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A multi-channel magnetoencephalography system using optically pumped magnetometers

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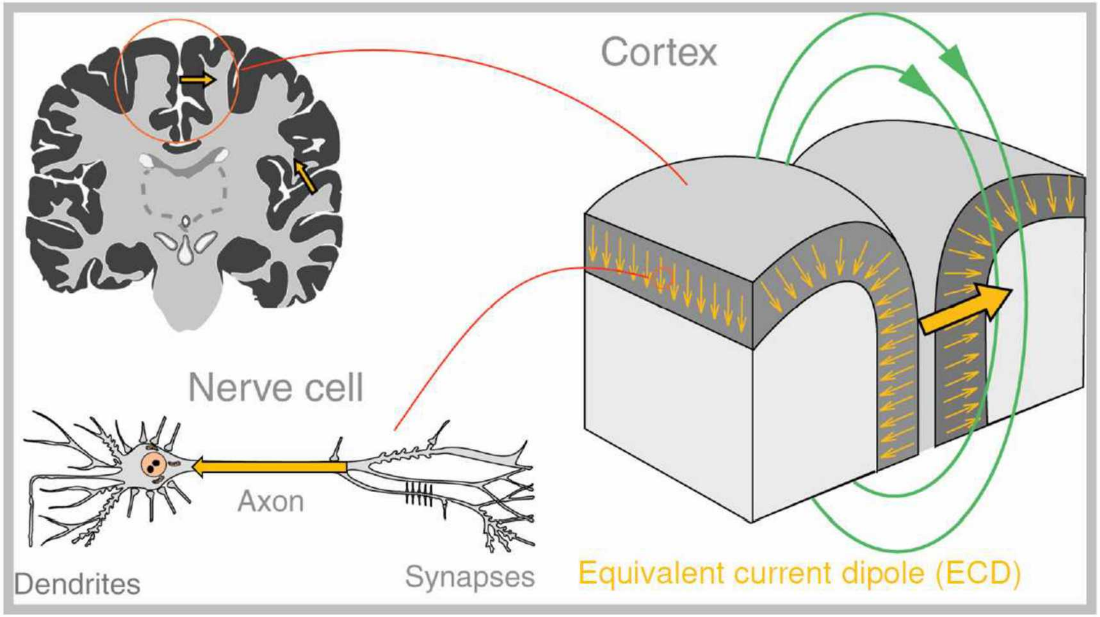
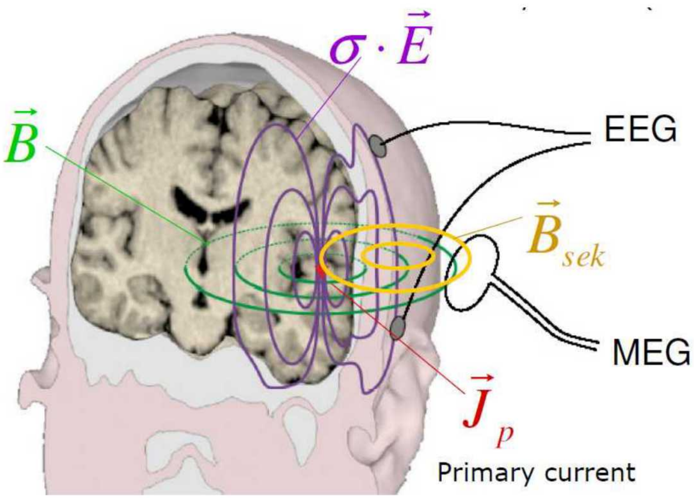
Outline

- **Introduction**
- Non-Invasive Functional Brain Imaging
  - Sensor Design
  - The Magnetoencephalography System
  - Auditory/Somatosensory Experiments
- Conclusion

Magnetoencephalography (MEG)



B. Maess, MPI for Human Cognitive and Brain Sciences



Lauri Parkkonen (Aalto University)

- Postsynaptic currents flowing in the dendrites of the pyramidal neurons constitute the primary current ($\overrightarrow{J_p}$).
- Both the primary and return currents contribute to the magnetic field sensed outside the subject's skull.

Traditional MEG System requires cryogenic temperature: Superconducting Quantum Interference Device (SQUID)

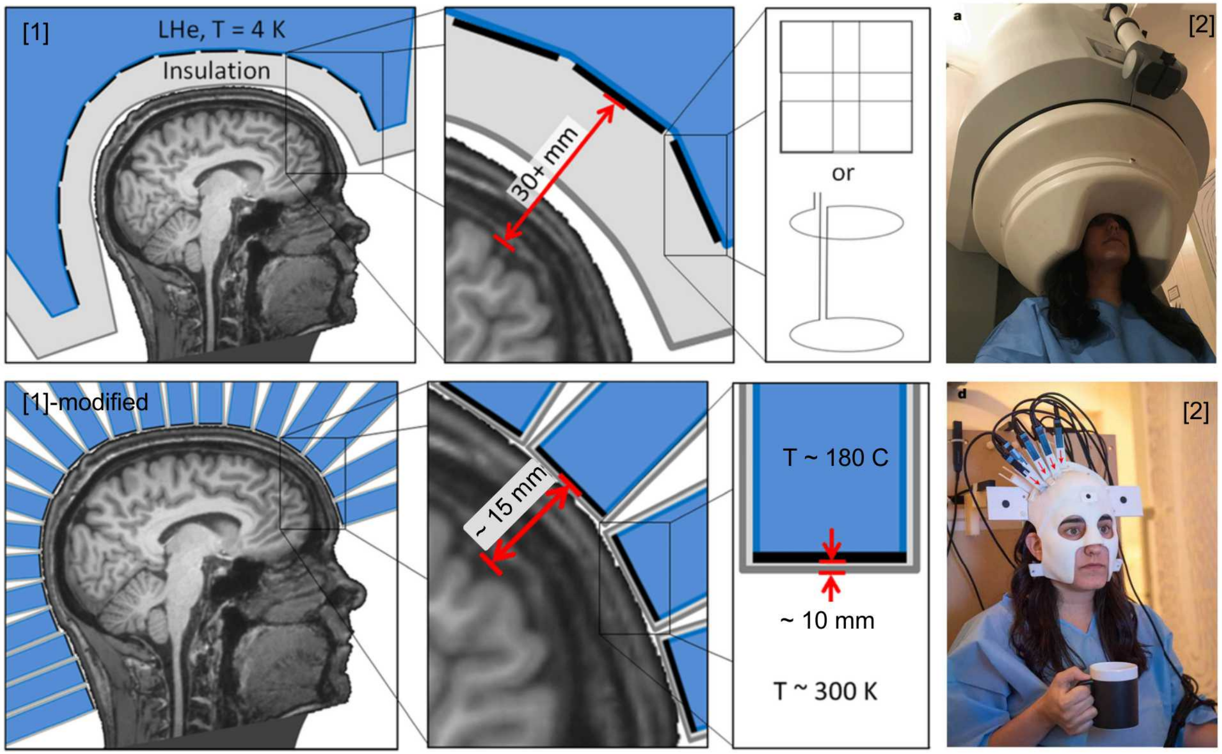
Elekta Neuromag® TRIUX

CTF cMEG

Tristan MAGViewTM

[1] Rainer Körber et al, "SQUIDs in biomagnetism: A roadmap towards improved healthcare," *in* Superconductor Science and Technology 29(11):113001, DOI: 10.1088/0953-2048/29/11/113001

