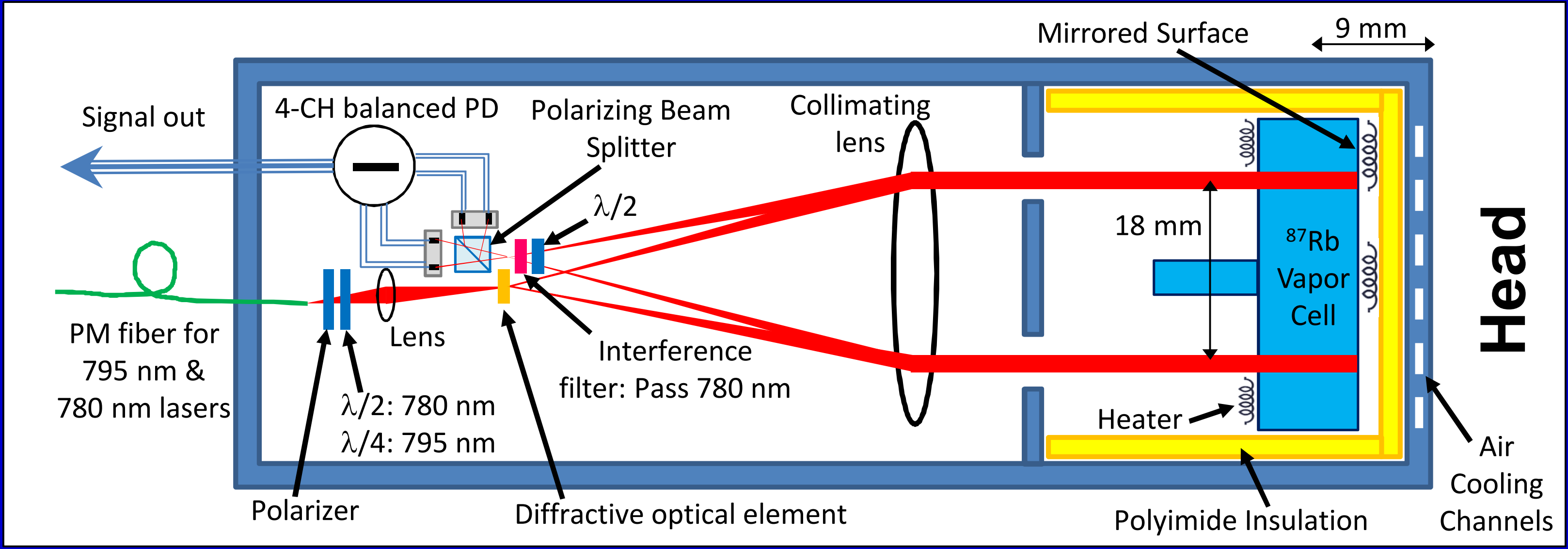
Field modulation/phase sensitive detection required to extract dispersive lineshape



4-Channel Sensor Design

- Four separated beams, 18 mm baseline, 2.5 mm FWHM beam diameter
- Vapor cell: 4 mm long, 600 Torr N_2
- Sensing Volume: 4 mm × π (1.25 mm)^2 = 20 mm^3
- Minimize distance from the head to the vapor cell: 9 mm → 12 mm with extra insulation





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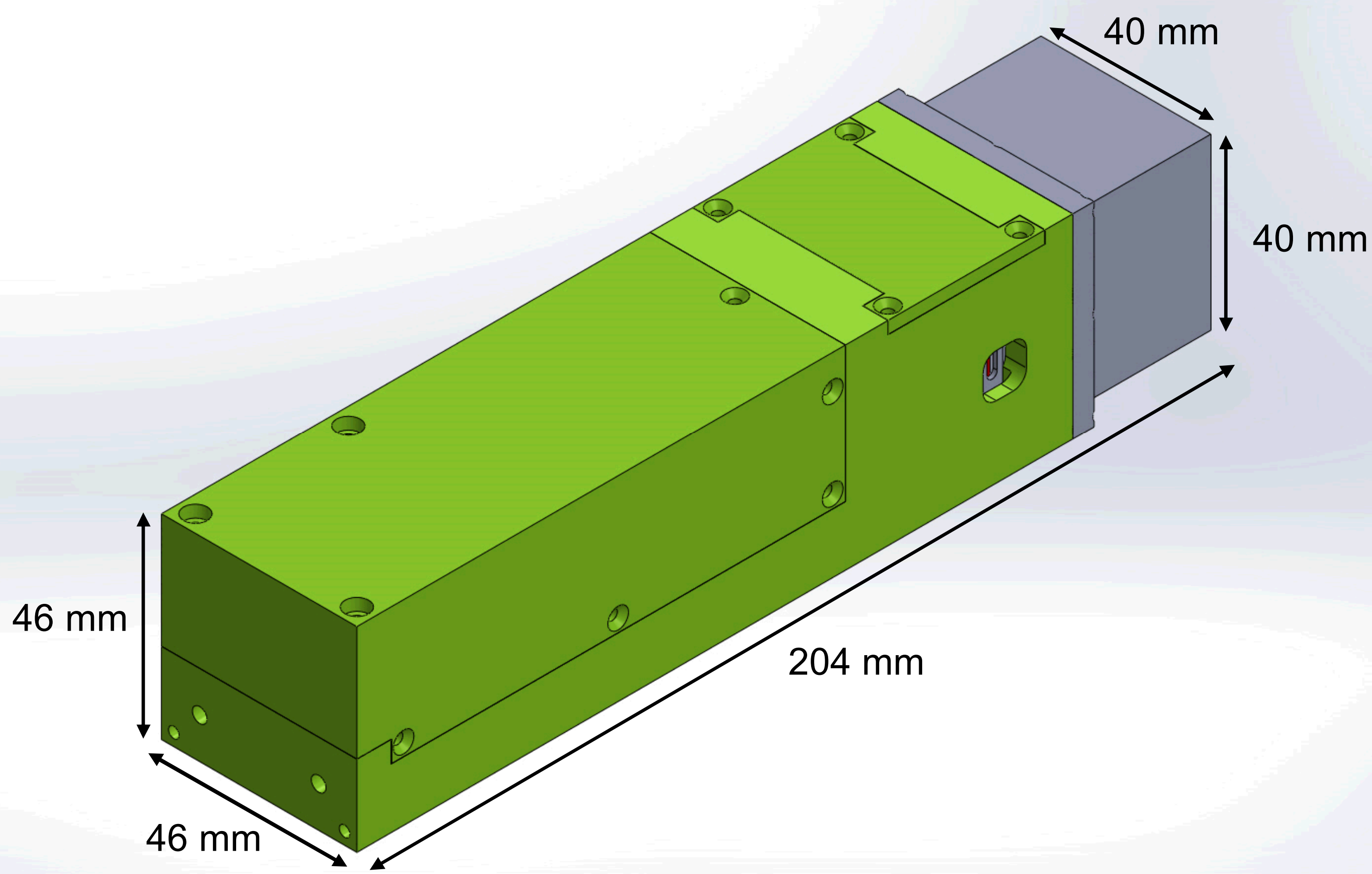
2nd Generation Sensor Design



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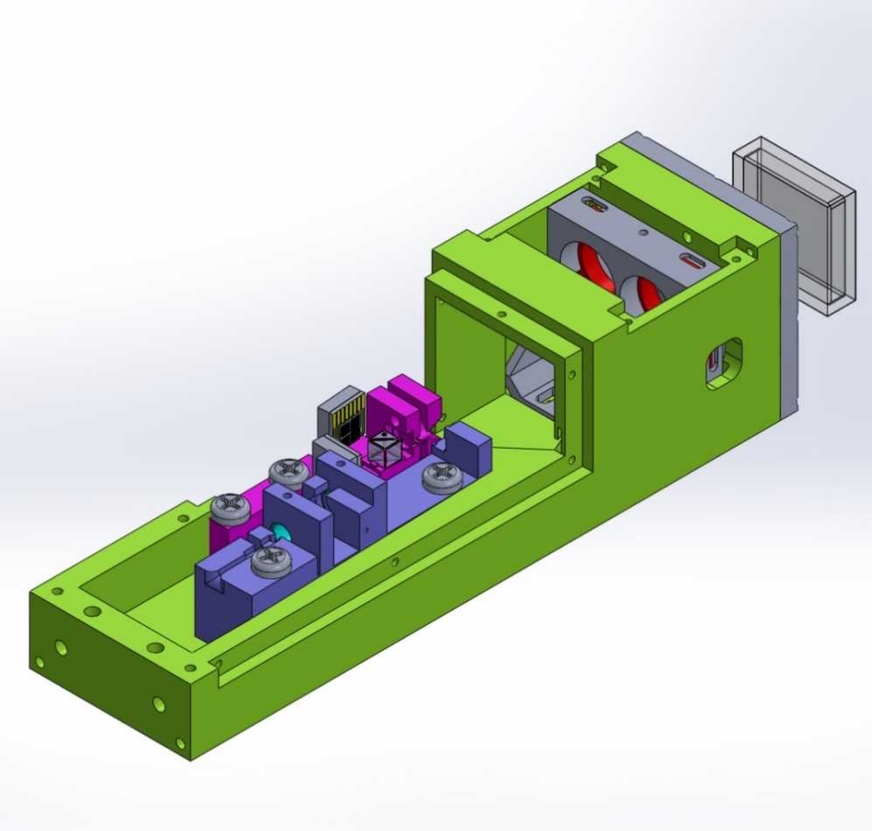
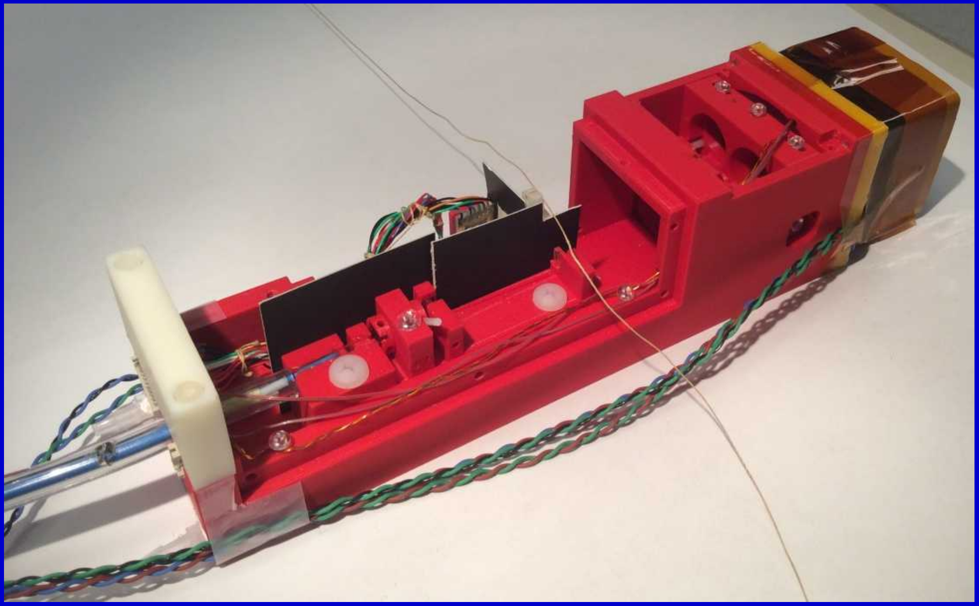
2nd Generation Sensor Design





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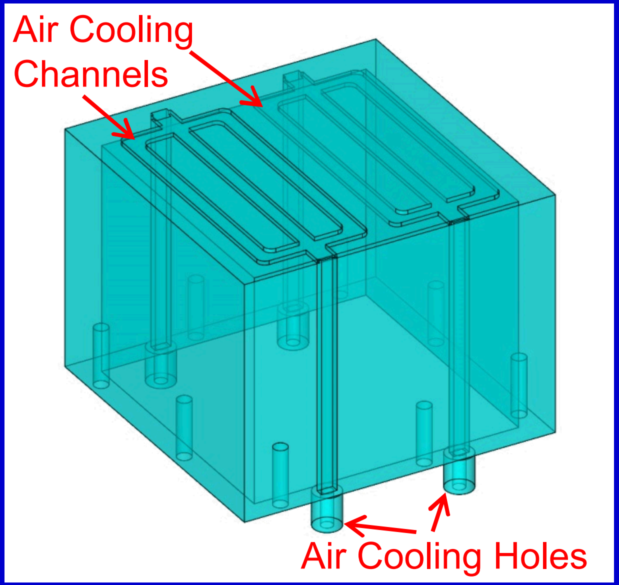
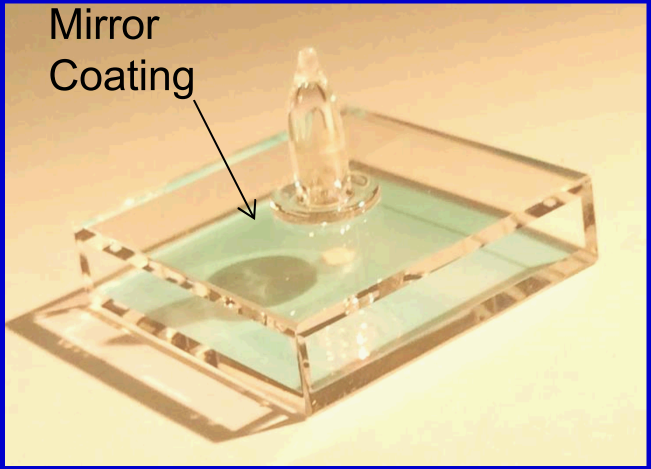
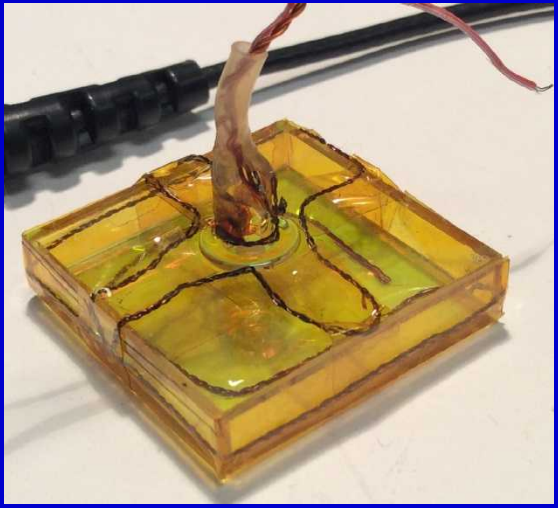
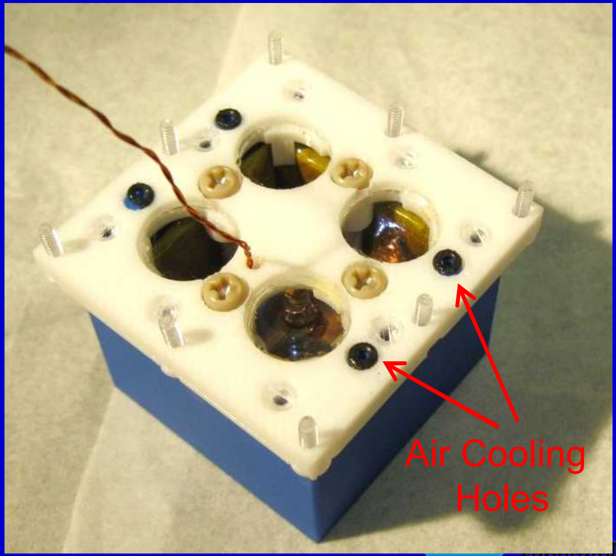
Vapor Cell and Oven



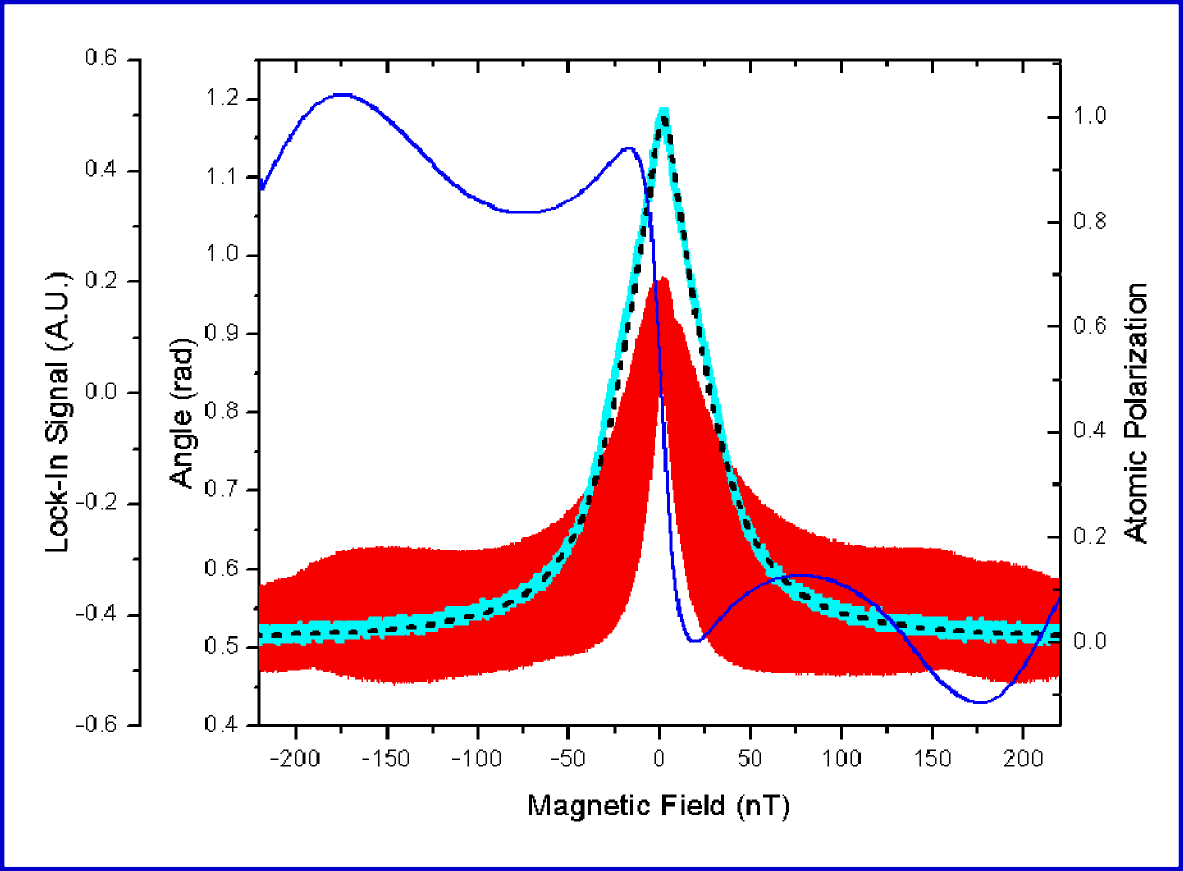
- Vapor cell inner dimensions: 4 mm x 25 mm x 25 mm
- Vapor cell material: Fused silica fails in a month. Switch to Pyrex (sourced from QuSpin).
- Heater: twisted pair of phosphor-bronze wire. Electrical insulation: Formvar fails and Polyimide so far so good.
  - Considering flex circuit material (slightly magnetic, 2-4 pT)
- Oven: 3D-printed ABS and polycarbonate plastic
- Insulation: Aerogel blanket: Pyrogel 2250 (slightly magnetic, ~50 pT); Polyimide blanket: Pyropel MD (less insulating)



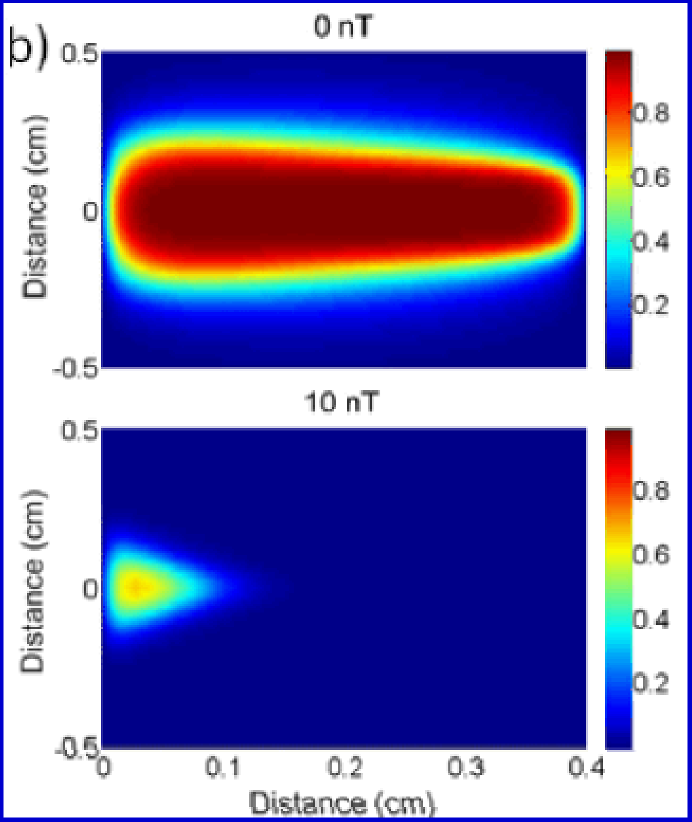




Magnetometer Signals



Calculated Atomic Polarization



Blue trace: Magnetometer (lock-in) signal

Beam propagation direction

Colombo AP, Carter TR, Borna A, Jau Y-Y, Johnson CN, Dagel AL, Schwindt PDD. *Optics Express*. 2016; **24**(14): 15403-16.