Optically Pumped Magnetometer (OPM) enables on-scalp MEG measurement

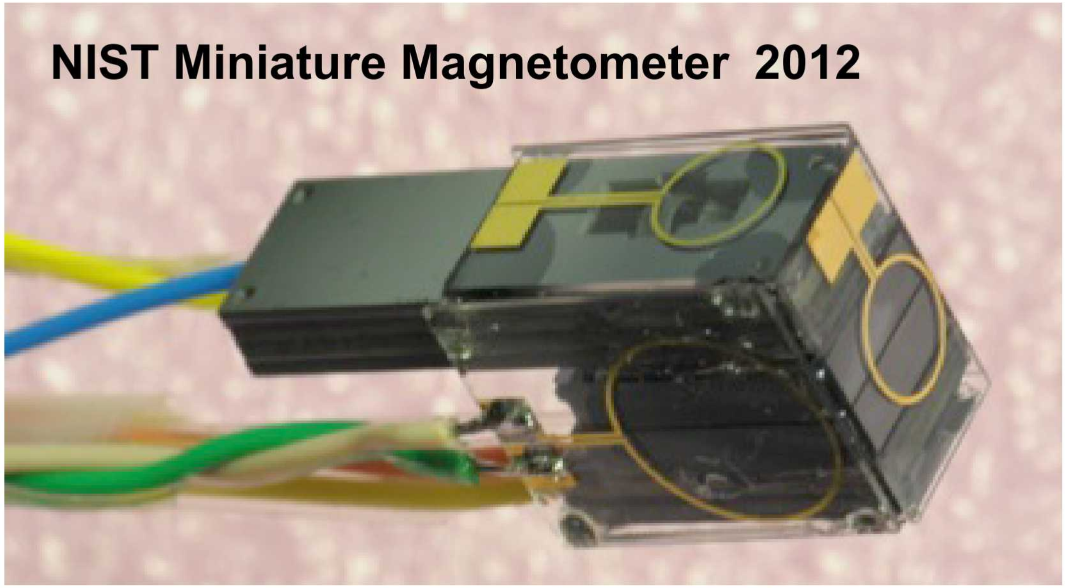


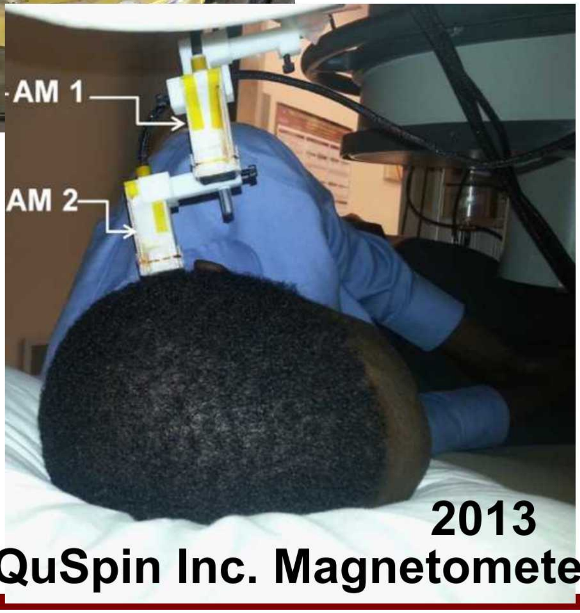
- SQUID require dewar and a rigid helmet due to liquid He (~ 4 °k).
- SQUID's helmet manufactured to fit 95% adult male subject's head size.
- Large sensor-source distance diminishes the magnetic field and high frequency spatial components are affected more severely.
- Optically Pumped Magnetometers (OPMs) enable on-scalp Magnetoencephalography enhancing spatial resolution of magnetoencephalography.
- Applications:
  - Brain Computer Interface (BCI)
  - Clinical, e.g. epilepsy

[1] Rainer Körber et al, "SQUIDs in biomagnetism: A roadmap towards improved healthcare," *in* Superconductor Science and Technology 29(11):113001, DOI: 10.1088/0953-2048/29/11/113001

[2] Boto E, Holmes N, Leggett J, Roberts G, Shah V, Meyer SS, et al. Moving magnetoencephalography towards real-world applications with a wearable system. Nature. 2018;555(7698):657.

OPMs for MEG: Early work





OPMs Developed for MEG*

*Demonstrated MEG Measurement. Likely incomplete.
Map from https://geology.com/world/world-map.shtml

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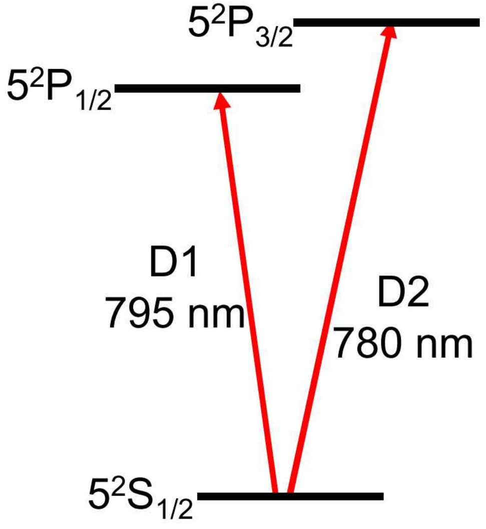
Two-color pump/probe scheme

Two optical resonances in Rubidium (fine structure)

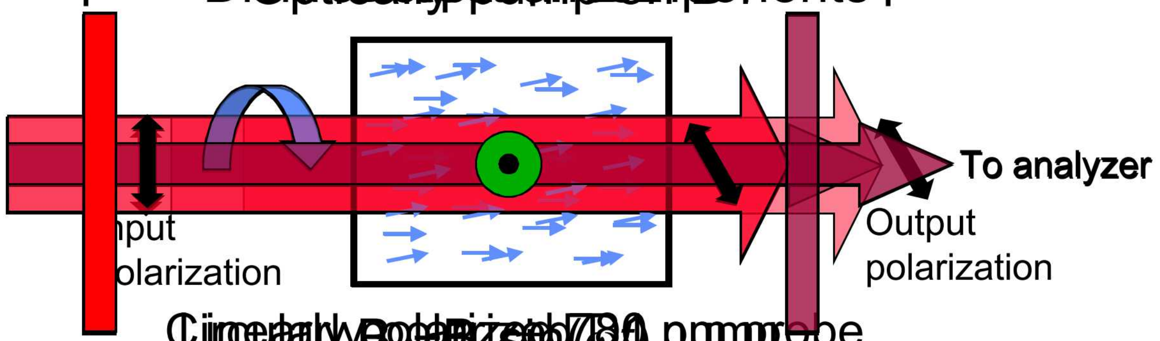
- Use D1 for optical pumping and D2 for probing

Based on: V. Shah and M. V. Romalis, PRA 80, 013416 (2009)

^{87}Rb Fine Structure

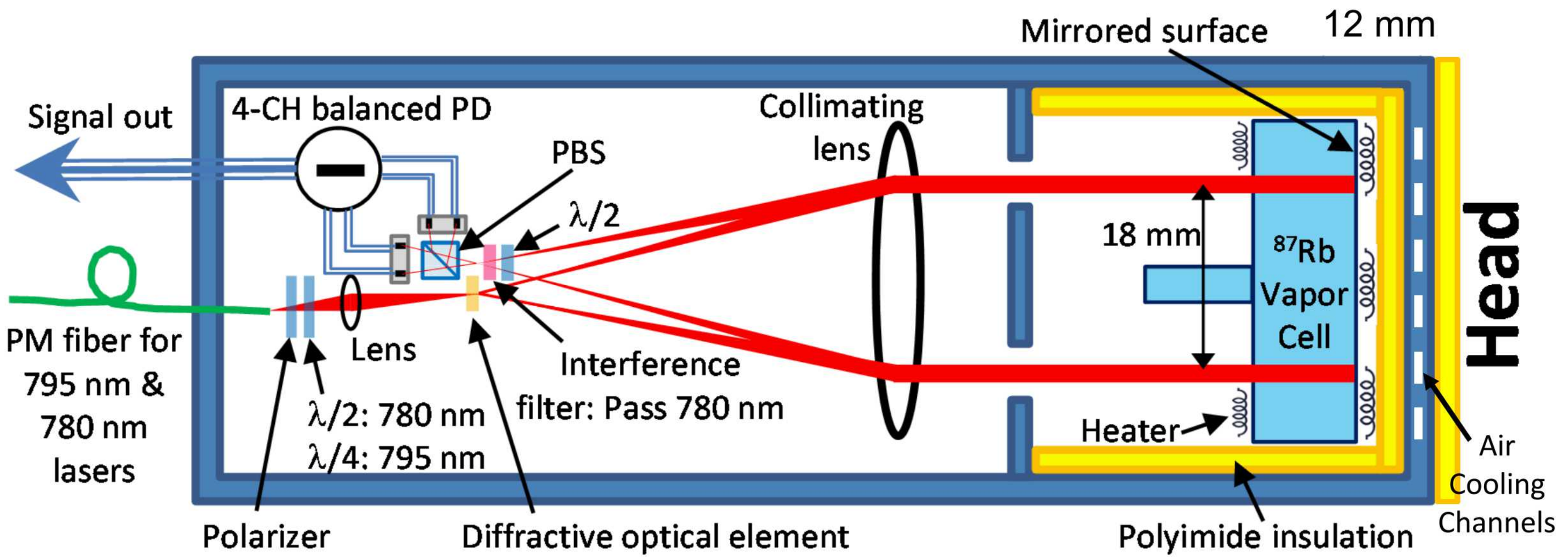


Field modulation/phase sensitive detection

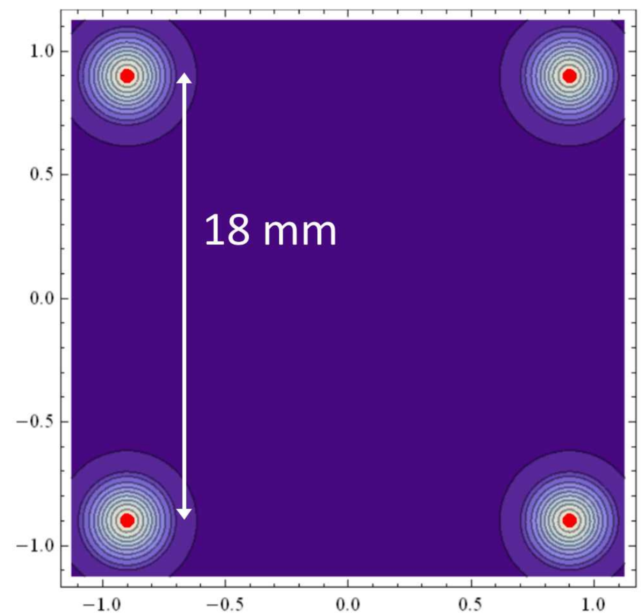


Oriented spins rotate the polarization

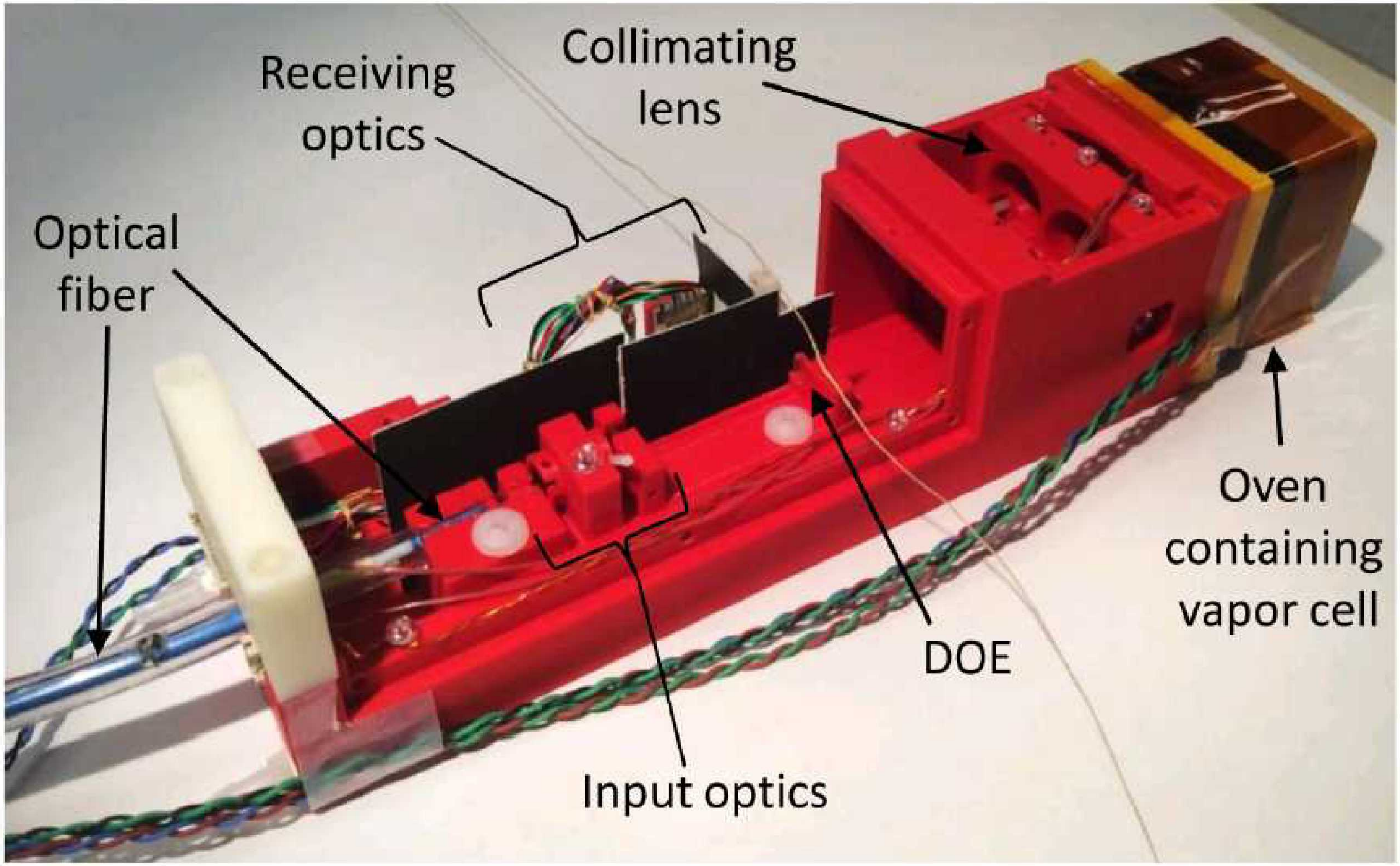
Four-Channel Sensor Design



- 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 $(1.25\text{ mm})^2 = 20\text{ mm}^3$
- Minimize distance from the head to the vapor cell: 9 mm → 12 mm with extra insulation



Sensor Implementation



A. P. Colombo *et al.*, "Four-channel optically pumped atomic magnetometer for magnetoencephalography," *Optics Express,* vol. 24, no. 14, pp. 15403-15416, 2016.

Signals to Detect

Spin Polarization Bloch Equation

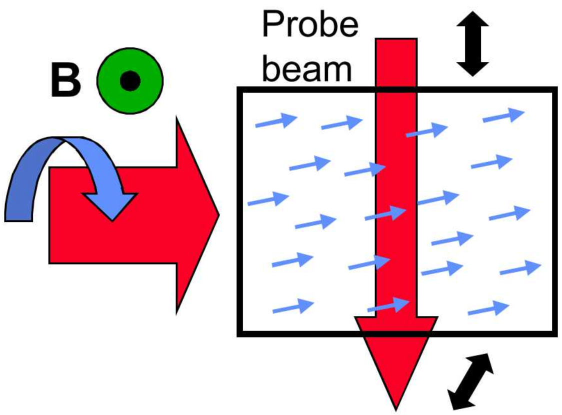
$$\frac{d\mathbf{S}}{dt} = \gamma \mathbf{S} \times \mathbf{B} + R(S_0 \hat{z} - \mathbf{S}) - \frac{\mathbf{S}}{T_2}$$