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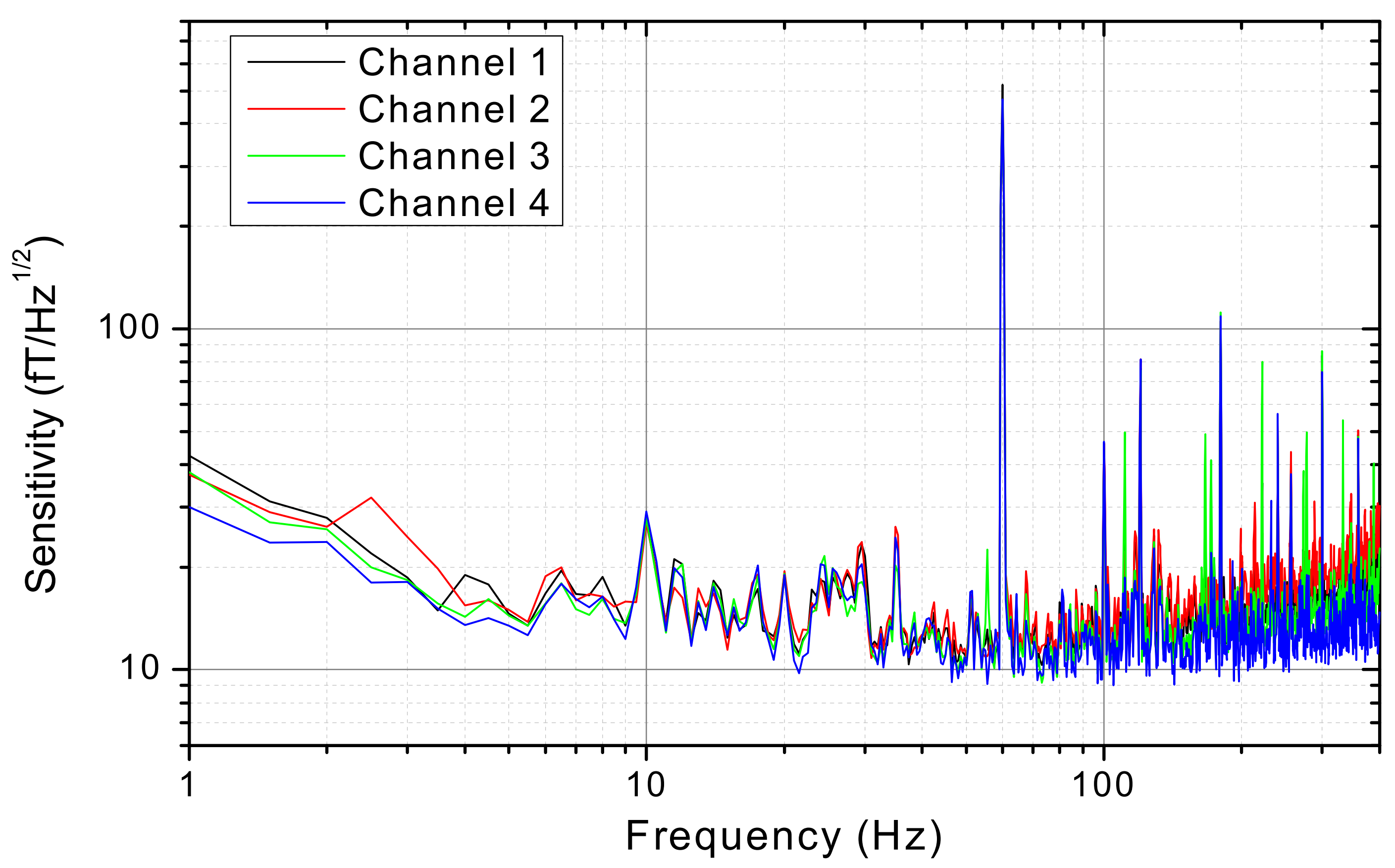
Prototype Performance in a Small Magnetic Shield: 4 Channels



- Current sensitivity: 10–20 fT/Hz$^{1/2}$ over 5–200 Hz

	Ch 1	Ch 2	Ch 3	Ch 4
DC Slope	0.158 V/nT	0.14 V/nT	0.158 V/nT	0.228 V/nT

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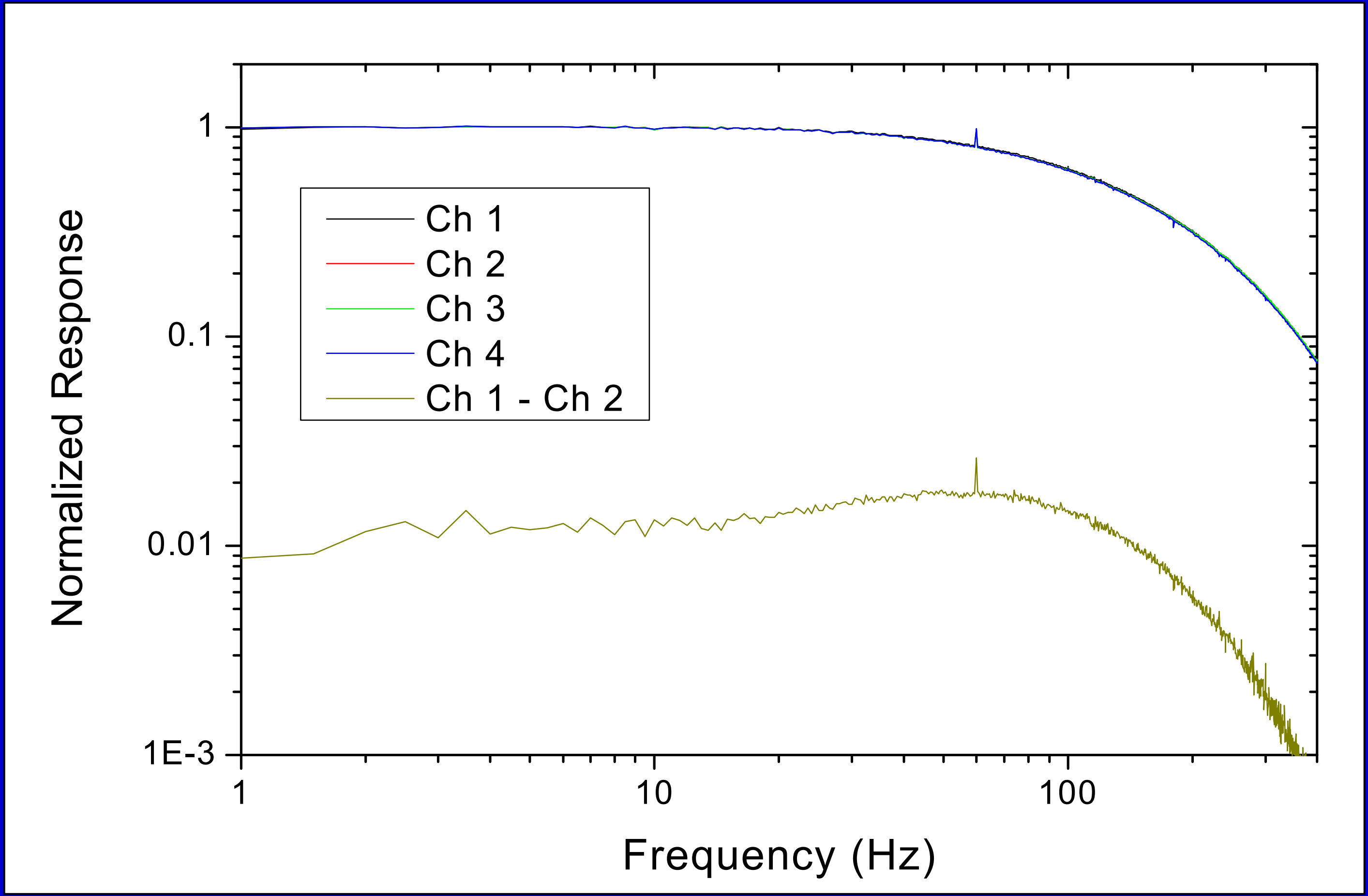
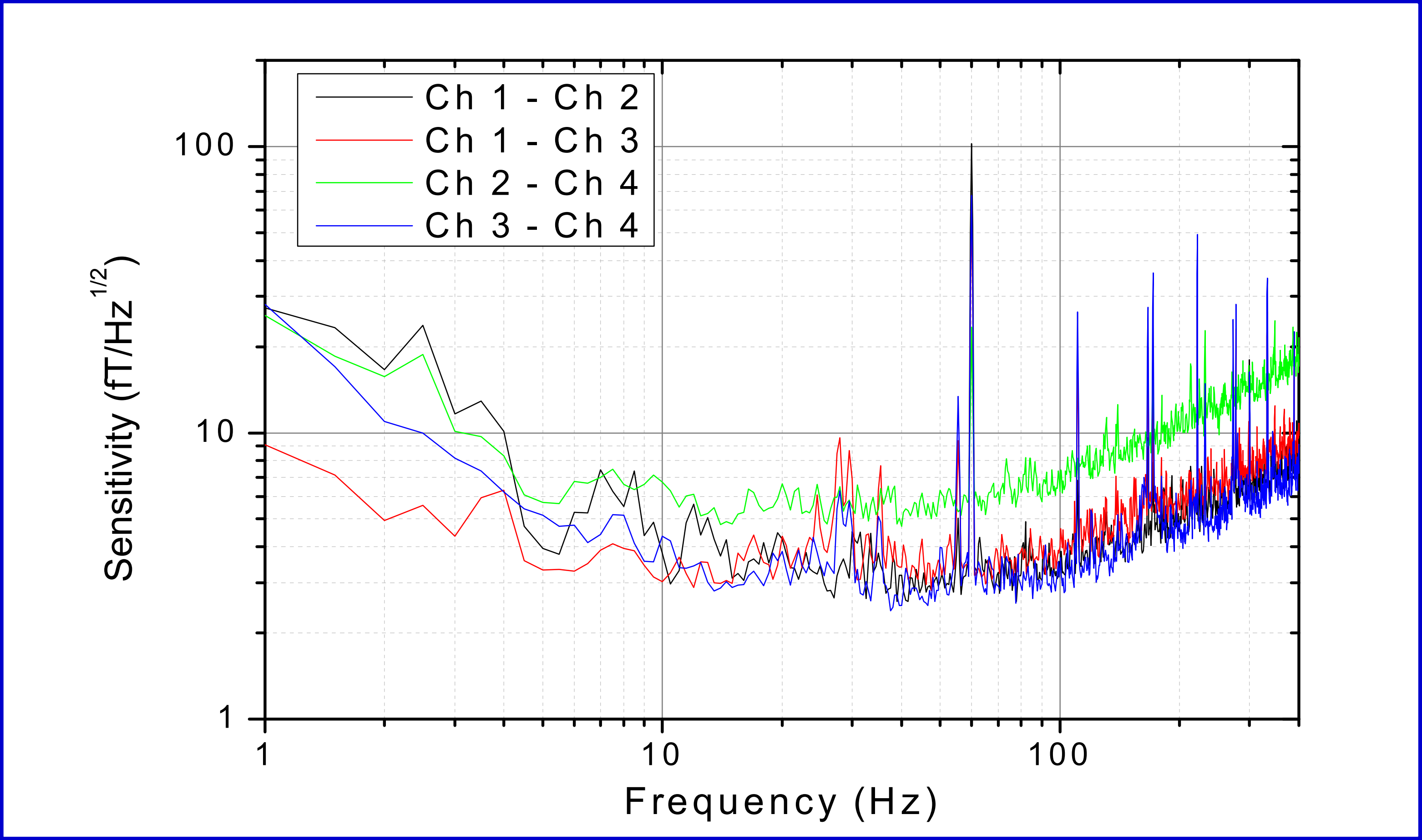
Bandwidth of the Four Channels



	Ch 1	Ch 2	Ch 3	Ch 4
3 dB Bandwidth	83 Hz	85 Hz	87 Hz	86 Hz

Gradiometer Performance



- Single channel sensitivity inferred from gradiometer.
- Gradiometer baseline is 18 mm.

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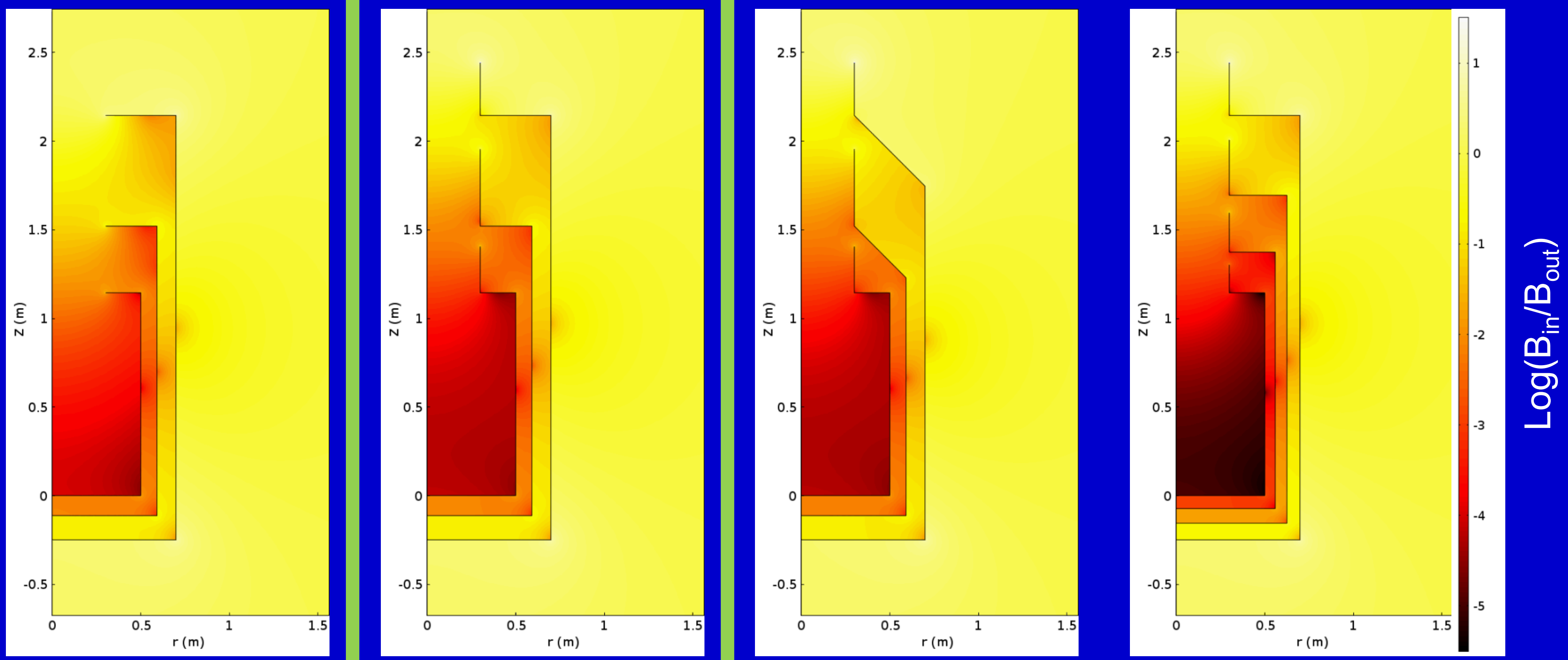
Magnetic Shield Modeling

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

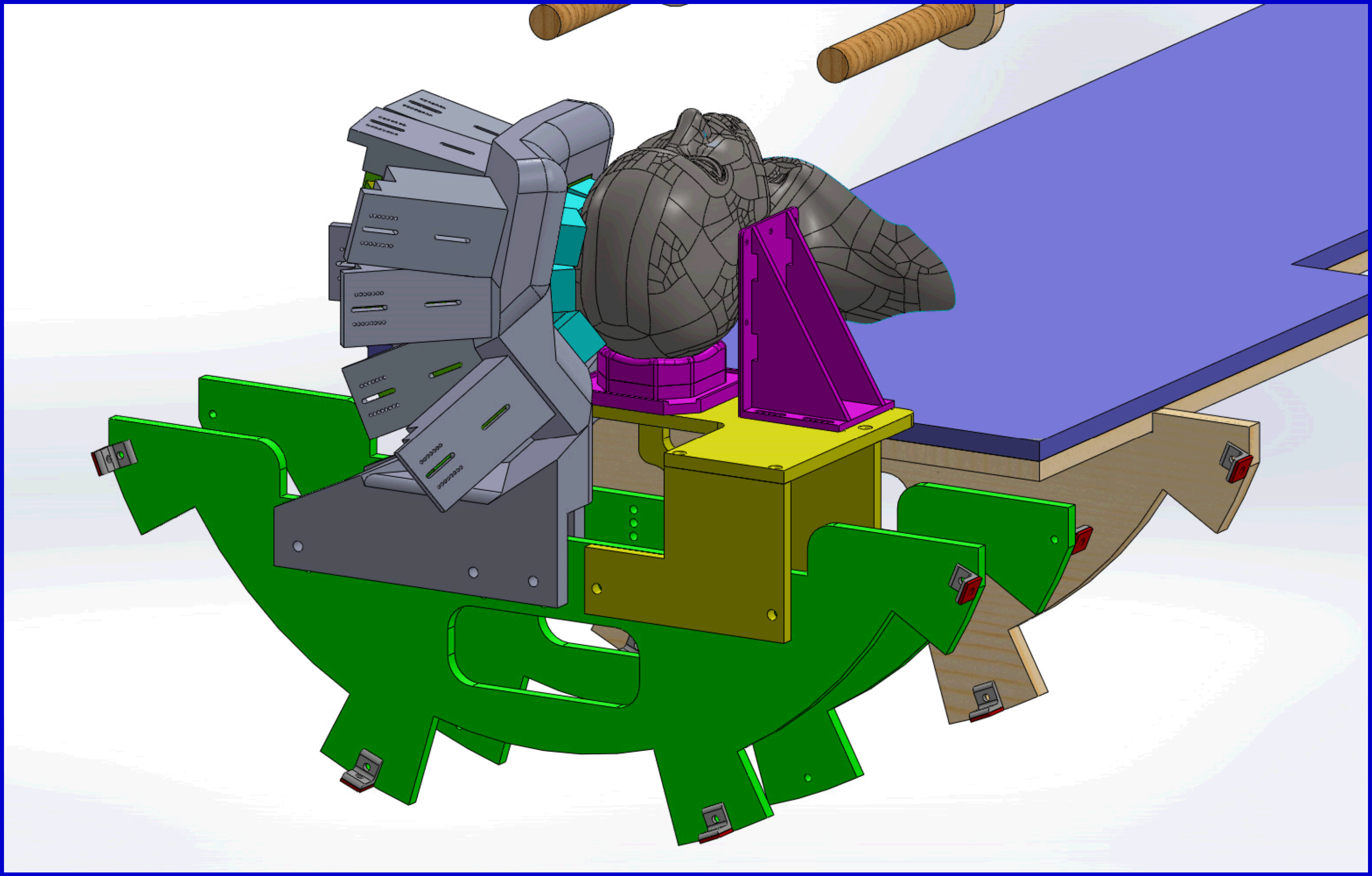


- Focused mainly on longitudinal shielding (transverse shielding much better)
- Asymmetric shield design with tubes leads to larger area of uniform field