Steady State Solution

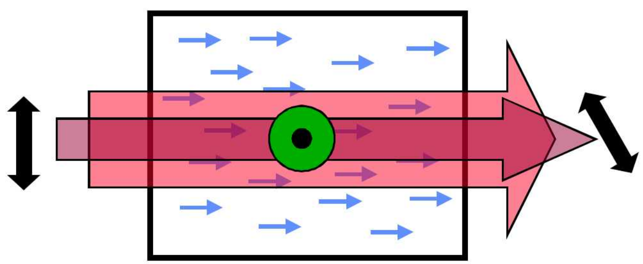
$$S_x = S_0 \frac{-\beta_y + \beta_x \beta_z}{1 + (\beta_x^2 + \beta_y^2 + \beta_z^2)} \qquad S_z = S_0 \frac{1 + \beta_z^2}{1 + (\beta_x^2 + \beta_y^2 + \beta_z^2)}$$

$$\boldsymbol{\beta} = \gamma \mathbf{B}/(R + T_2^{-1})$$

Transverse Pump

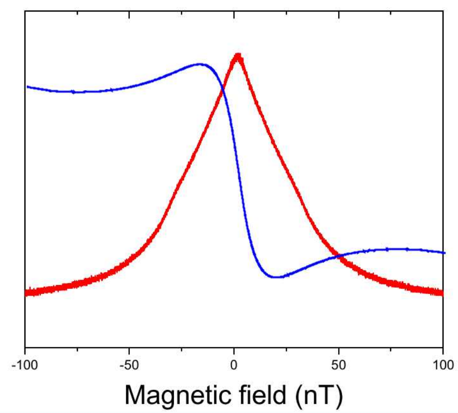


Detect the Pump
or a Collinear Probe

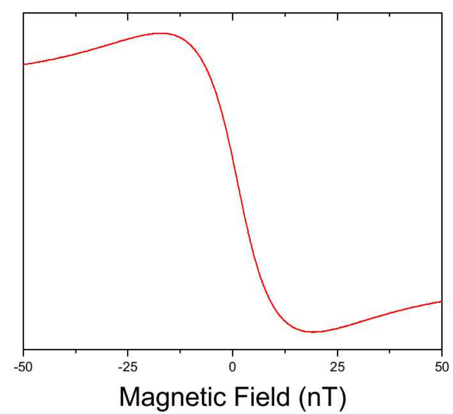


$B_0 + B_1 \sin(\omega t)$

Atomic Polarization, S_z
Pump Transmission,
or Angle of Light Polarization



Atomic Polarization, S_x
or Angle of Light Polarization

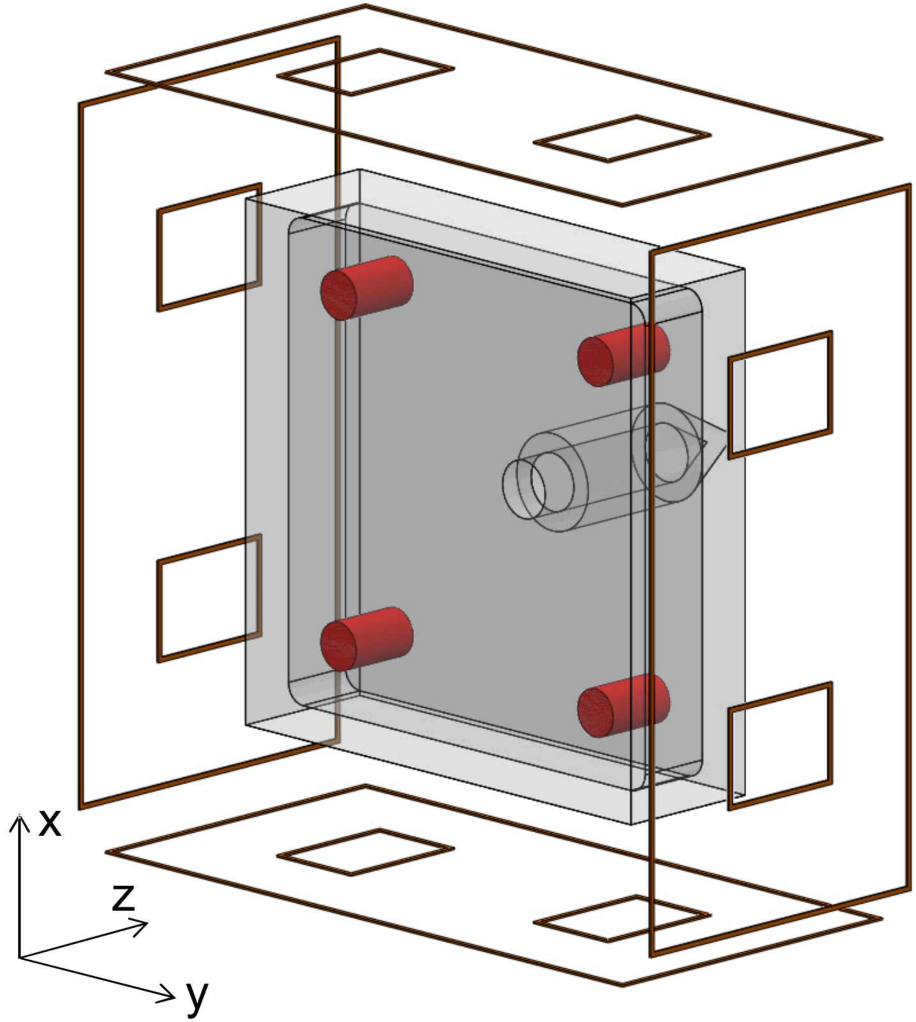


Todor Karaulanov et al 2016 *Meas. Sci. Technol.* **27** 055002

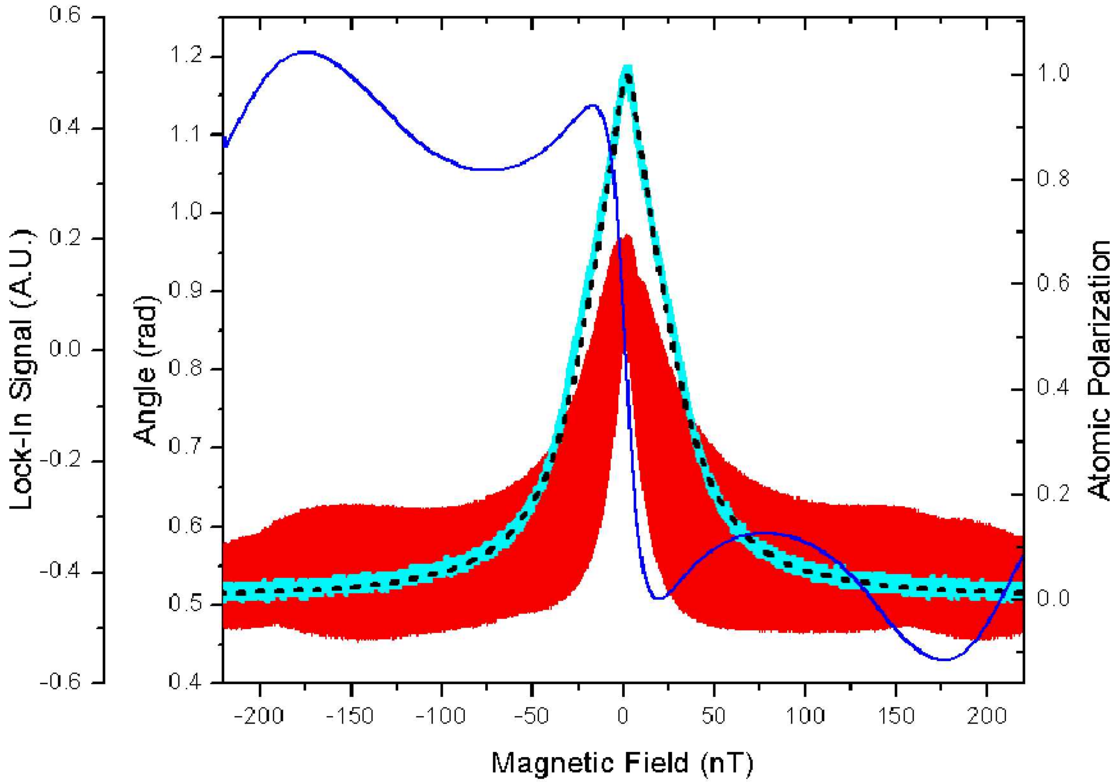
Coils and Field Modulation

- On-Sensor Coils
  - Outer coil 18 mm x 36 mm, Current = +1
  - Current: ~6 mA
- Field modulation
  - 140 nT amplitude
  - ω = 2π 1 kHz
- Magnetometer response at ω

$$S_z(t) \propto \frac{\beta_y}{1+\beta_y^2} \sin \omega t \, J_0\left(\frac{\gamma B_1}{\omega}\right) J_1\left(\frac{\gamma B_1}{\omega}\right)$$



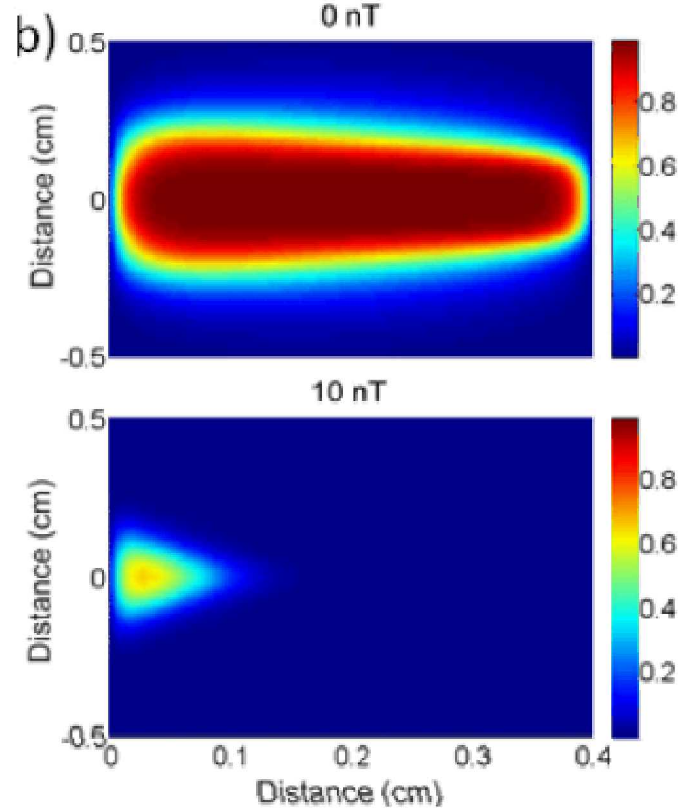
Magnetometer Signals



Blue trace: Magnetometer (lock-in) signal

$$S_z(t) \propto \frac{\beta_y}{1+\beta_y^2} \sin \omega t \, J_0\left(\frac{\gamma B_1}{\omega}\right) J_1\left(\frac{\gamma B_1}{\omega}\right)$$

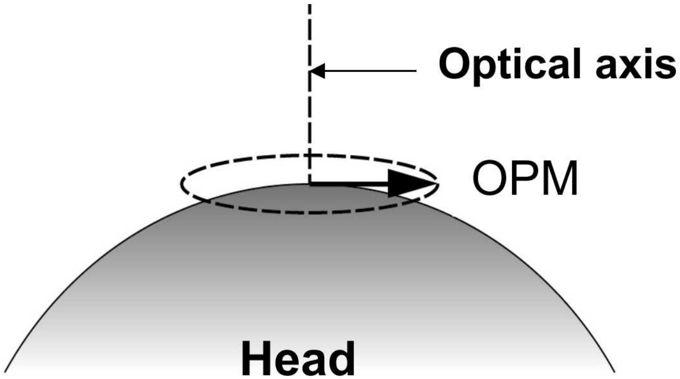
Calculated Atomic Polarization



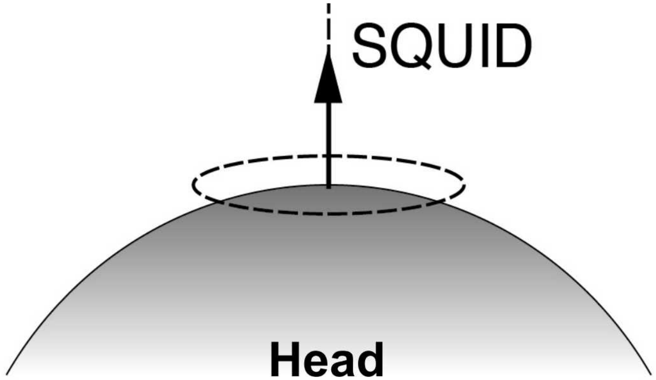
Beam propagation direction

Measured Field Components

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



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



Tangential vs. Normal Fields

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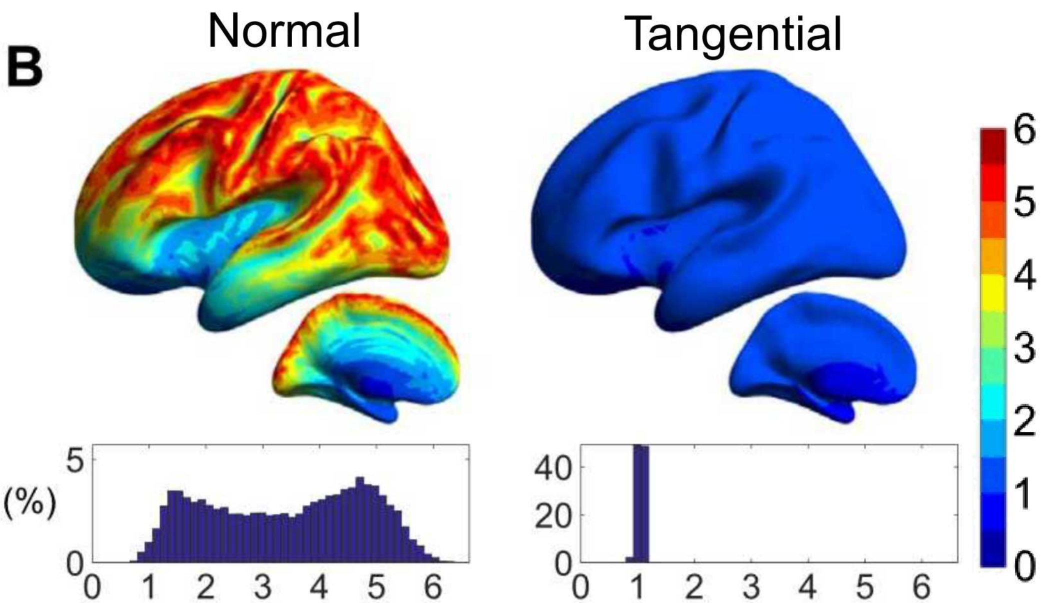
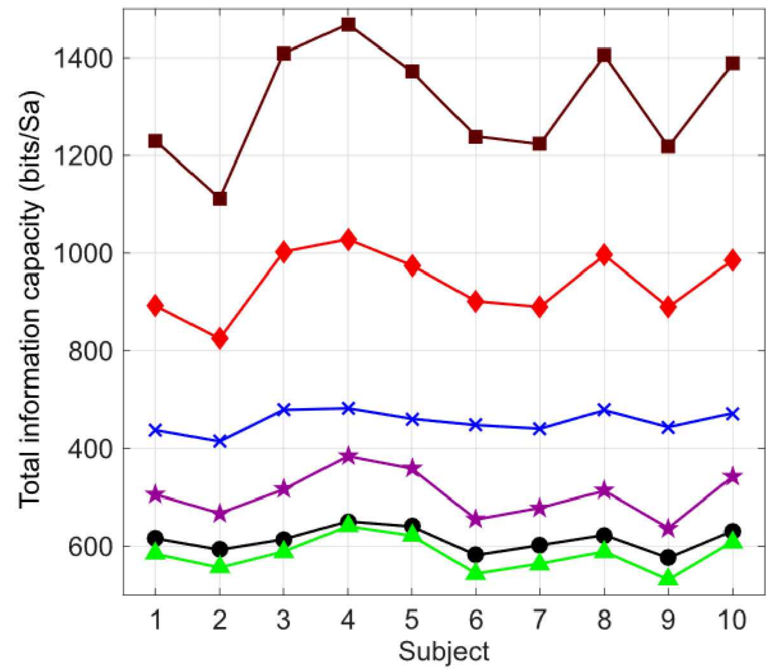
Iivanainen, J., Stenroos, M., & Parkkonen, L. (2017). Measuring MEG closer to the brain: Performance of on-scalp sensor arrays. NeuroImage, 147, 542-553.