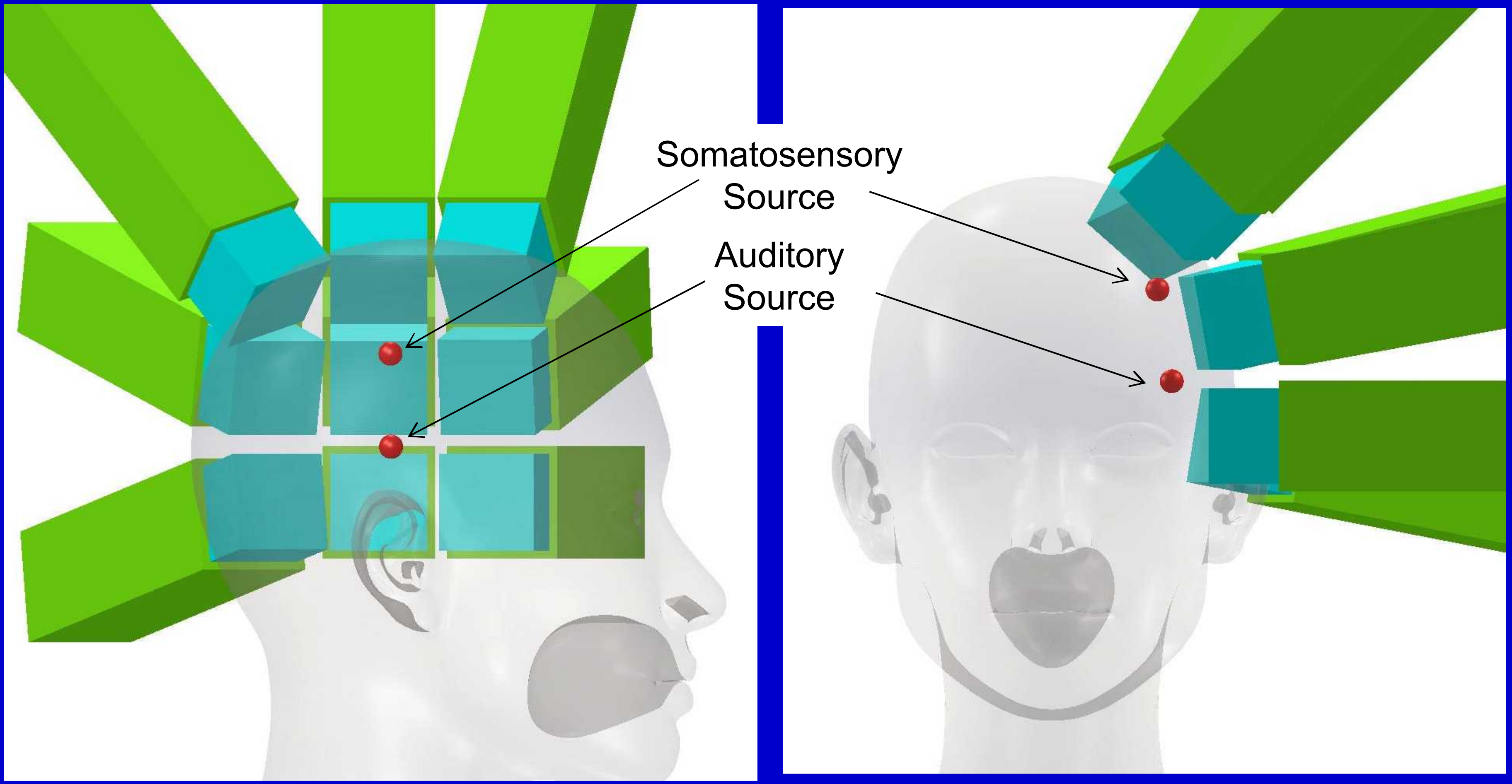
- Longitudinal Shielding factor: 17,000
- Measured: 1,300
- Cost: $62,000




Solid Model of the MEG Array and Subject Support

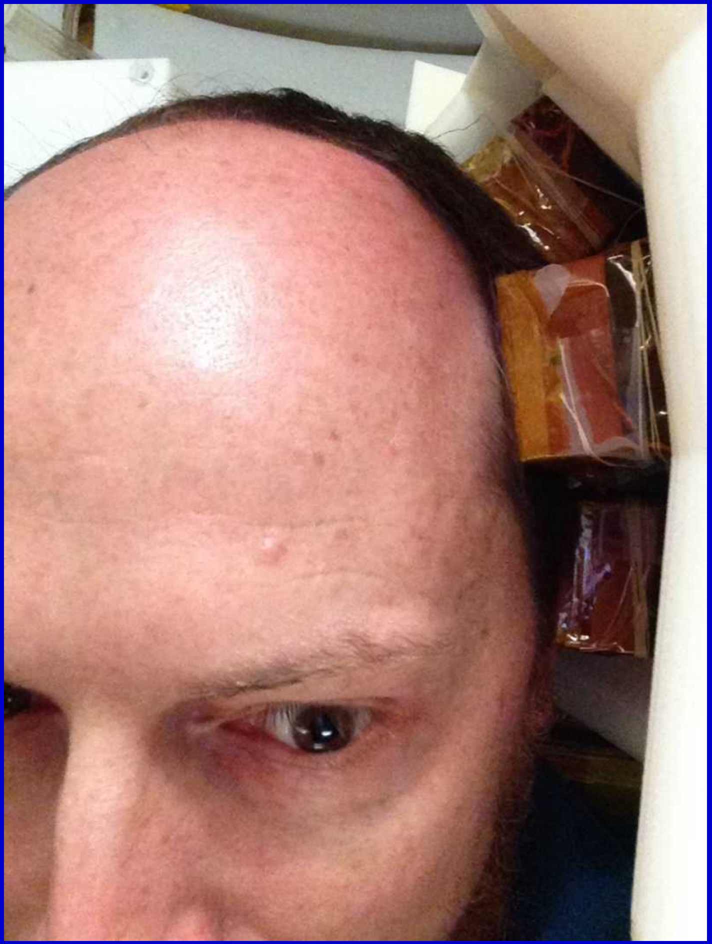


36-Channel Array on the Head

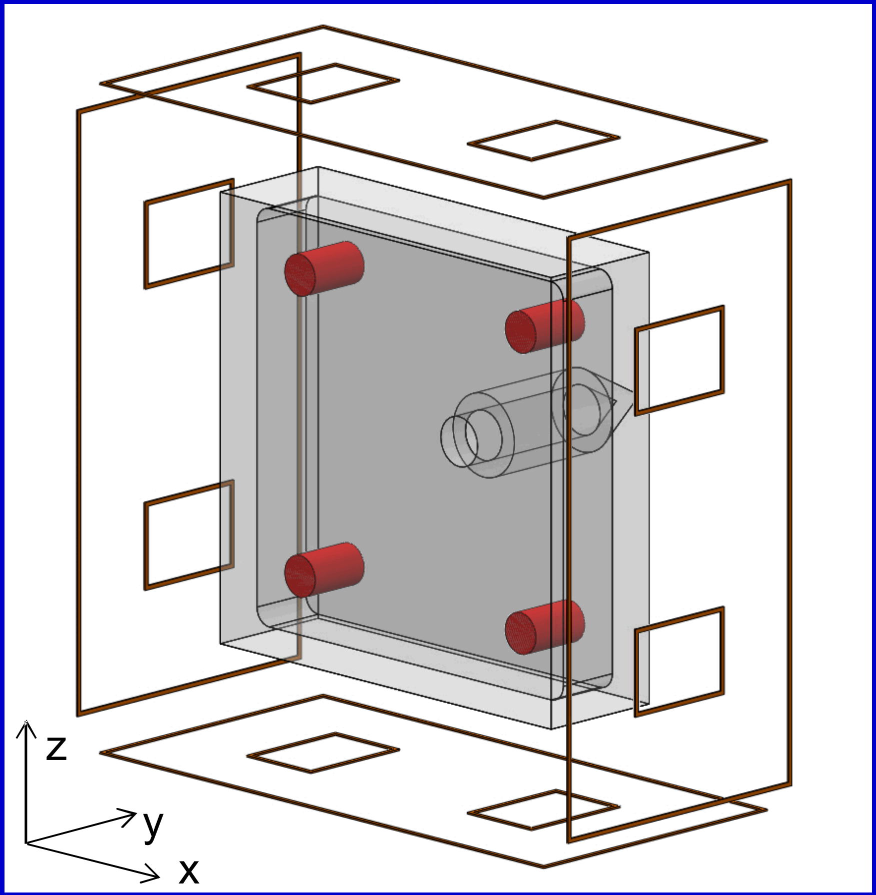


20-Channel Array Installed

5-sensor, 20-channel array



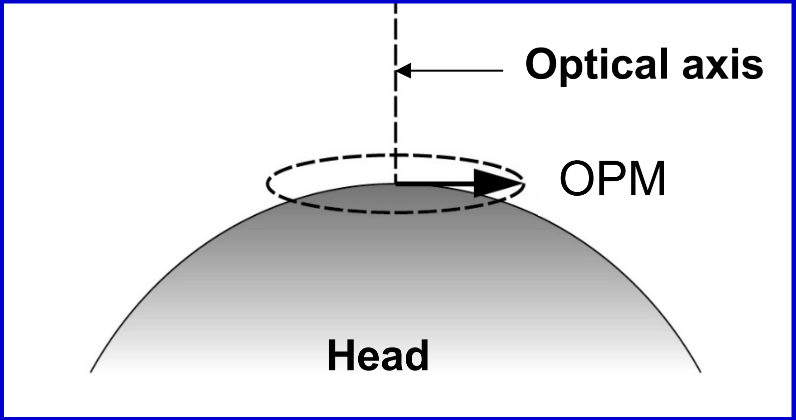
Field Modulation and Coils



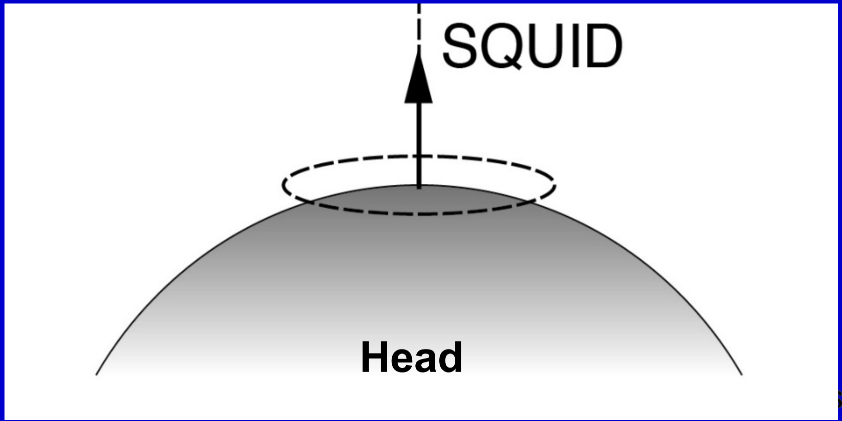
Outer coil 18 mm x 36 mm, Current = +1

Inner coils 5 mm x 7 mm, Current = +1, offset from center is 9 mm

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



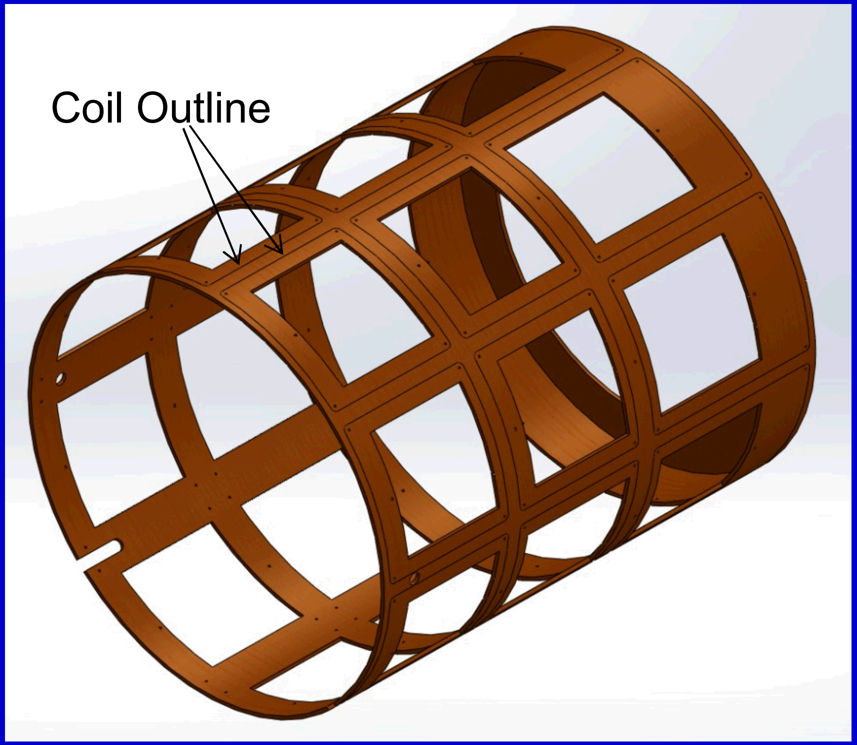
SQUIDs typically measure fields perpendicular to scalp (coils are parallel to scalp)

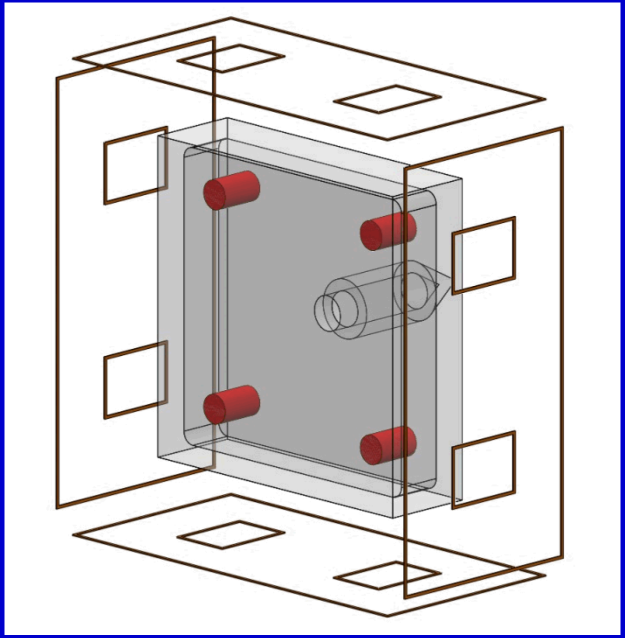


Magnetic Field Control and Data Acquisition

Magnetic Field Control

- 63 coils to control
- 18 large coils *a la* Romalis
  - Homogenize the field across the array
  - Optimization using the sensor array
- 5 x 9 = 45 on-sensor coils
  - Mainly to provide modulation
- 96-channel analog output from National Instruments
  - Filtering with a custom buffer board

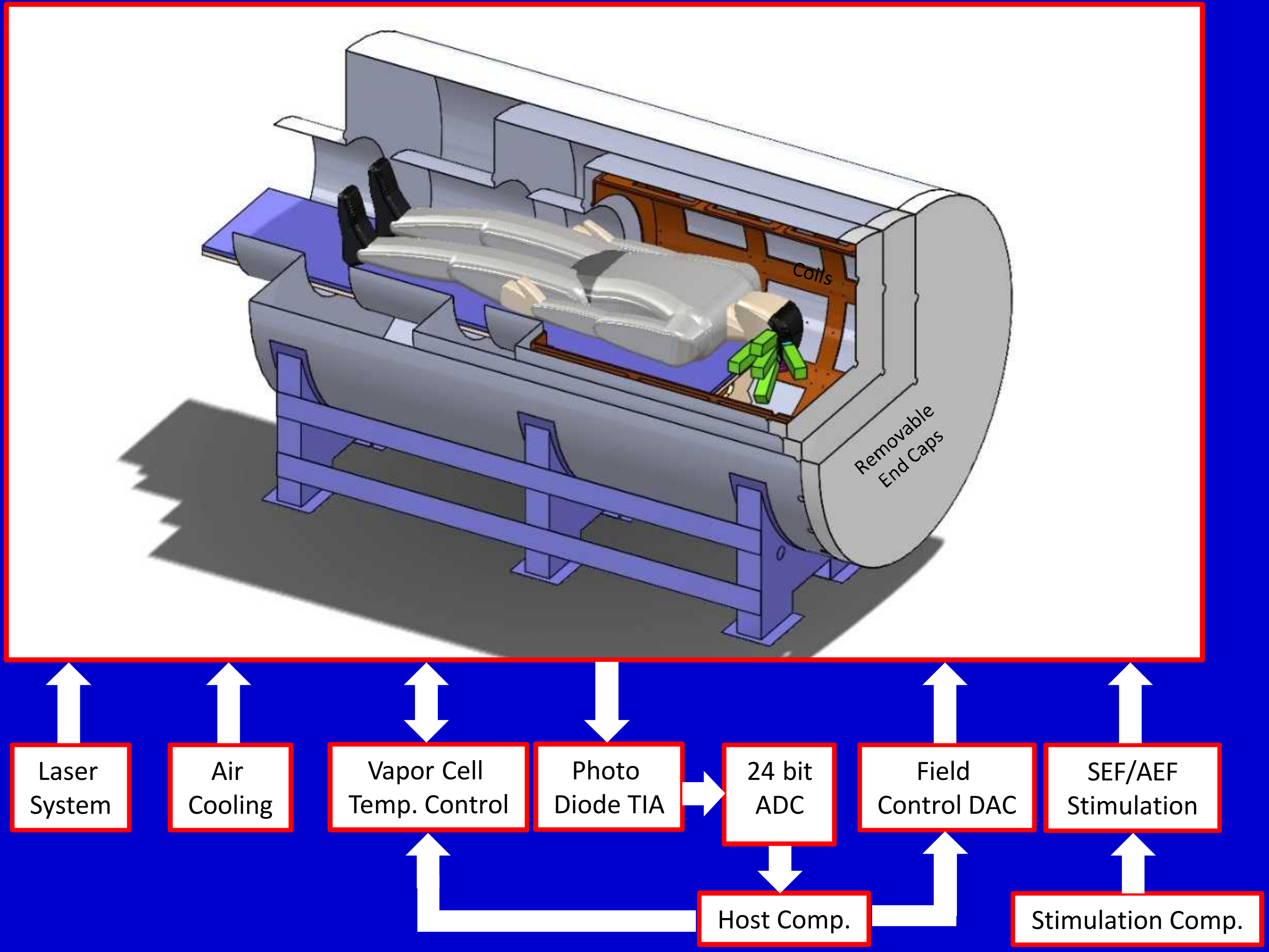




Data Acquisition

- Two 20-channel custom-built transimpedance amplifier (QuSpin)
- NI 48-channel 24-bit analog input card
  - Other channels for stimulation triggers, eye blink, and heartbeat monitor
- LabView software lock-in