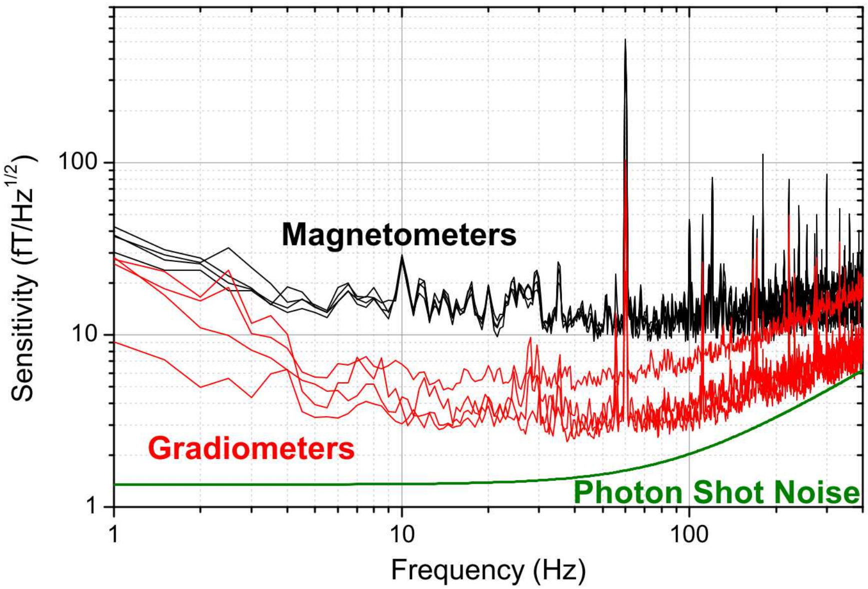
$$\mathrm{PV}_i = \frac{\| \mathbf{p}_i \|}{\| \mathbf{v}_i \|}$$

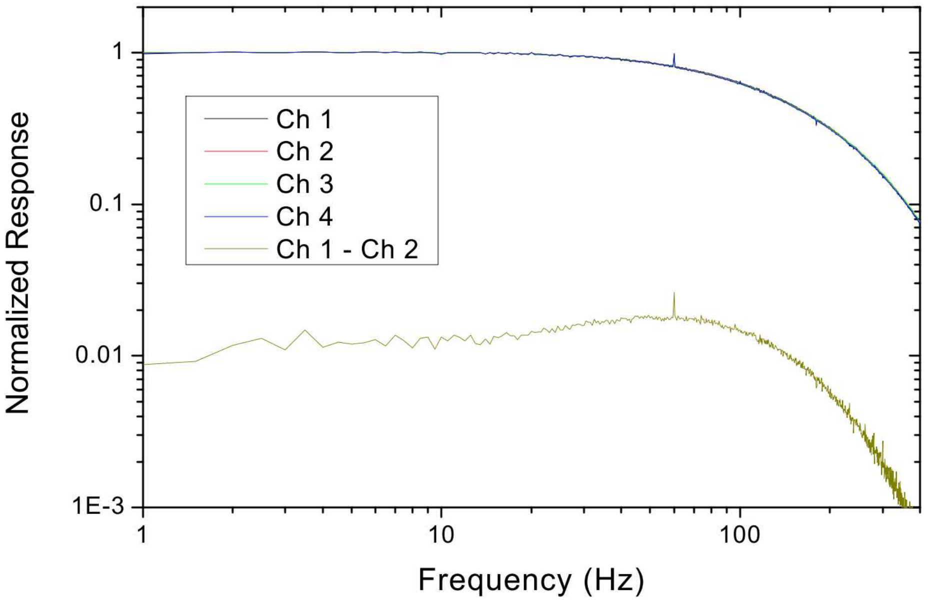
Label	Array	Number of sensors	Average (bits/Sa)	Normalized (bits/Sa/ch)
■	aOPM	306	1307	4.3
◆	tOPM	204	939	4.6
×	nOPM	102	656	6.4
★	aSQUID	306	506	1.7
●	mSQUID	102	413	4.0
▲	gSQUID	204	383	1.9



Prototype Sensor in a Small Magnetic Shield

Upper input range ~ 1 nT





	Ch 1	Ch 2	Ch 3	Ch 4
Gain (*V/nT*)	0.158	0.141	0.158	0.228
3-dB BW (*Hz*)	83	85	87	86
Mag. Noise (fT/rt-Hz)	13.4	13.2	13.1	12.1
Grad. Noise (fT/cm/rt-Hz)	4.1	3.3	3.5	2.7

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MEG System: Block Diagram

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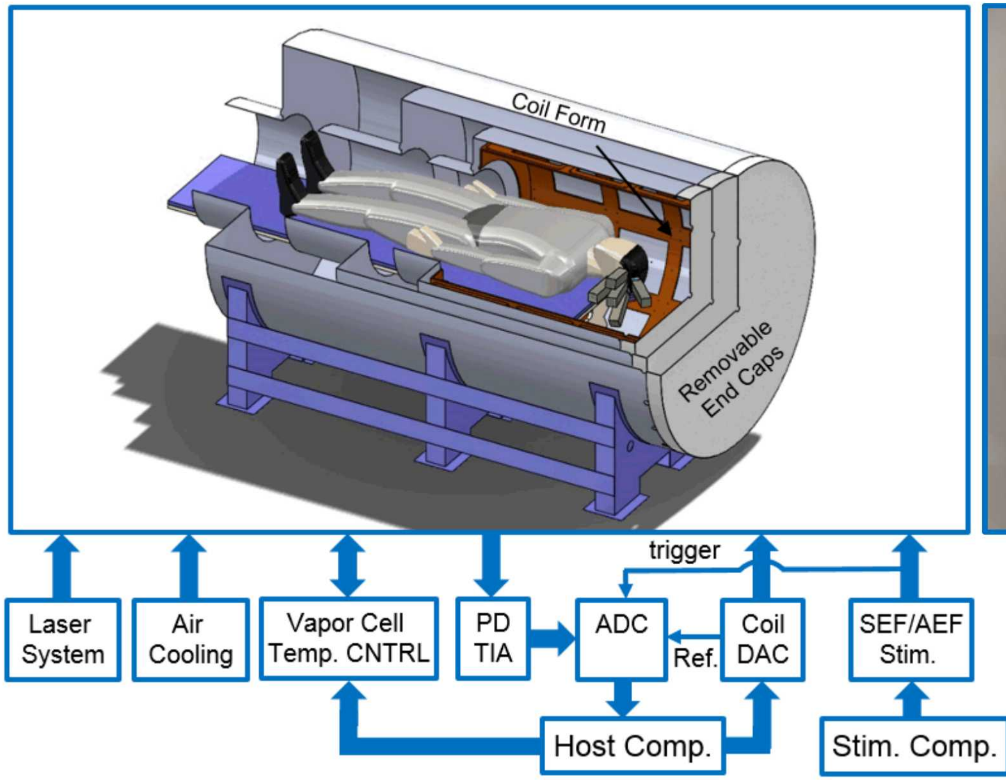
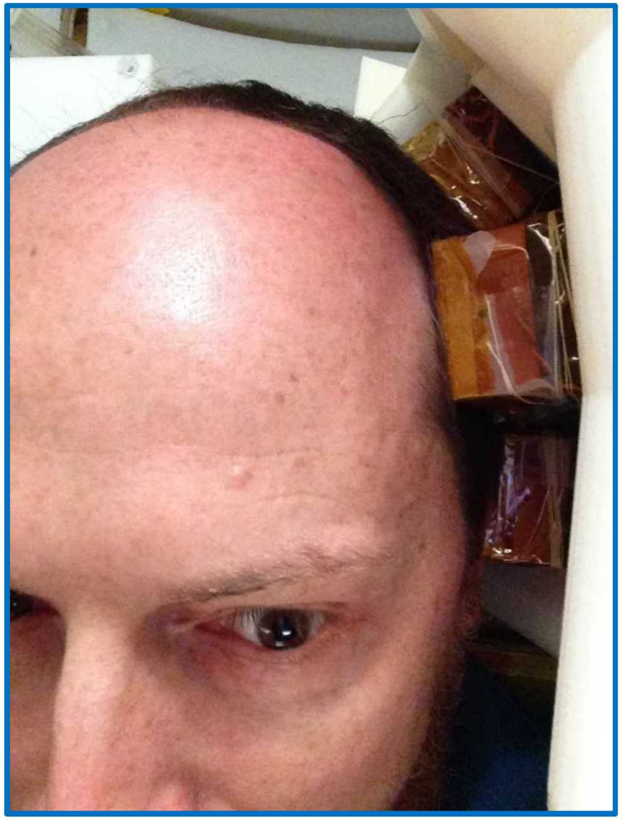


- 24-ch, 6 sensor, OPM array
- Human-sized magnetic shield
- Custom laser source
- Custom electronics
- Custom LabView-based data acquisition and control software
- Custom Matlab-based MEG data analysis pipeline

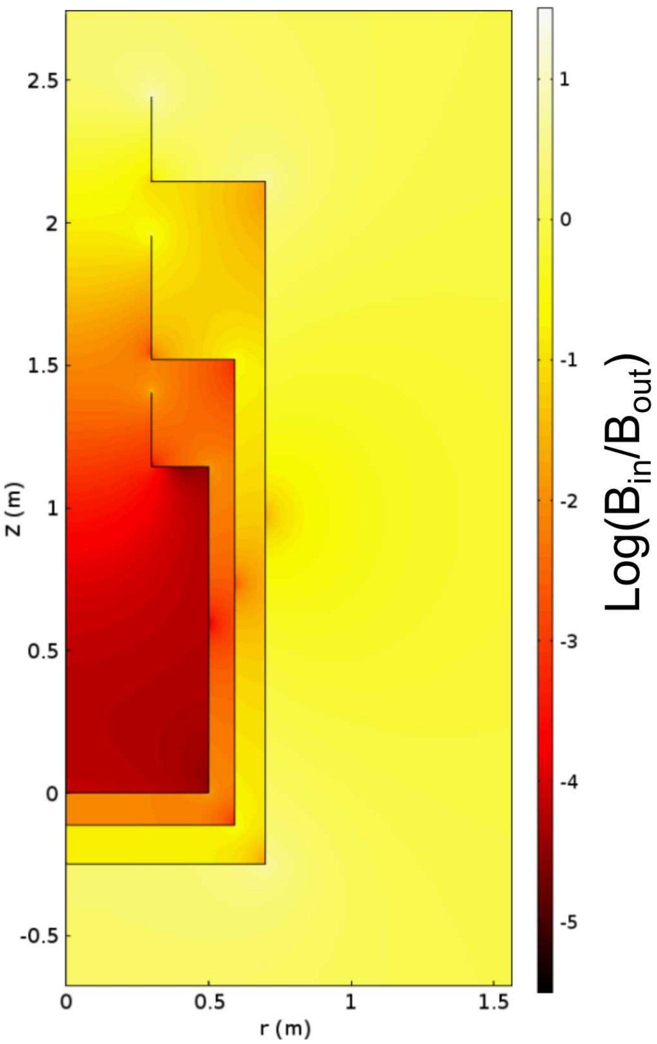
MEG System: The 24-Channel Array

6-sensor, 24-channel array

Partially covers the left hemisphere



Magnetic Shield



- Design 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

Insert Person Here

MEG System: Inside the Magnetic Shield

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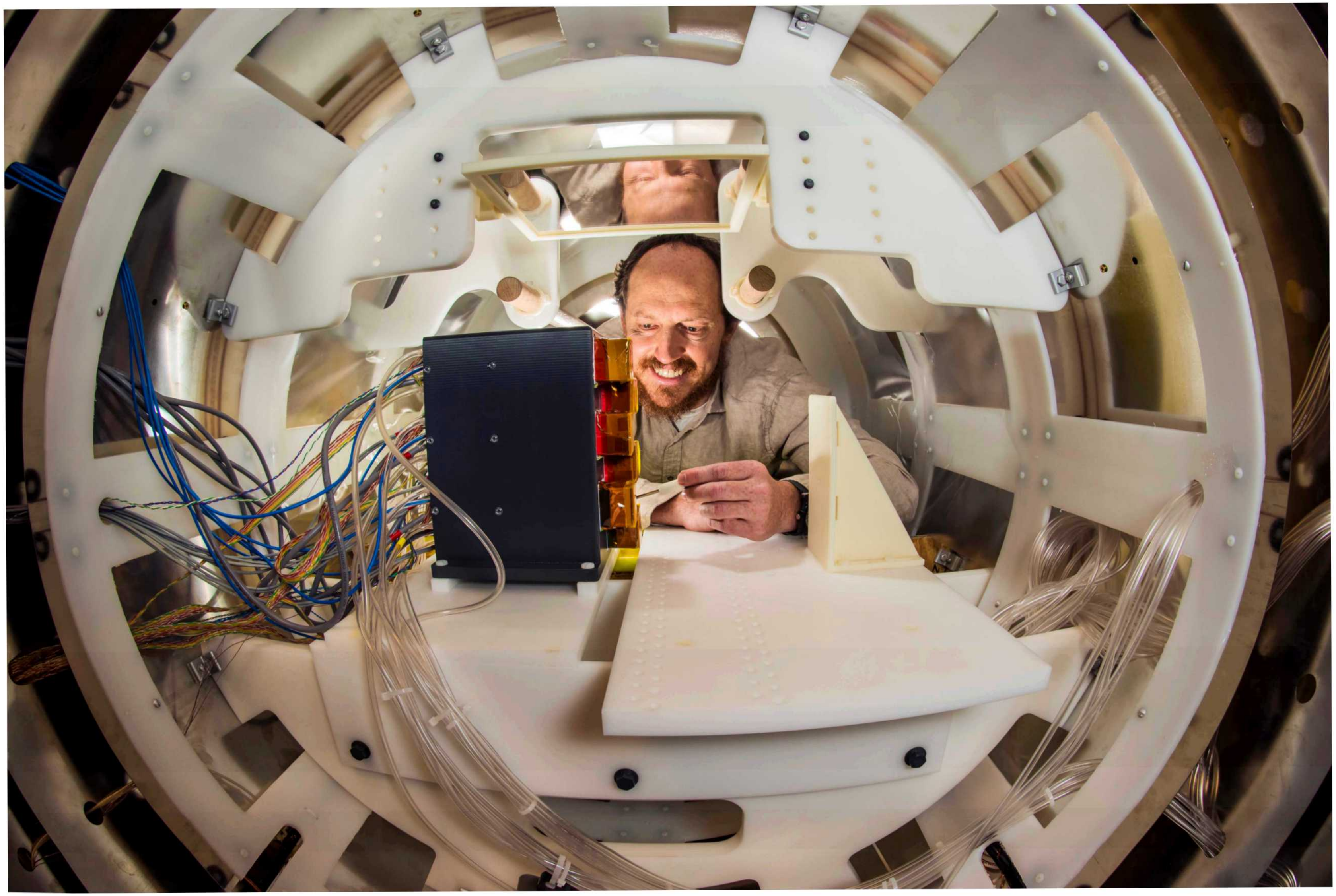