Putting It All Together



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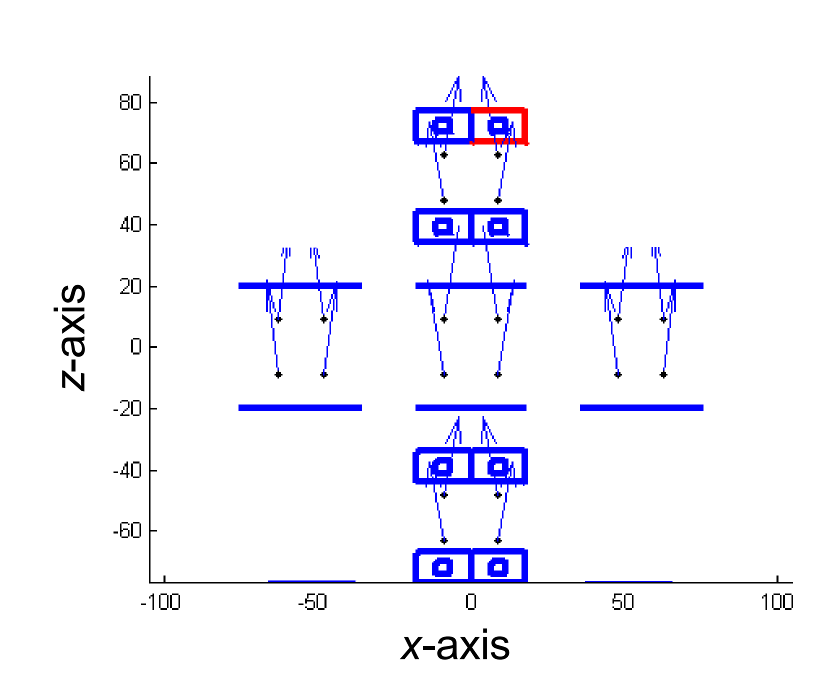
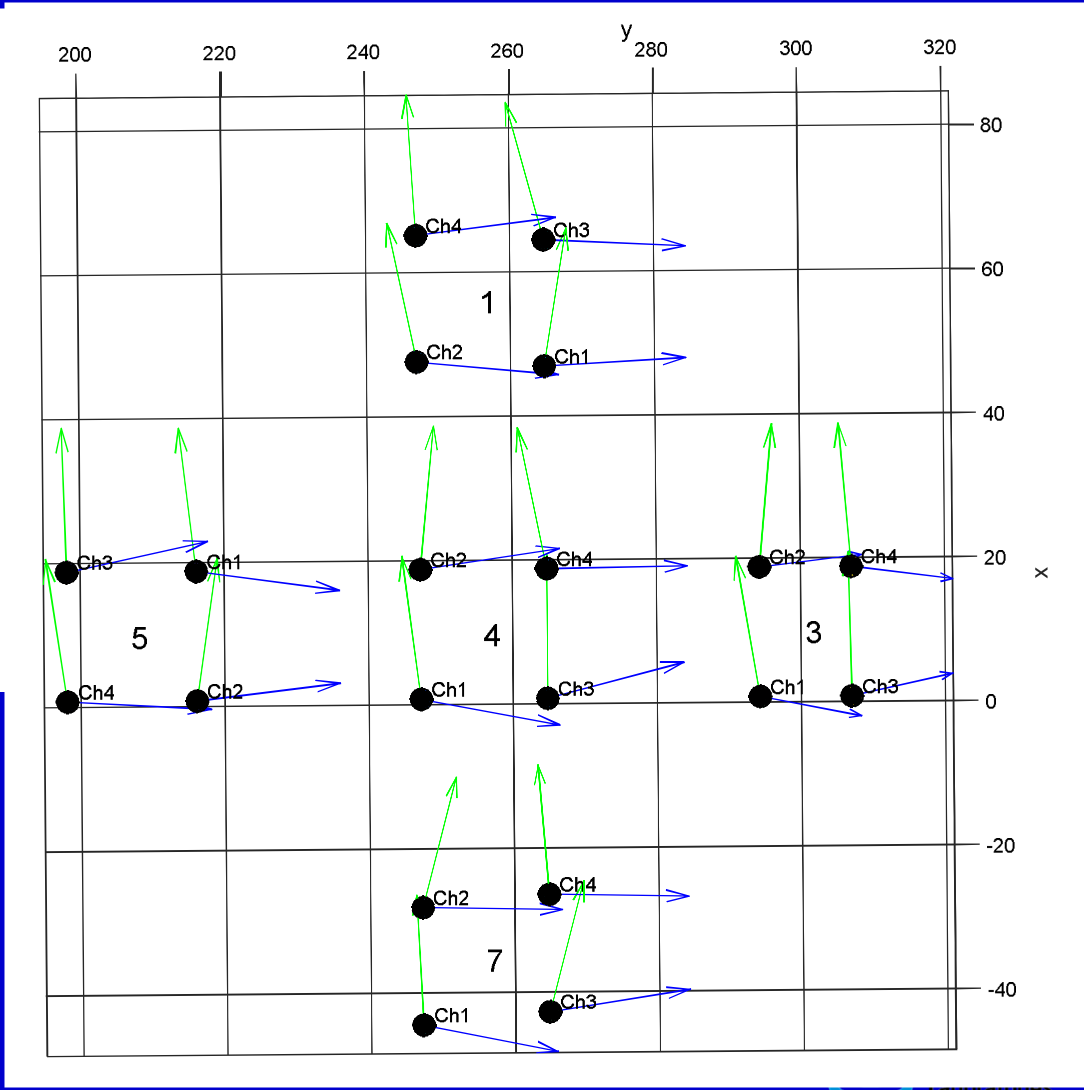
20-Sensor Array

Modeled



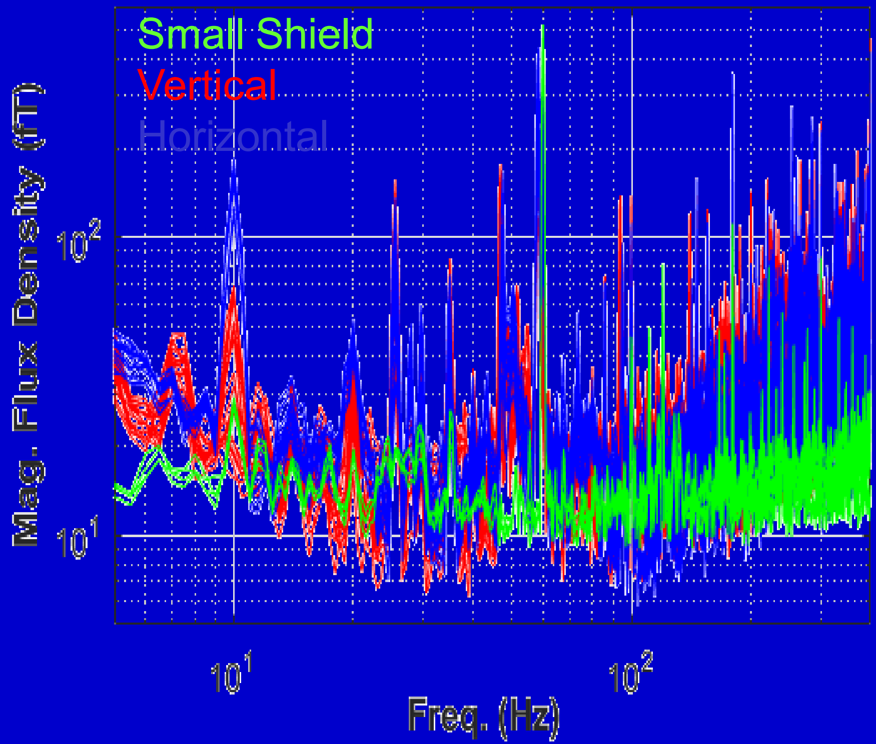
Measured



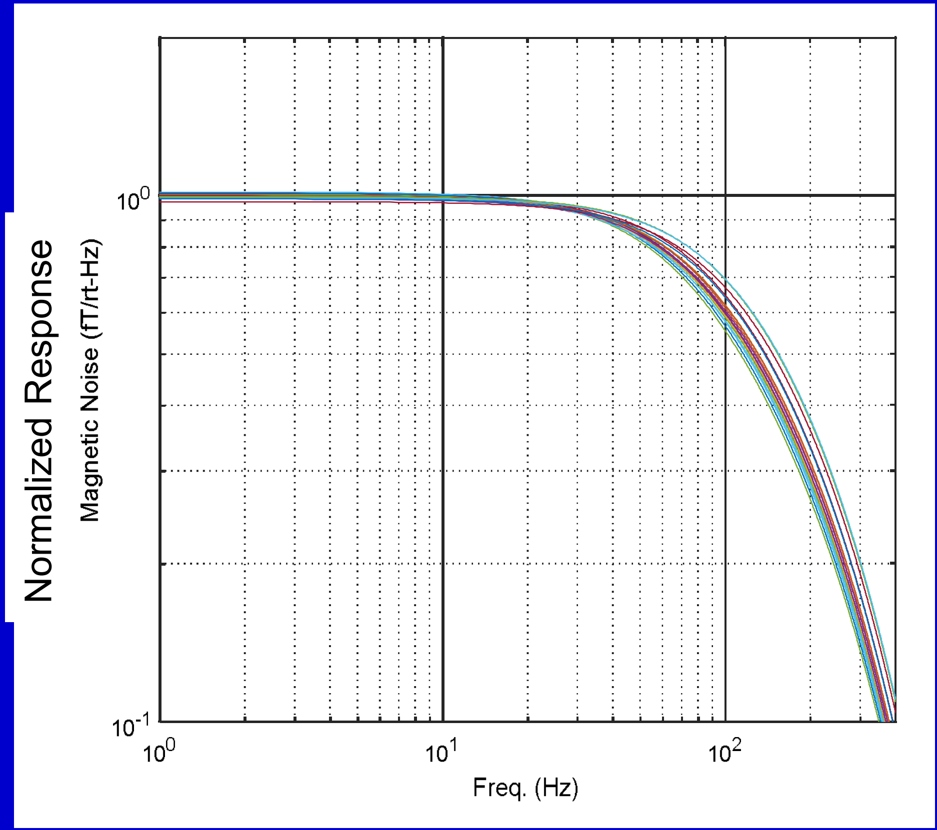
- Field direction difficult to know exactly
- Calibrate each sensor to know its measurement direction

Measuring the Performance of the 20-Channel Array

Magnetometer noise (not normalized)
Vertical field component

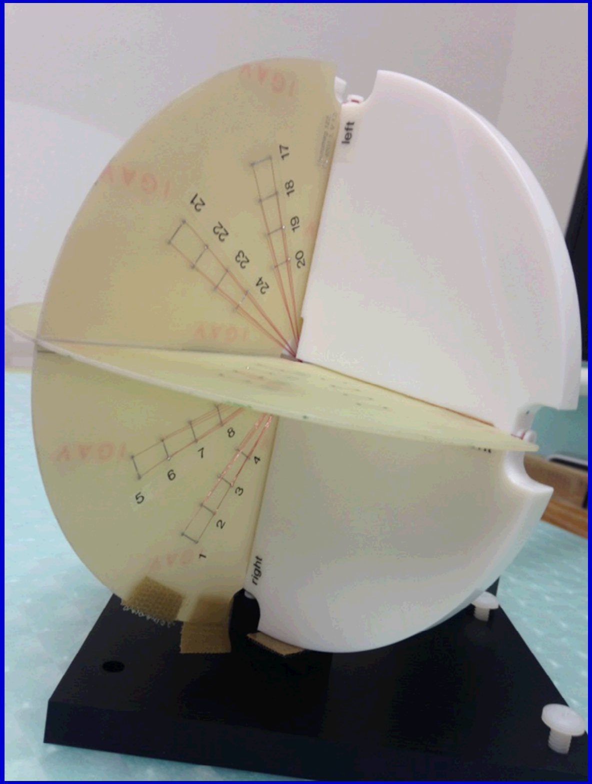


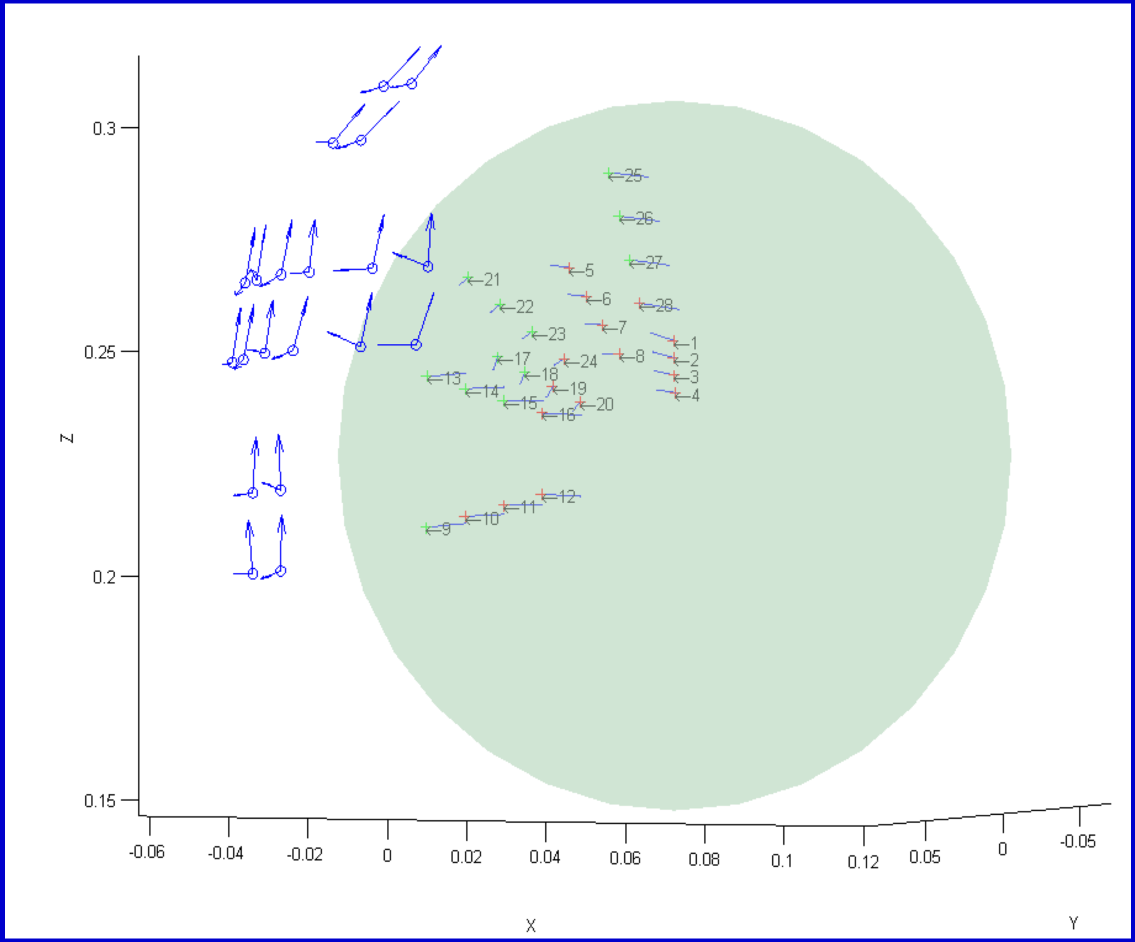
Frequency Response



Phantom Studies

- Old Neuromag phantom
- Applied 1 mA at 10 Hz
- Green mark indicates < 10 mm localization accuracy





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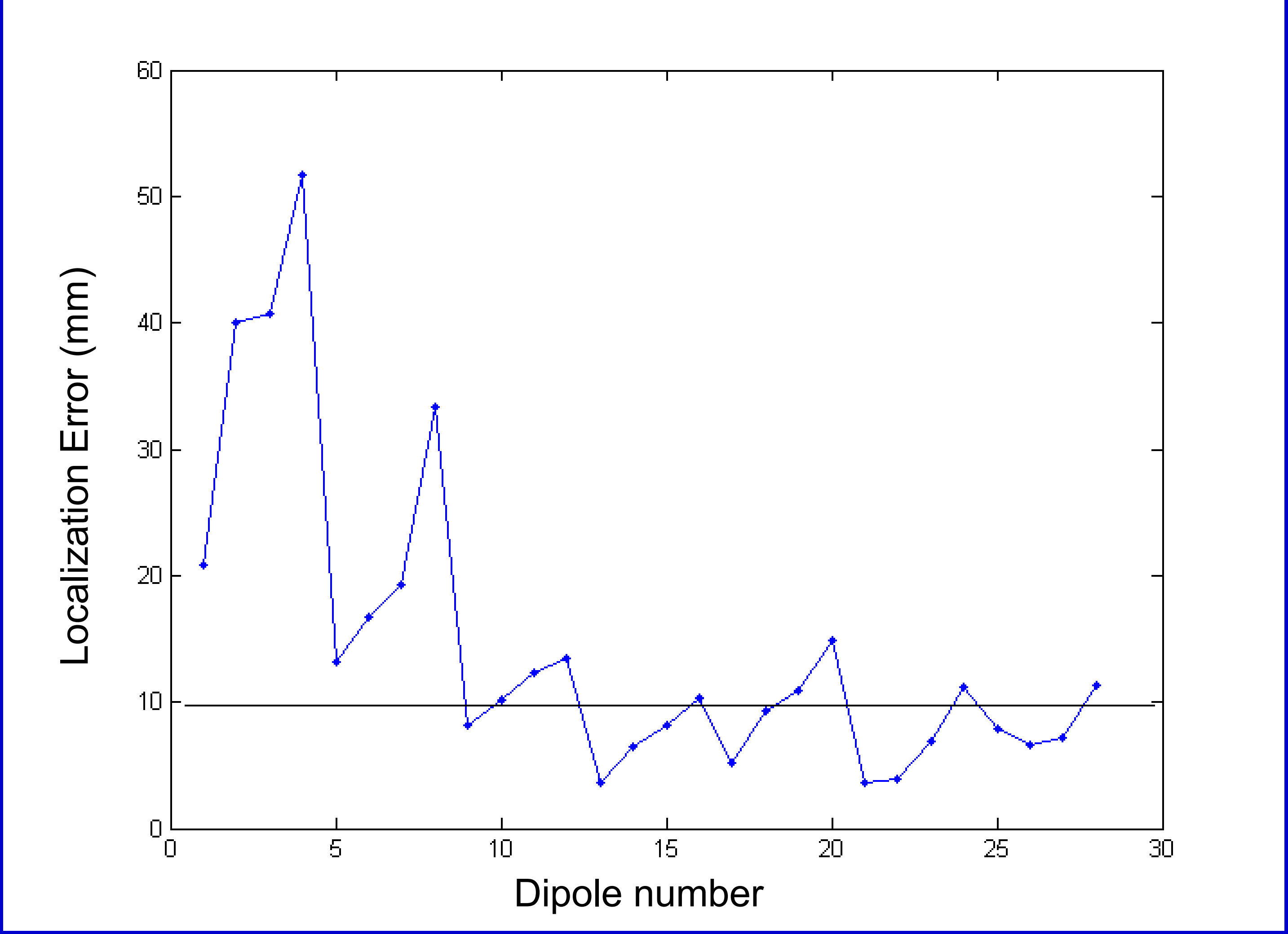
Phantom dipole localization error



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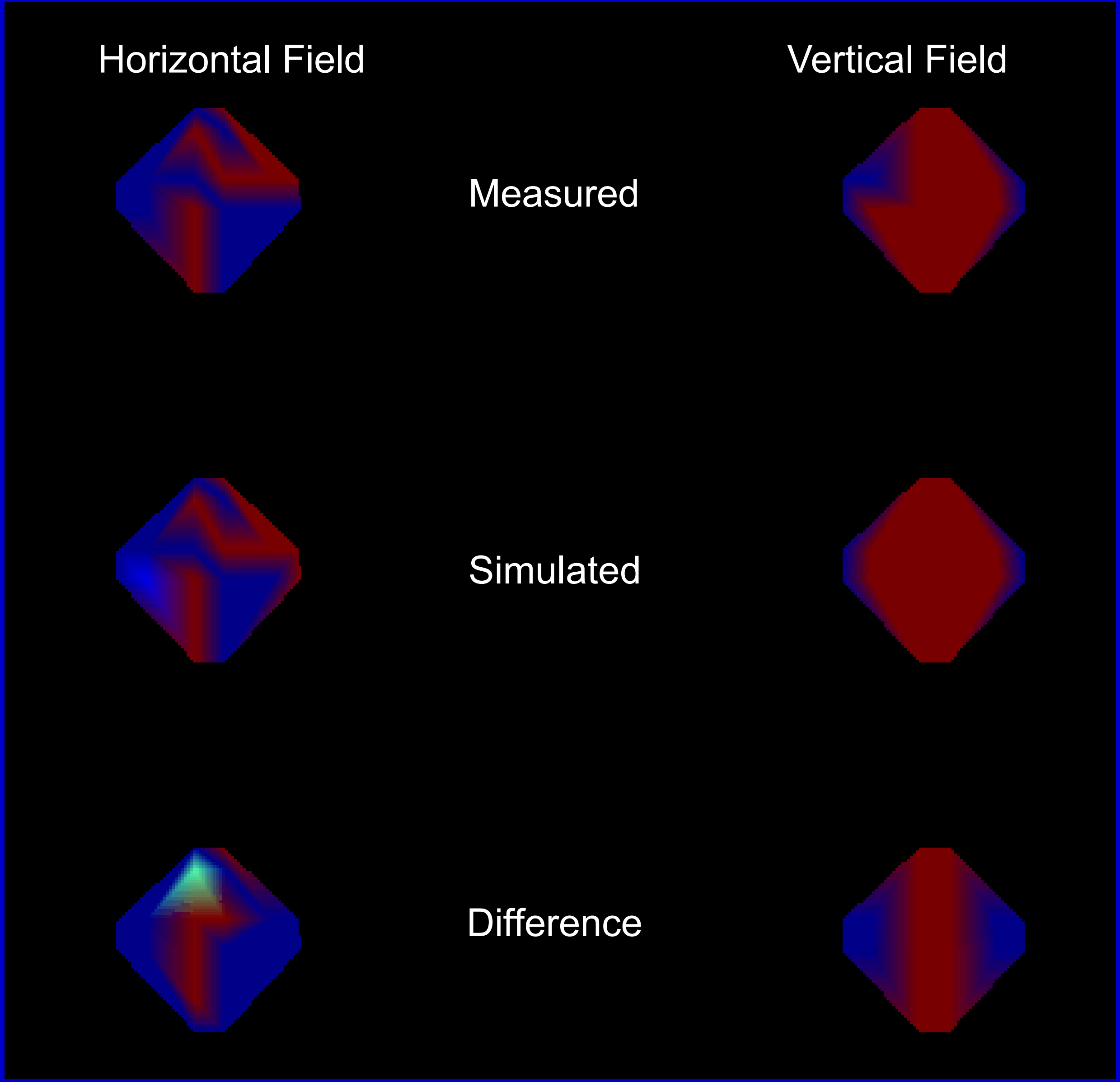
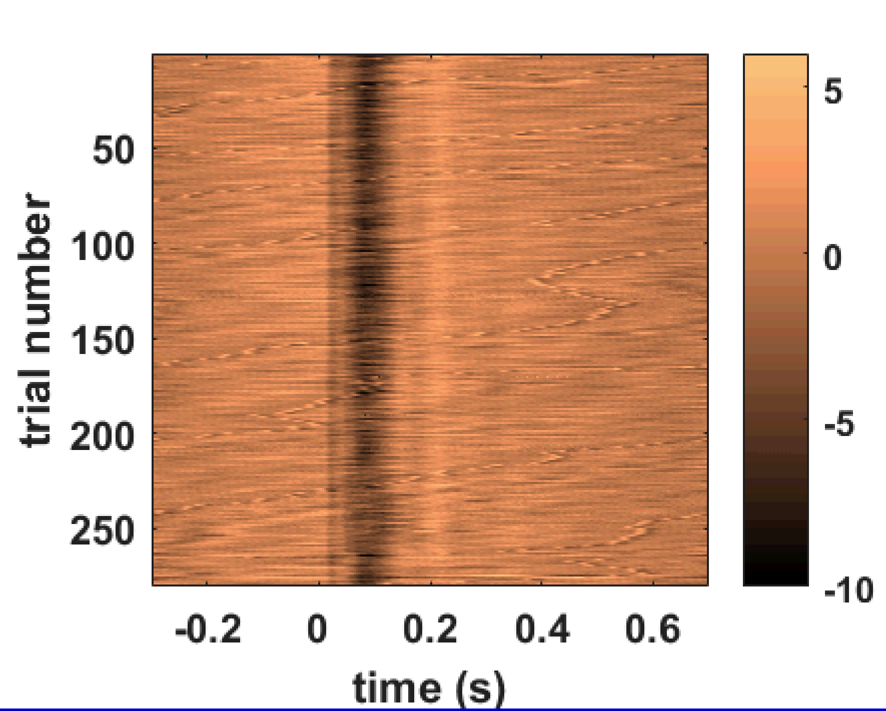
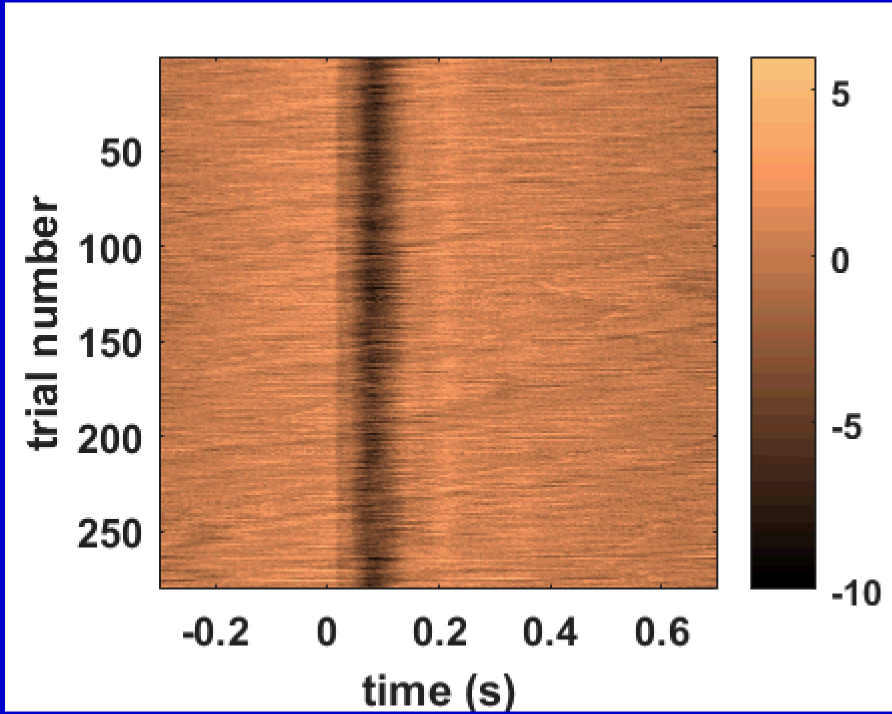
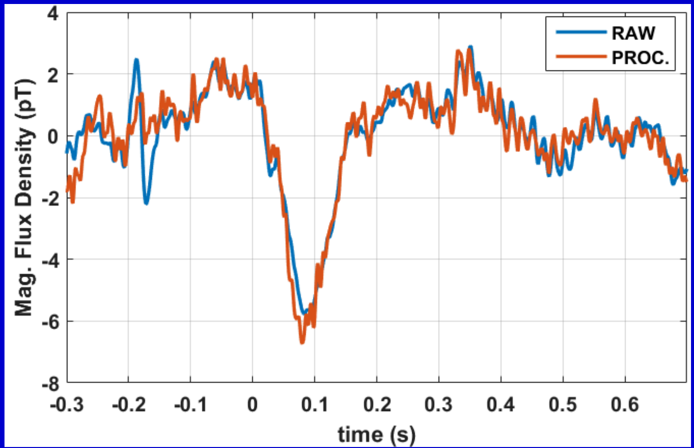
Field Maps of Dipole Sources

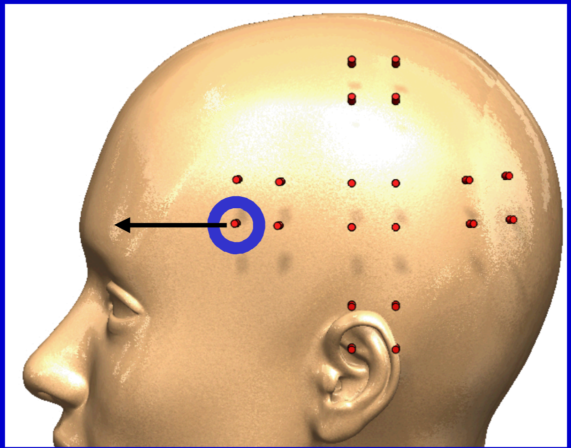


Median Nerve Stimulation, Somatosensory Evoked Fields: Single Trial Data









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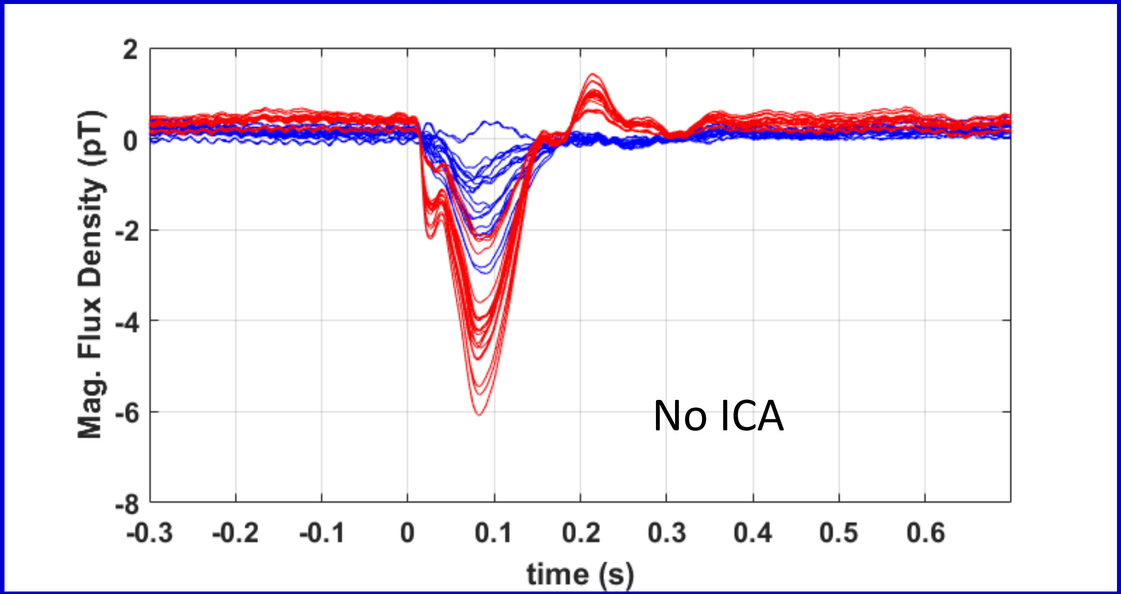
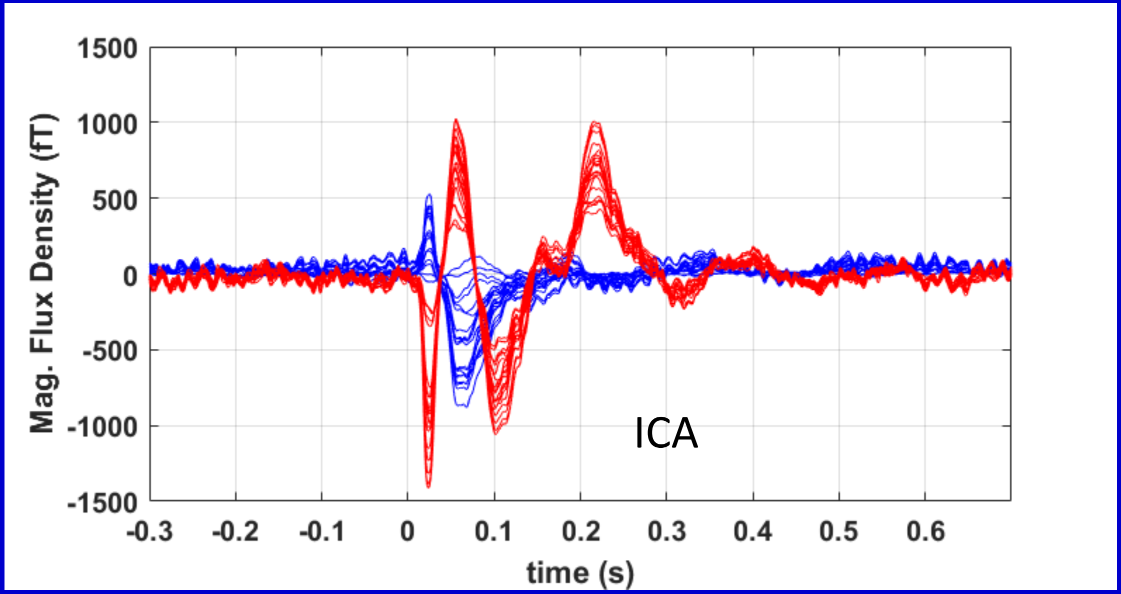
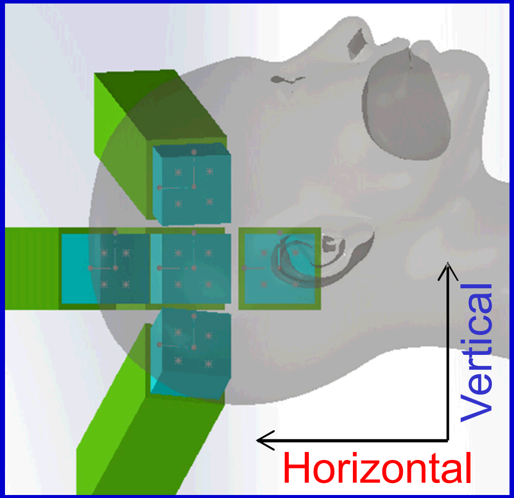
Median Nerve Stimulation, Somatosensory Evoked Fields (SEF): Averaged Data





- Filter: 1 to 200 Hz
- Trials: 360
- Baseline offset removed
- Use independent component analysis to remove noise and unwanted signals



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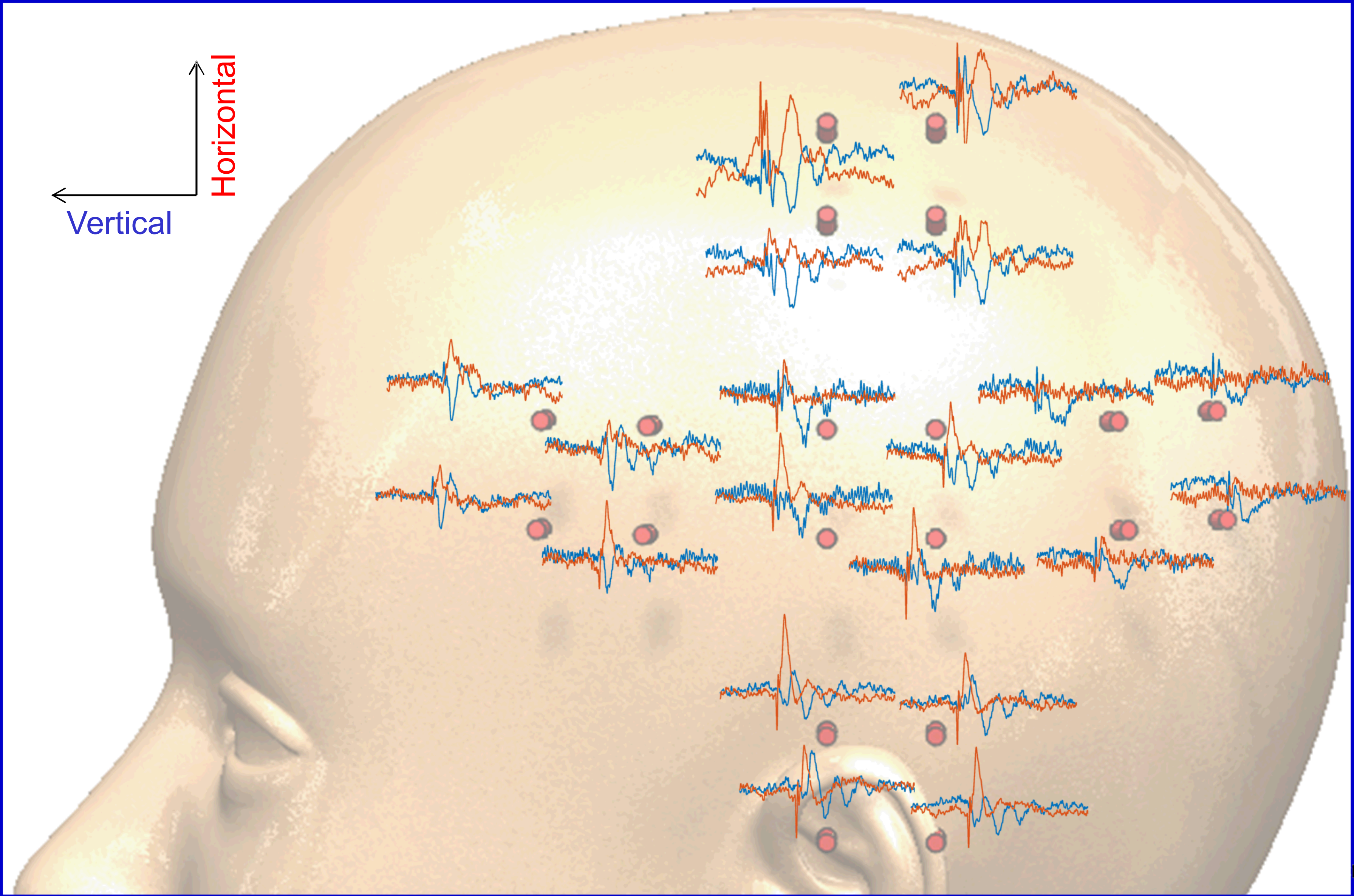
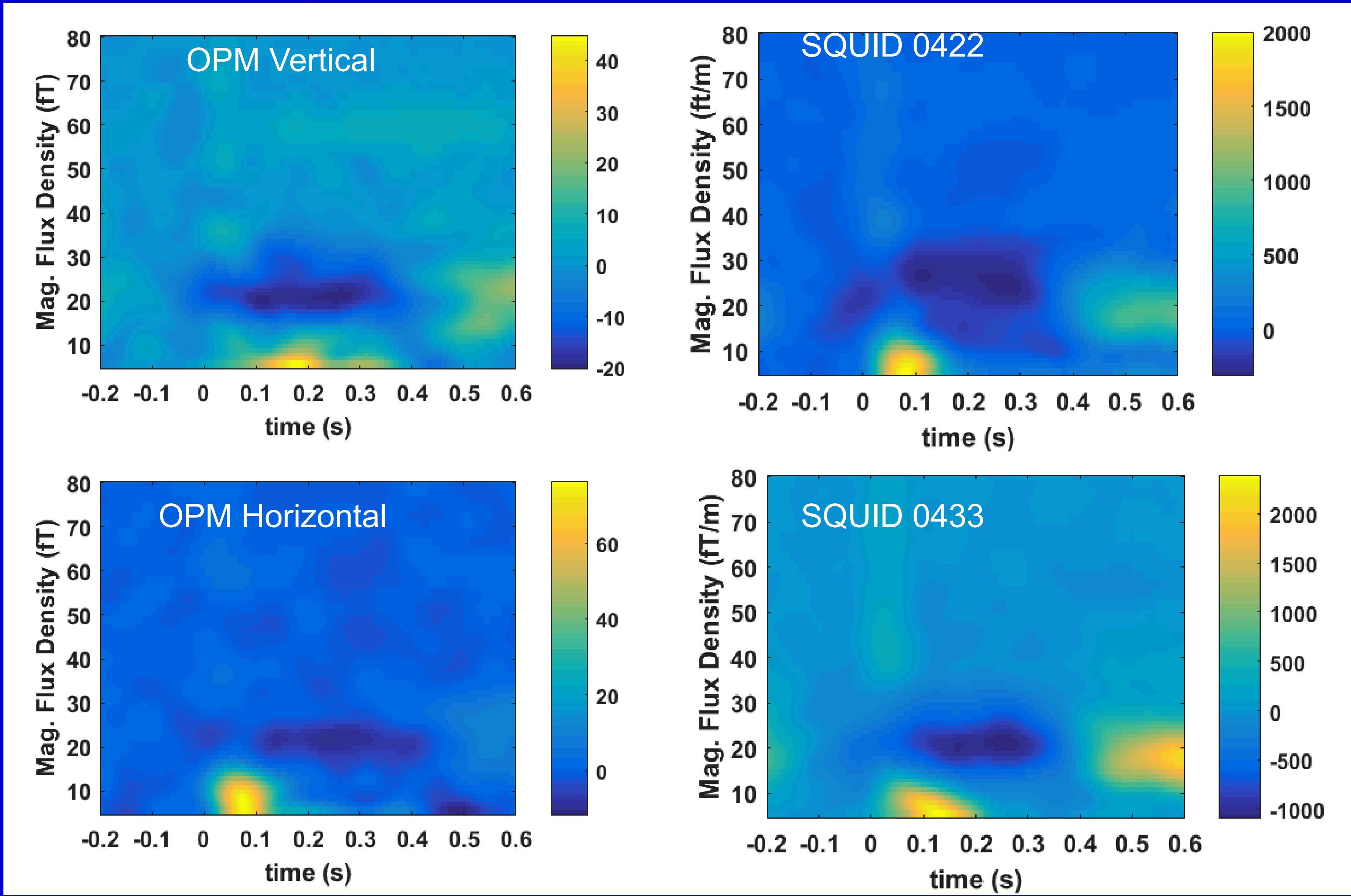
Spatial Distribution of Signals



Comparison to SQUID Measurements



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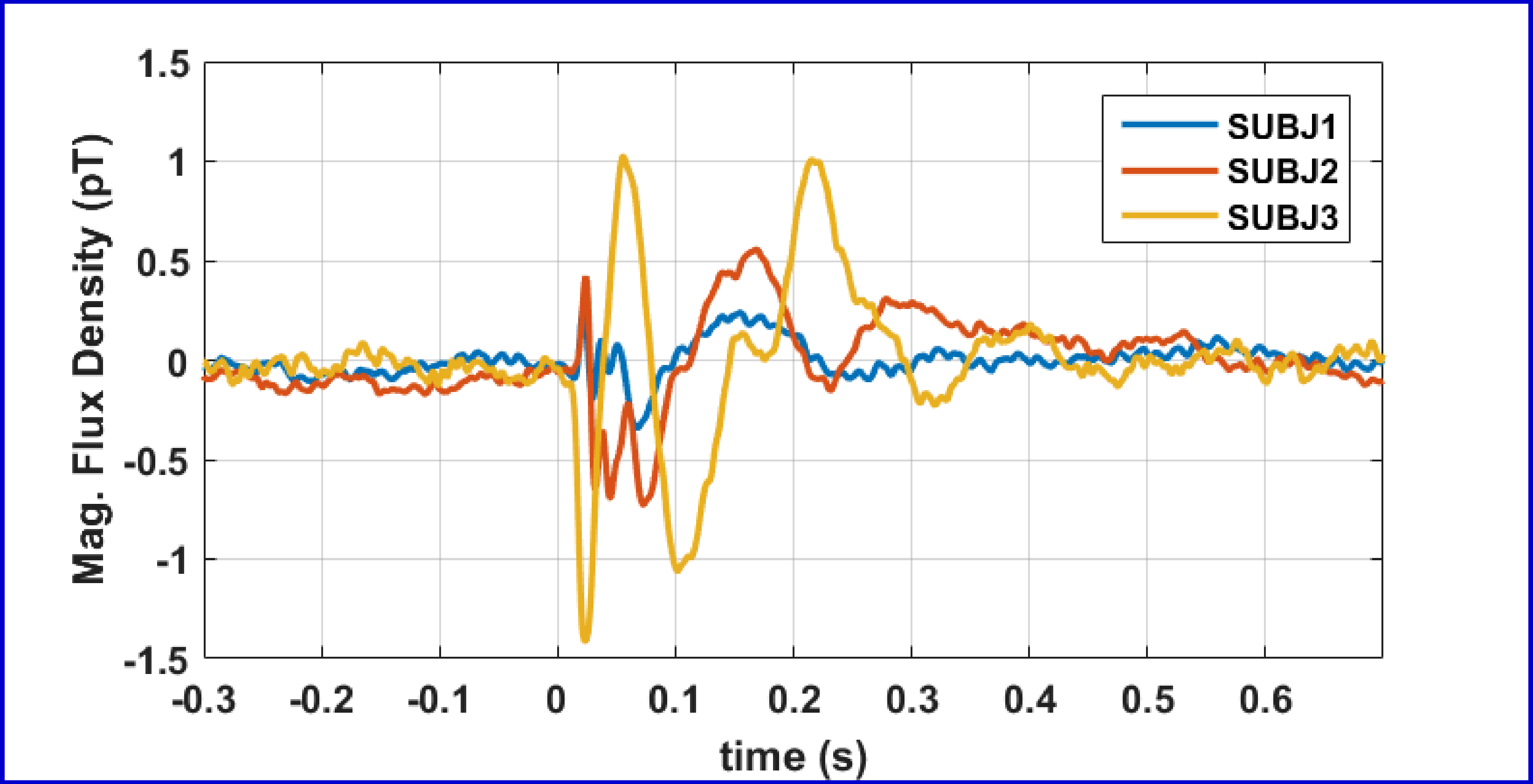
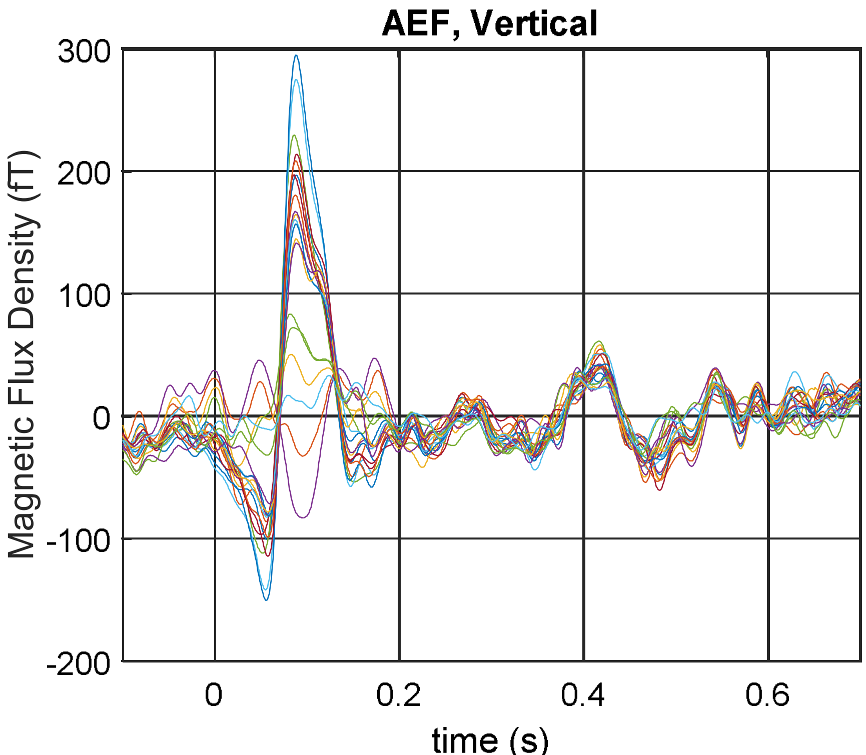
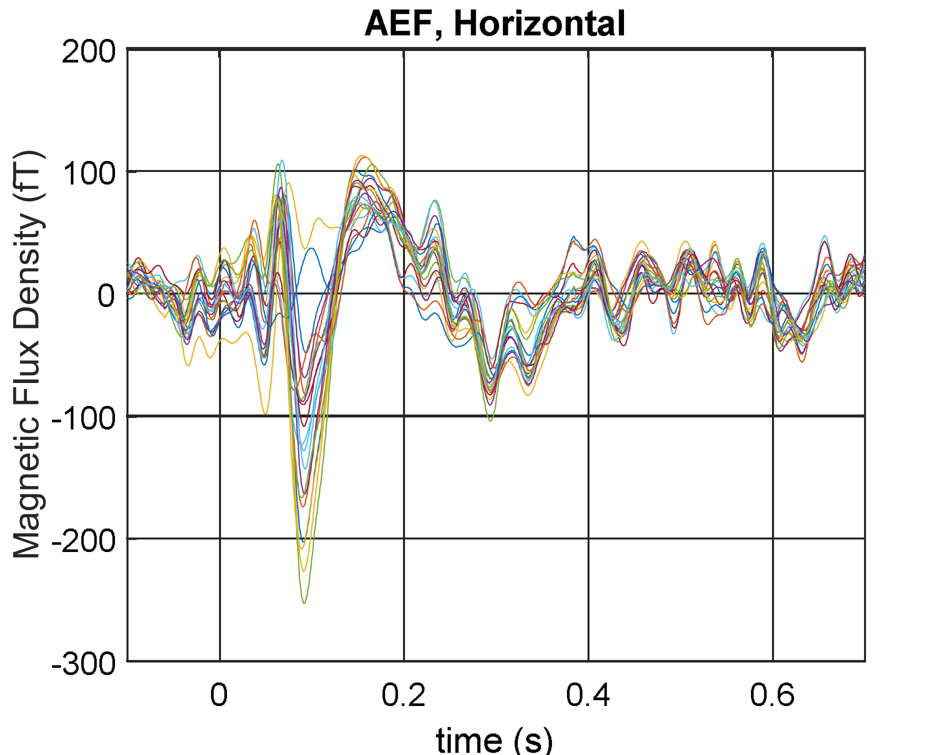
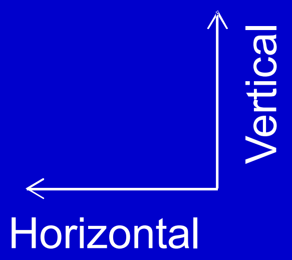
Measurement of Three Human Subjects

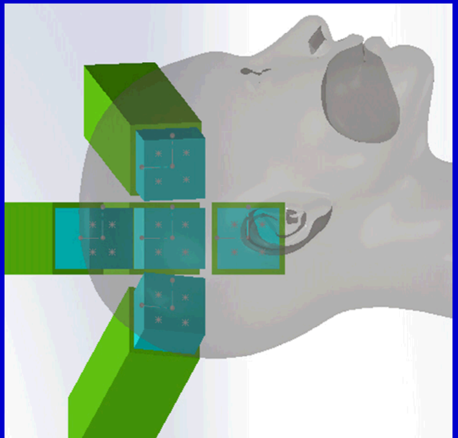


Auditory Stimulation
Auditory Evoked Fields, (AEF)









- Filter: 1 to 100 Hz
- Tone: 1000 Hz for 100 ms
- Trials: 456
- Baseline offset removed

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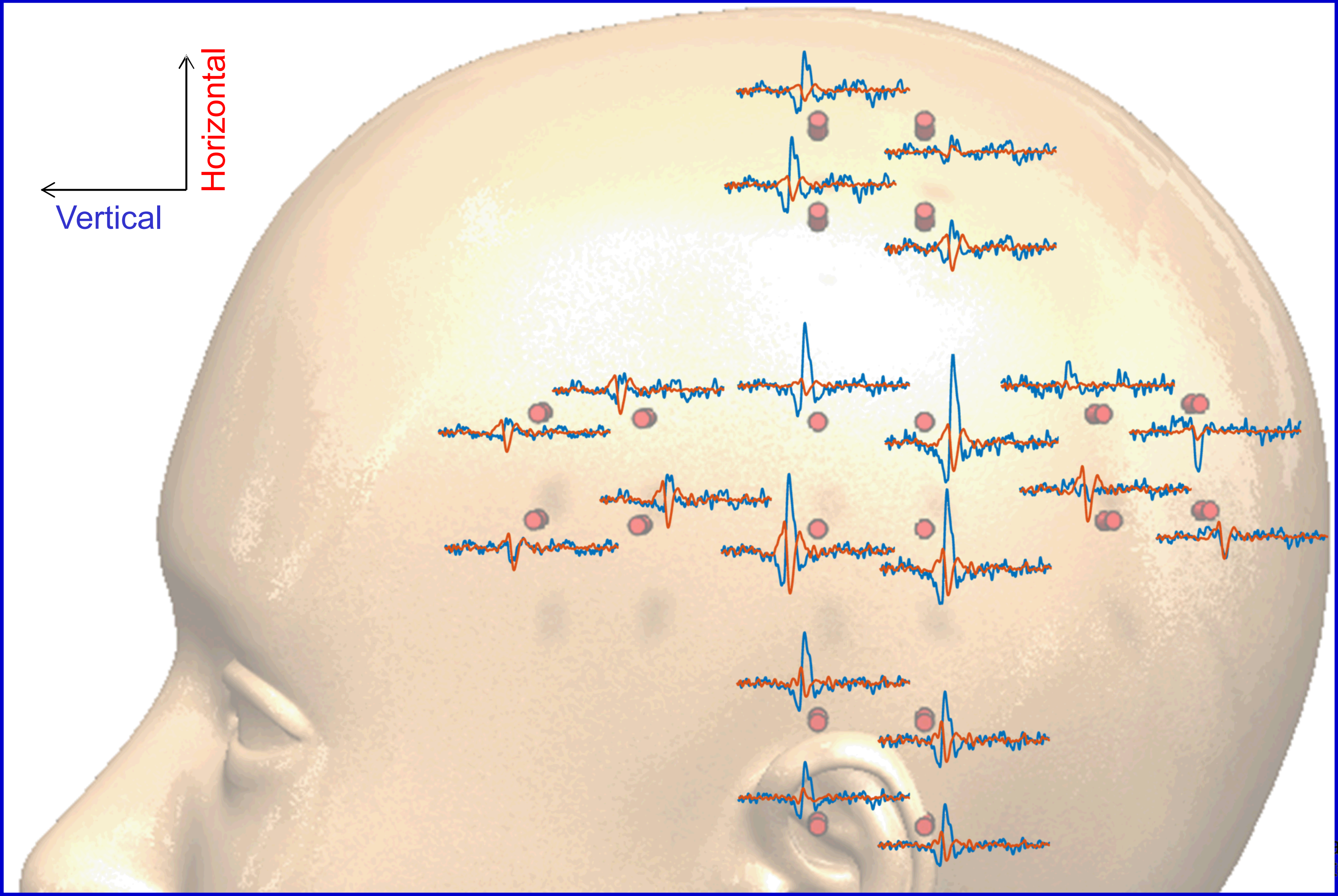
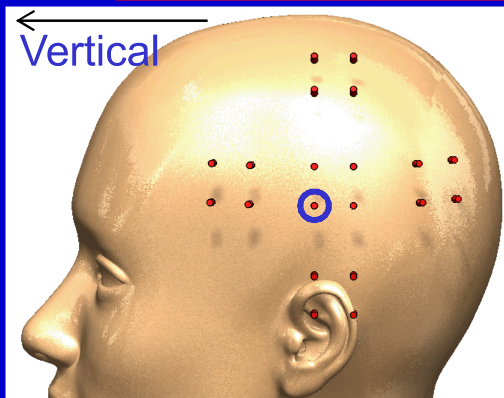
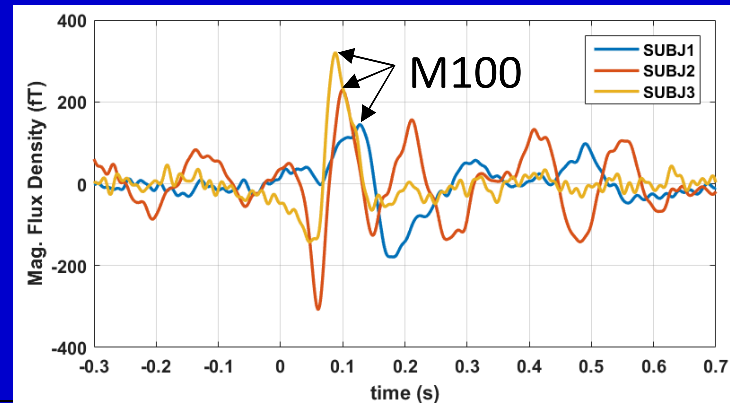
Spatial Distribution of Signals



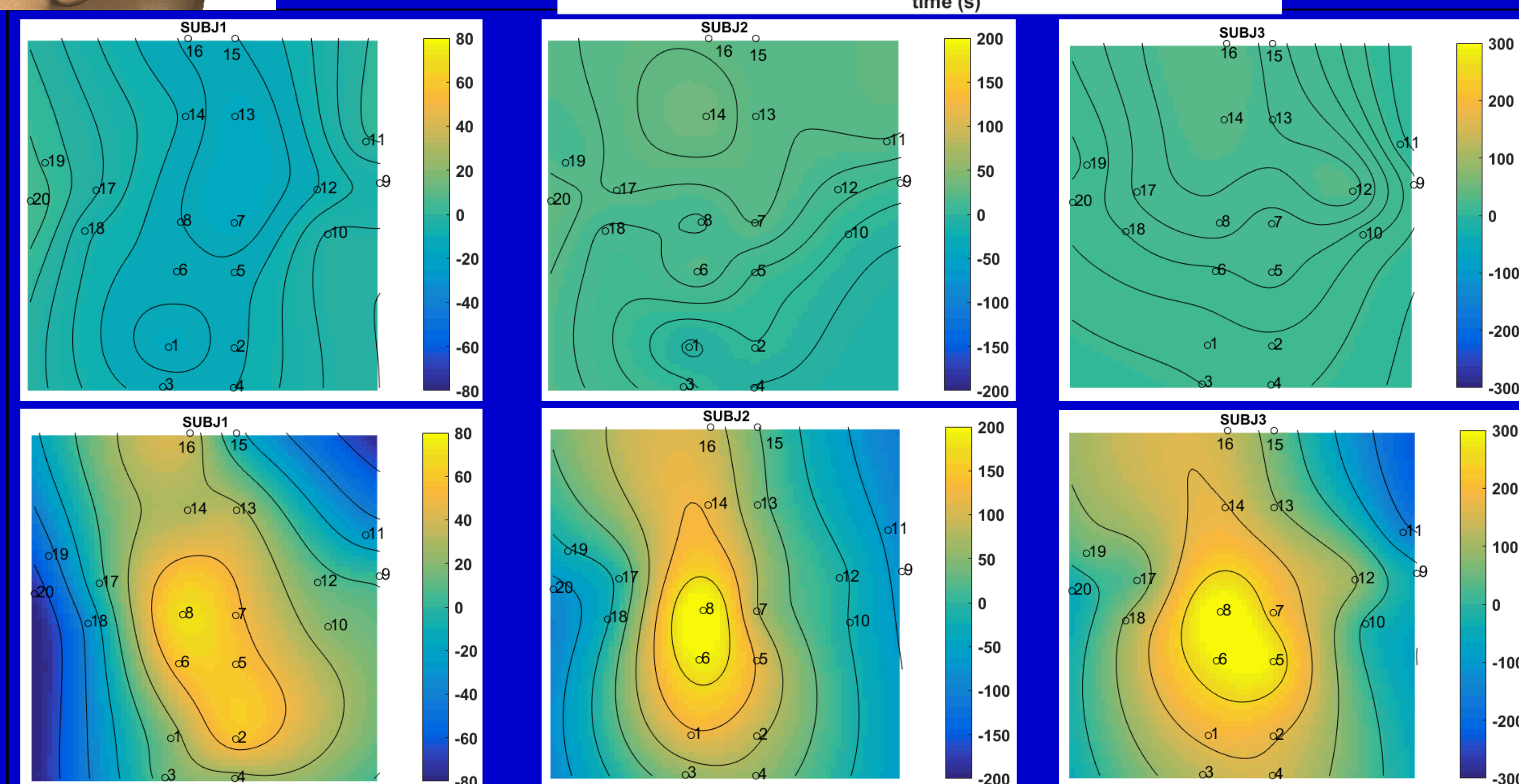
AEF in Three Subjects





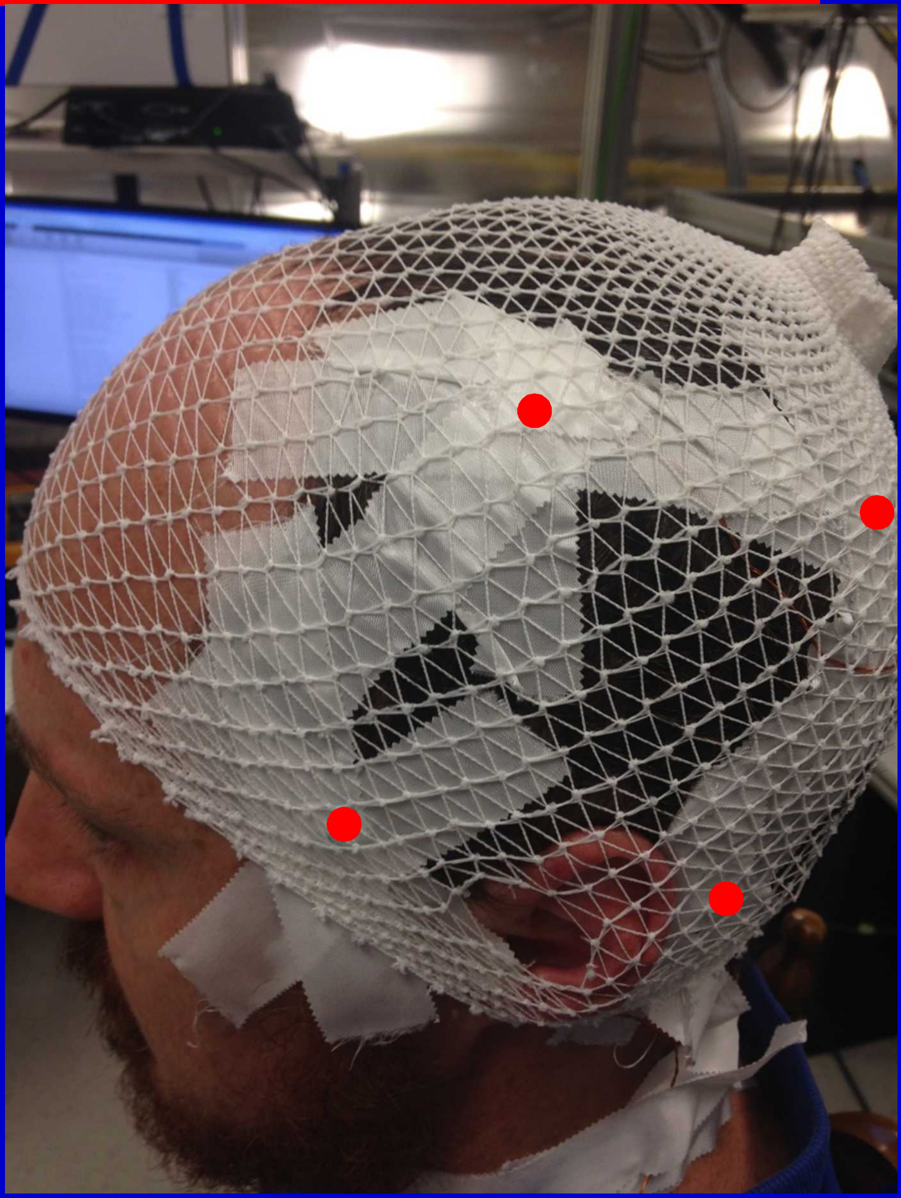
Pre-stimulous

M100

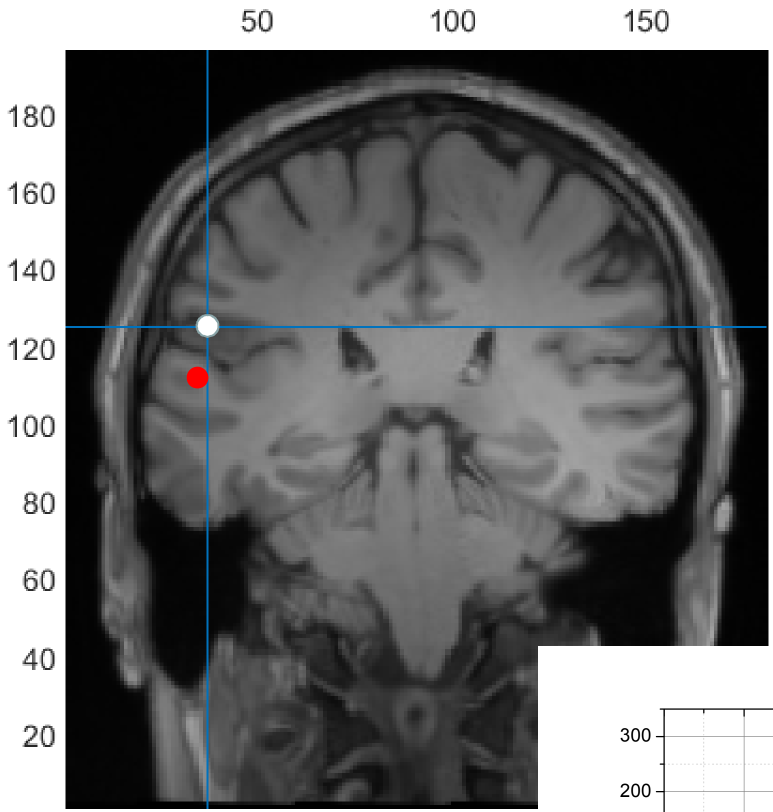


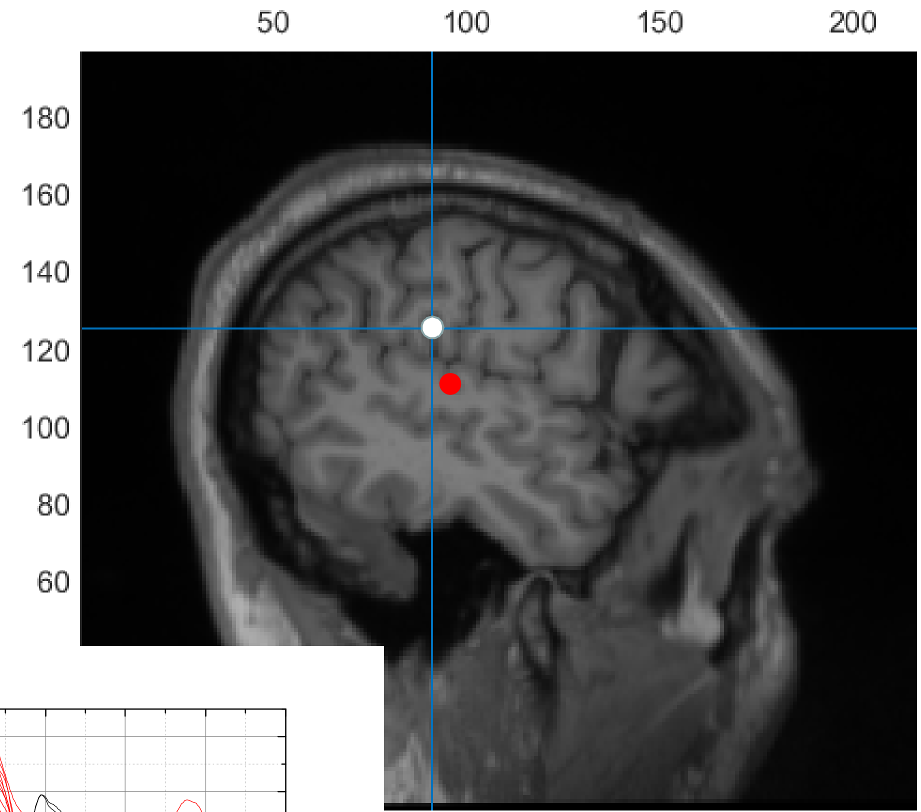
Registering the Head to the Array

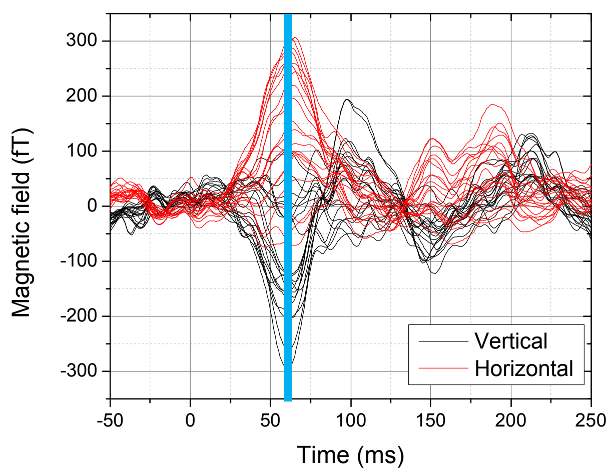
- Place four head localization coils on the head
  - Need to be close to the array
- Use a Polhemus system to digitize the head and the head localization coils
- Localize the coils with the array



Preliminary Source Localization of AEF







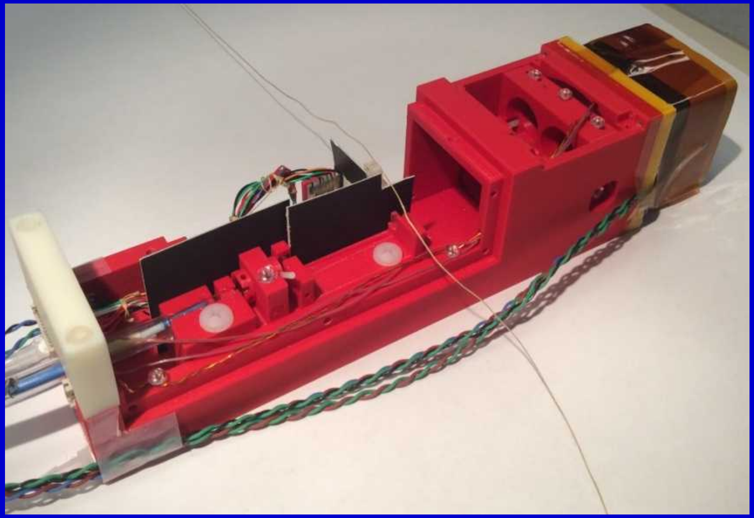
- Red dot: Elekta Neuromag system and software
- White dot: OPM data and Fieldtrip analysis software
- Difference: 1.5 cm

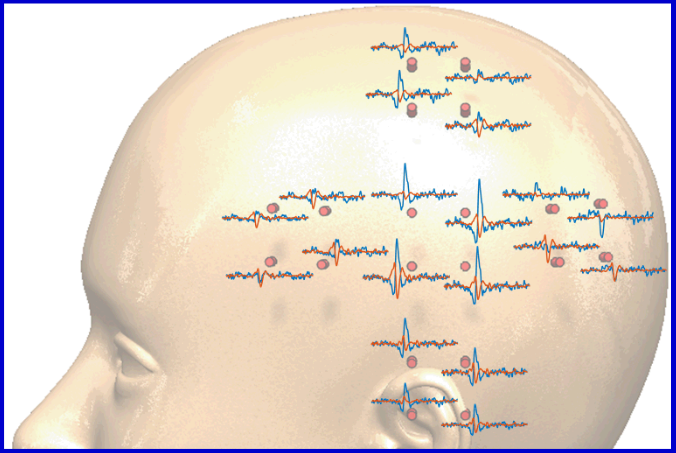
Errors due to:

- Imperfect calibration of sensors' position, gain, and orientation
- Poor positioning of the head localization coils, lack of good fit

Conclusion

- Current status
  - Constructed person-sized magnetic shield
  - Five functioning sensors installed
  - Collecting auditory and somatosensory data
- 2nd generation sensor
  - Compact, 4-channel sensor design
  - 18 mm channel separation
  - 5 $fT/Hz^{1/2}$ sensitivity, 80-90 Hz bandwidth
- Future
  - Refine signal processing techniques to reduce the noise
    - Work on reducing technical noise sources
  - Improve localization magnetic sources within the brain and compare to SQUID MEG data
  - Work toward an array with more coverage
  - Move toward neuroscience applications





Acknowledgements

- Sandia MEG Team: Peter Schwindt, Anthony Colombo, Yuan-Yu Jau, Tony Carter, Amber Dagel, 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

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NIBIB National Institute of Biomedical Imaging and Bioengineering

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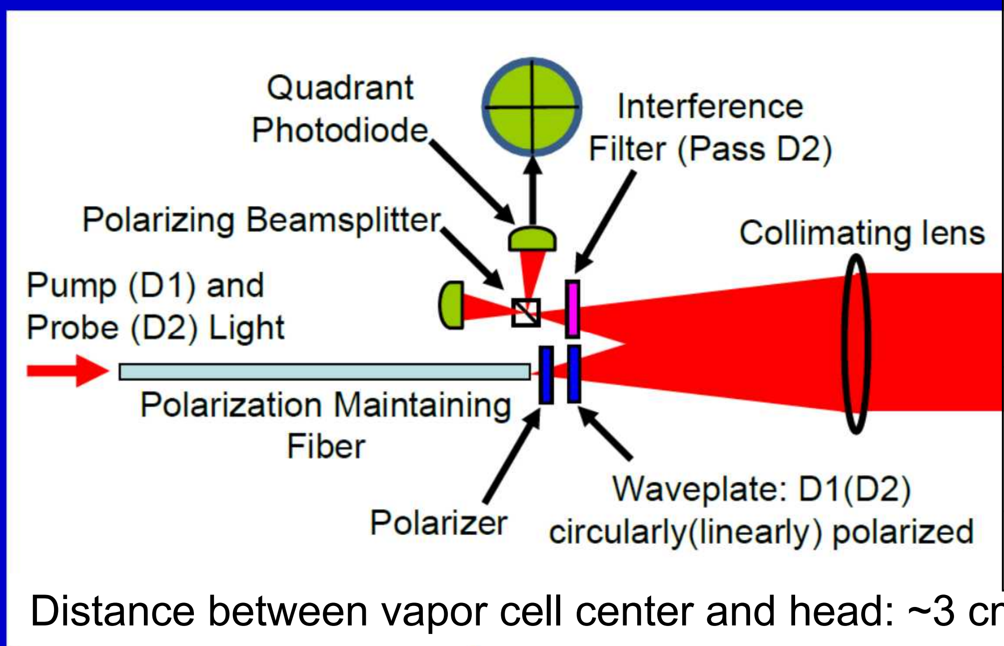
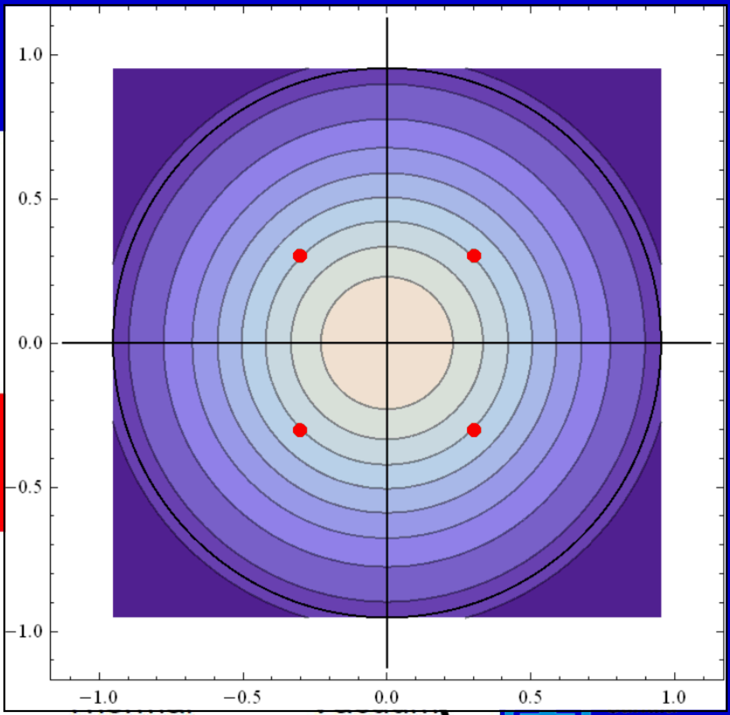
Backup

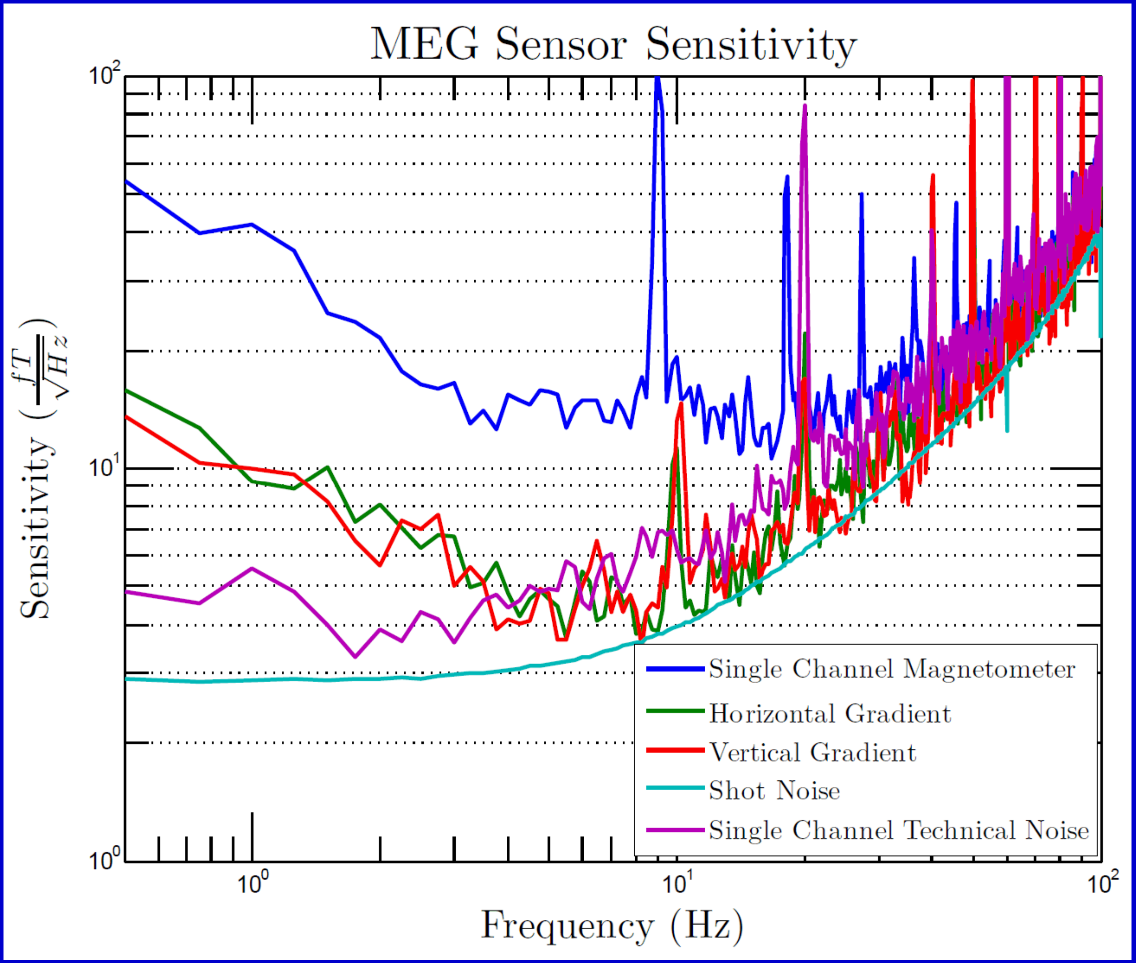
1^{st} Generation Sensor Design

- 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: gives a gradiometer baseline of ~4-5 mm





Magnetometer Performance



- Gradient measures intrinsic sensitivity
- <5 fT/Hz$^{1/2}$ at 10 Hz
- Noise floor consistent with magnetic shield noise
- Bandwidth = 17 Hz; Could be improved with more pump power or higher temperature

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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

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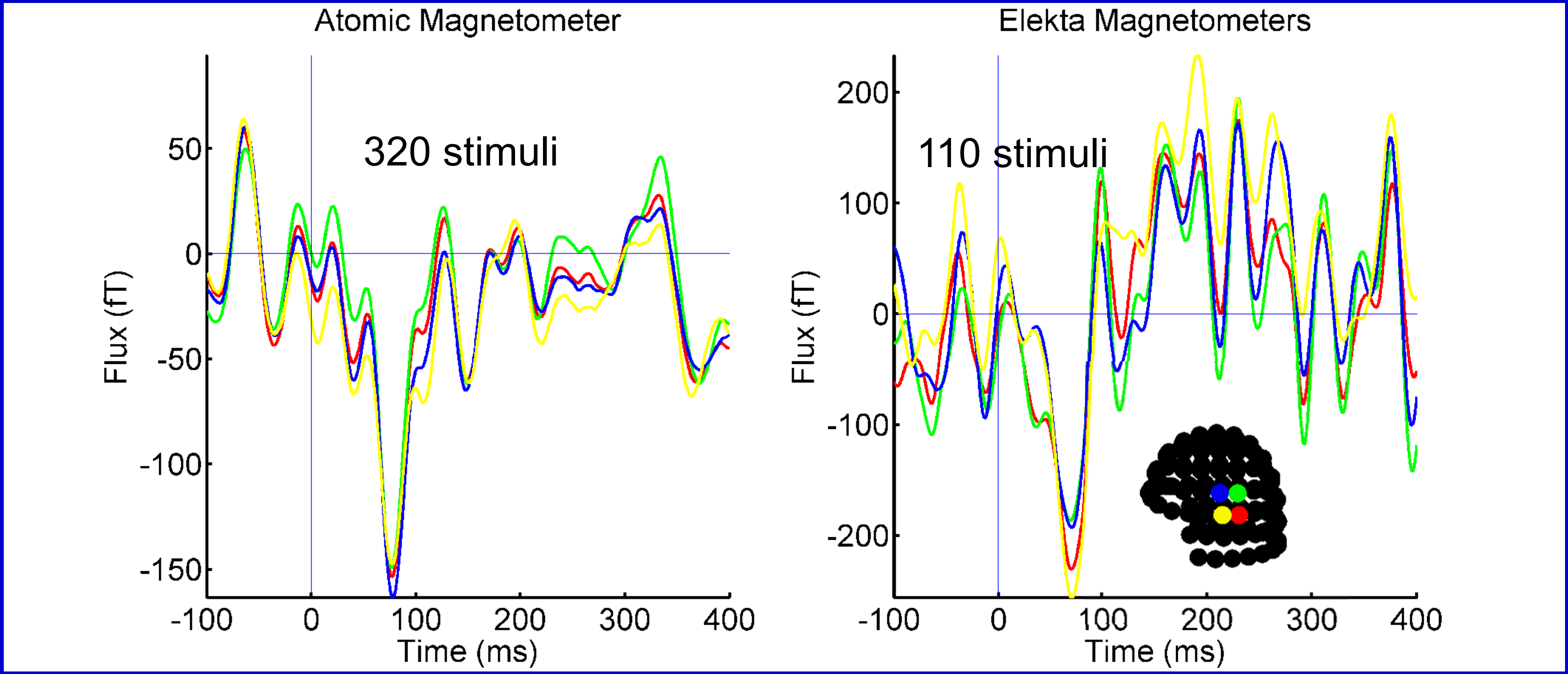
Comparison of the Optically Pumped Magnetometer to the SQUIDs

Auditory Stimulation



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

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

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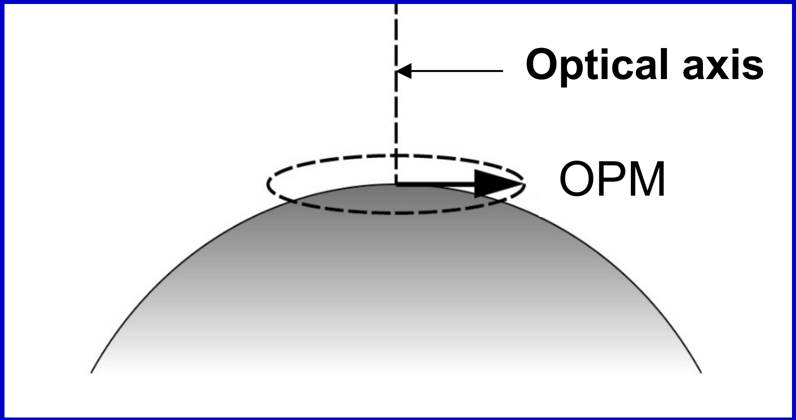
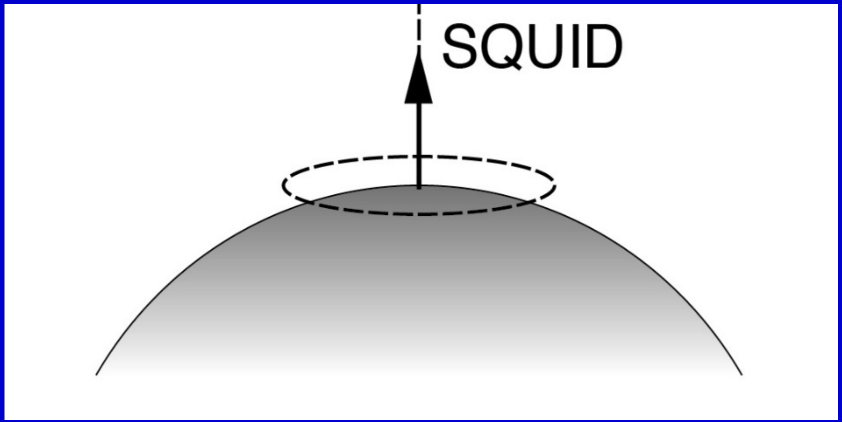
OPM vs SQUID

SQUID and OPM signals are not identical. Why?

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

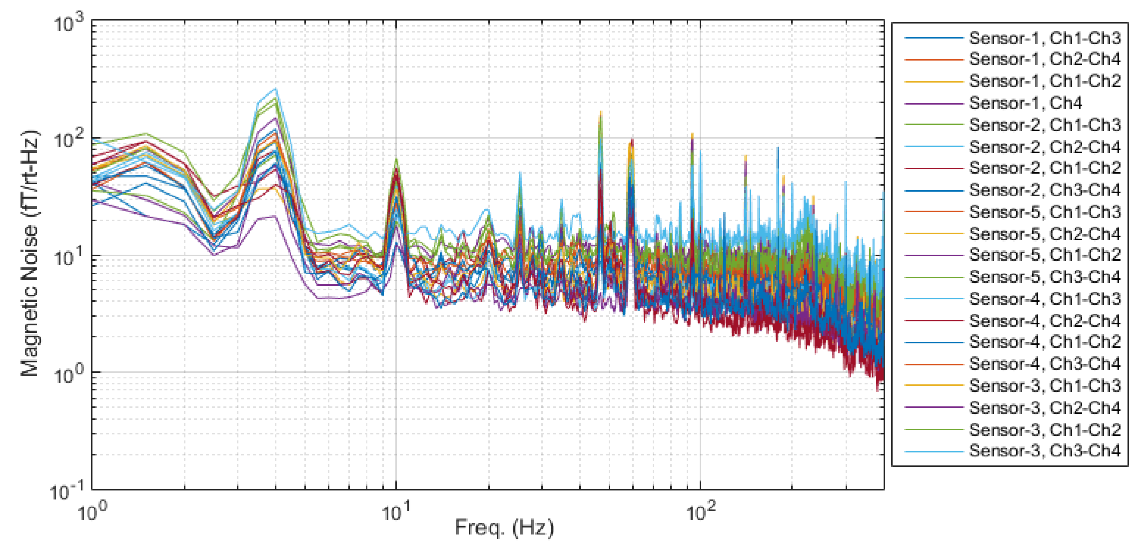
SQUIDs measure fields perpendicular to scalp (coils are parallel to scalp)

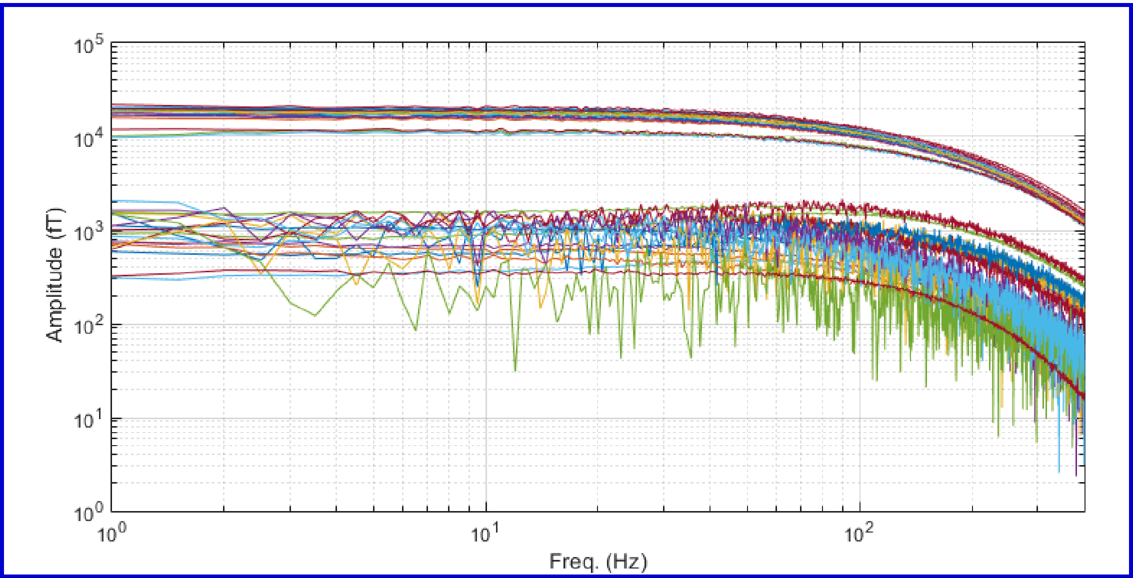




- Magnetometer channel separation: ~5mm
- SQUID channel separation: ~30 mm
- Different bandwidth (OPM: ~20 Hz, SQUID: ~ kHz)

Gradiometer





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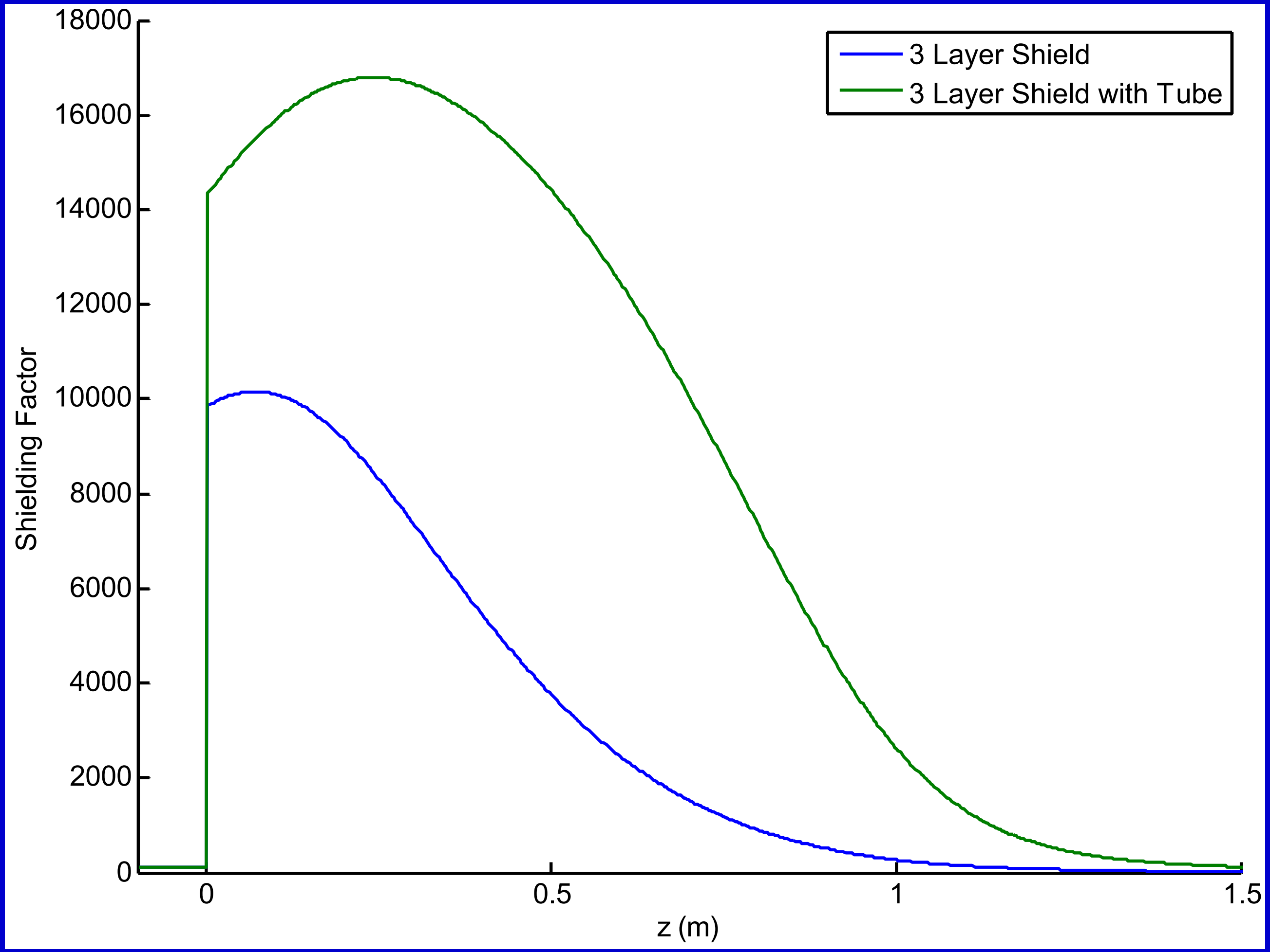
3-Layer Shields



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

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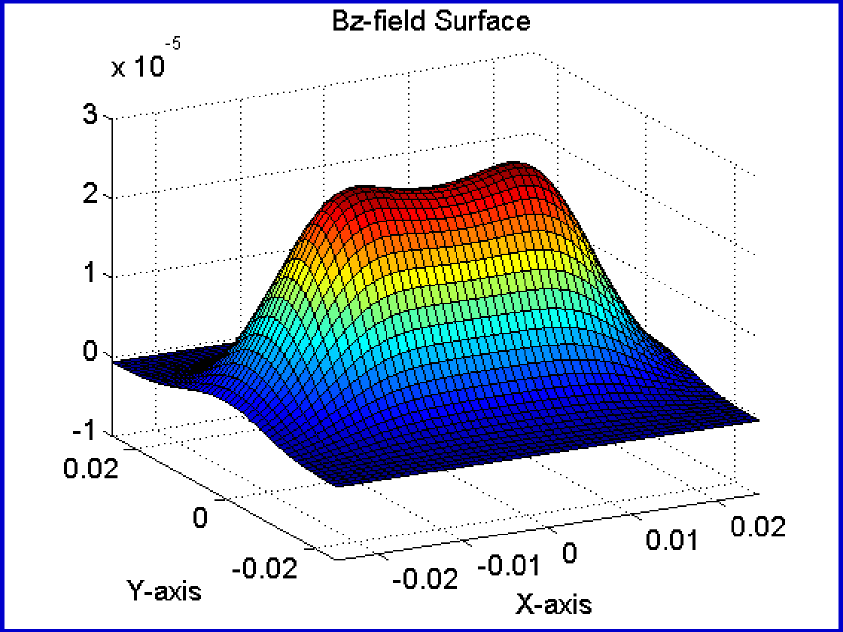
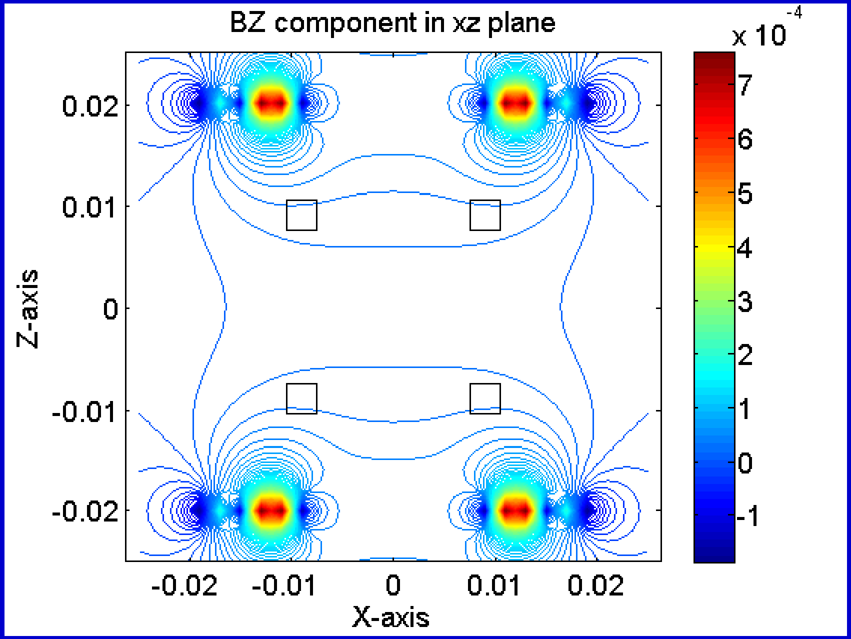
Field of the Modulation Coils

x-y plane through two sensor volumes



x-z plane



Gradient through the sensor area in the x-z plane
Delta Bx is 14%
Delta Bz is 24%

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