MEG System: Array Characterization

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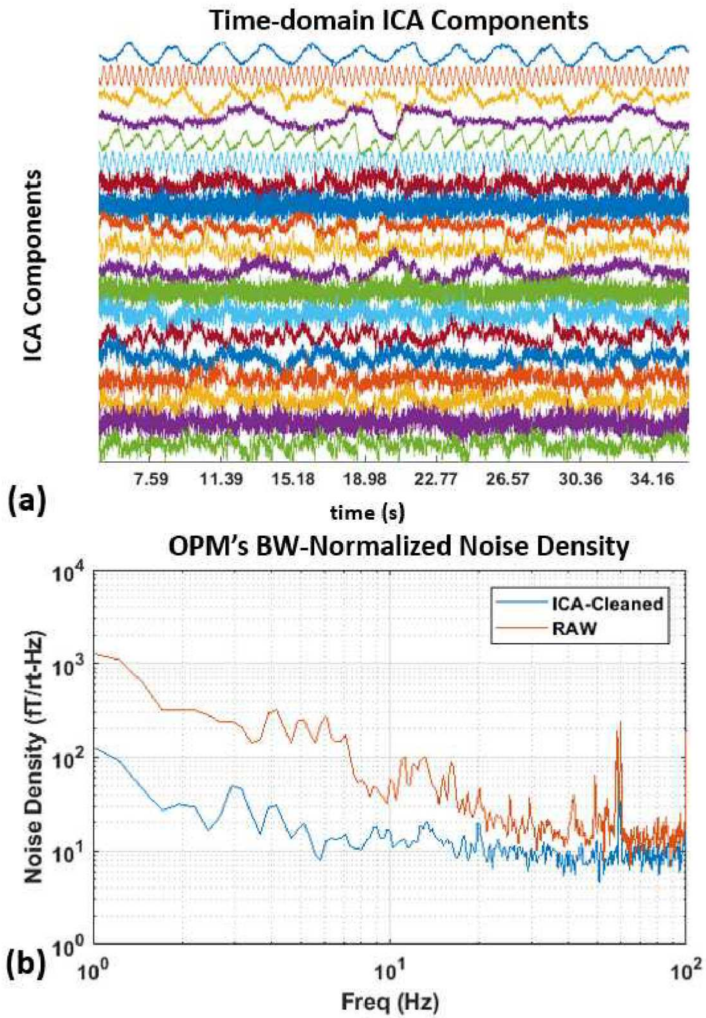
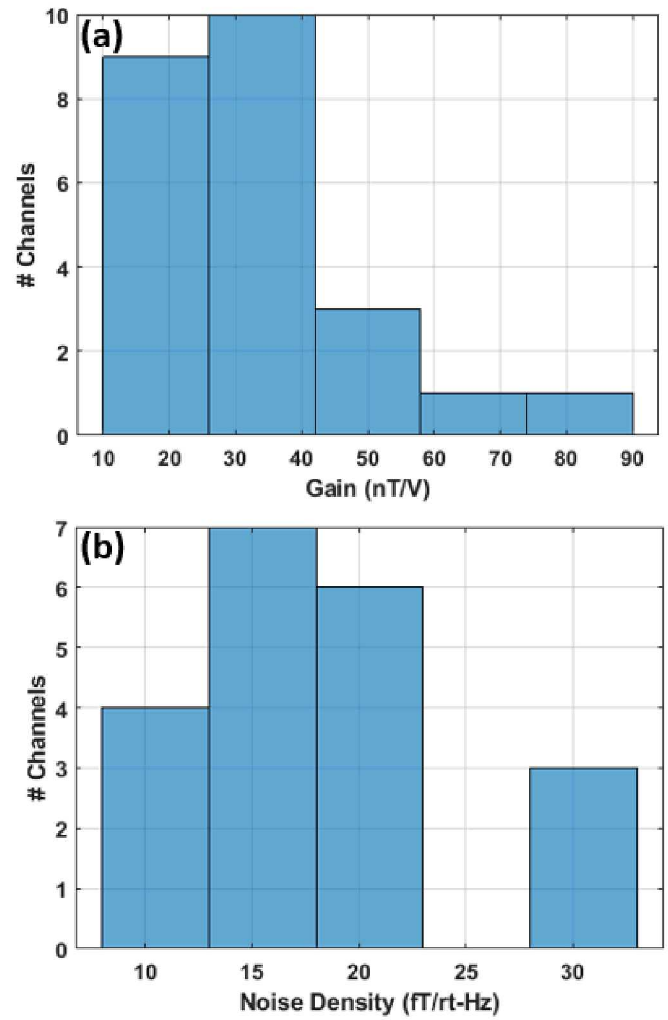
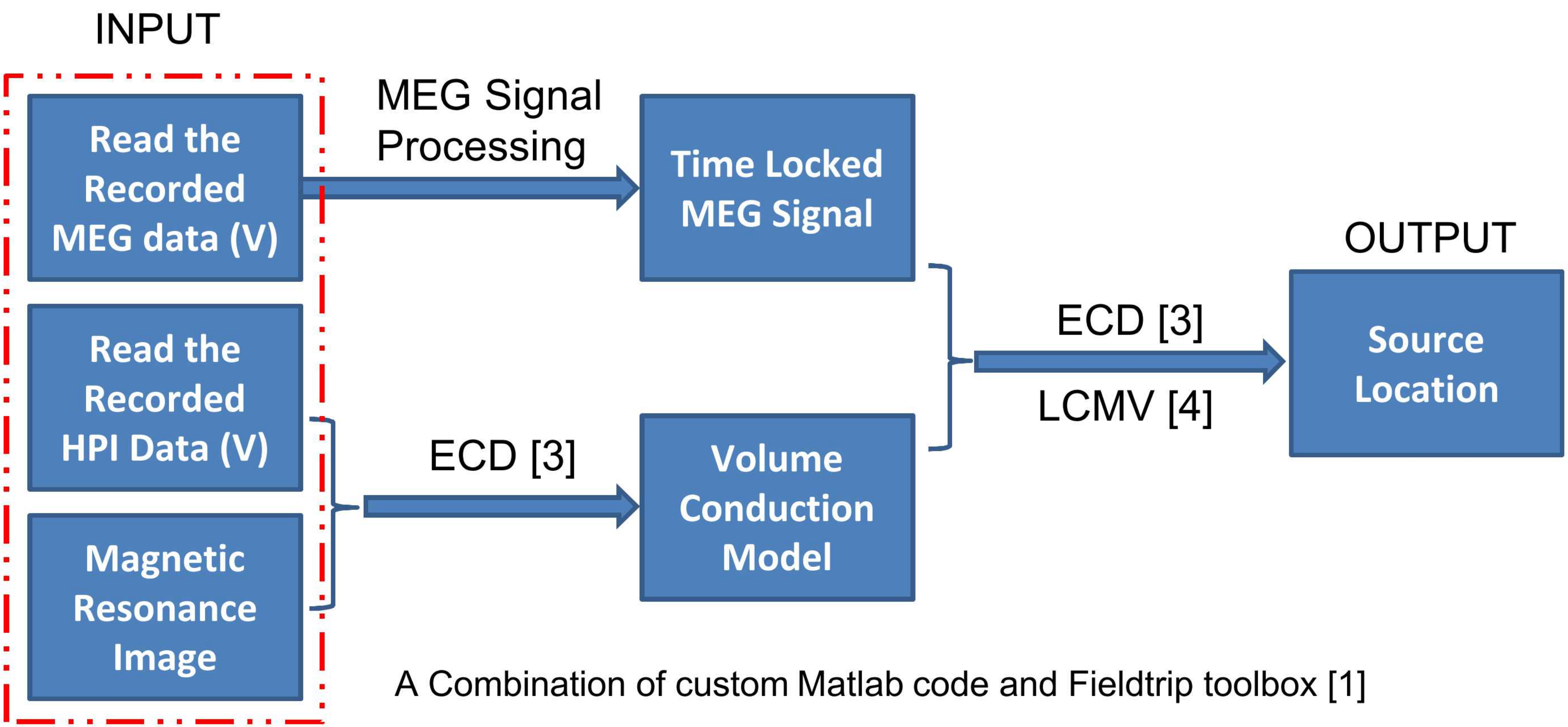


Noise clean-up using independent component analysis (ICA): (a) The ICA components, (b) noise density comparison of the raw data versus ICA-cleaned data.



OPM Array Characterization: the histograms of (a) gain across channels, and (b) channels average noise density estimated between 10-44 Hz.

MEG System: Signal Processing Pipeline



A Combination of custom Matlab code and Fieldtrip toolbox [1]

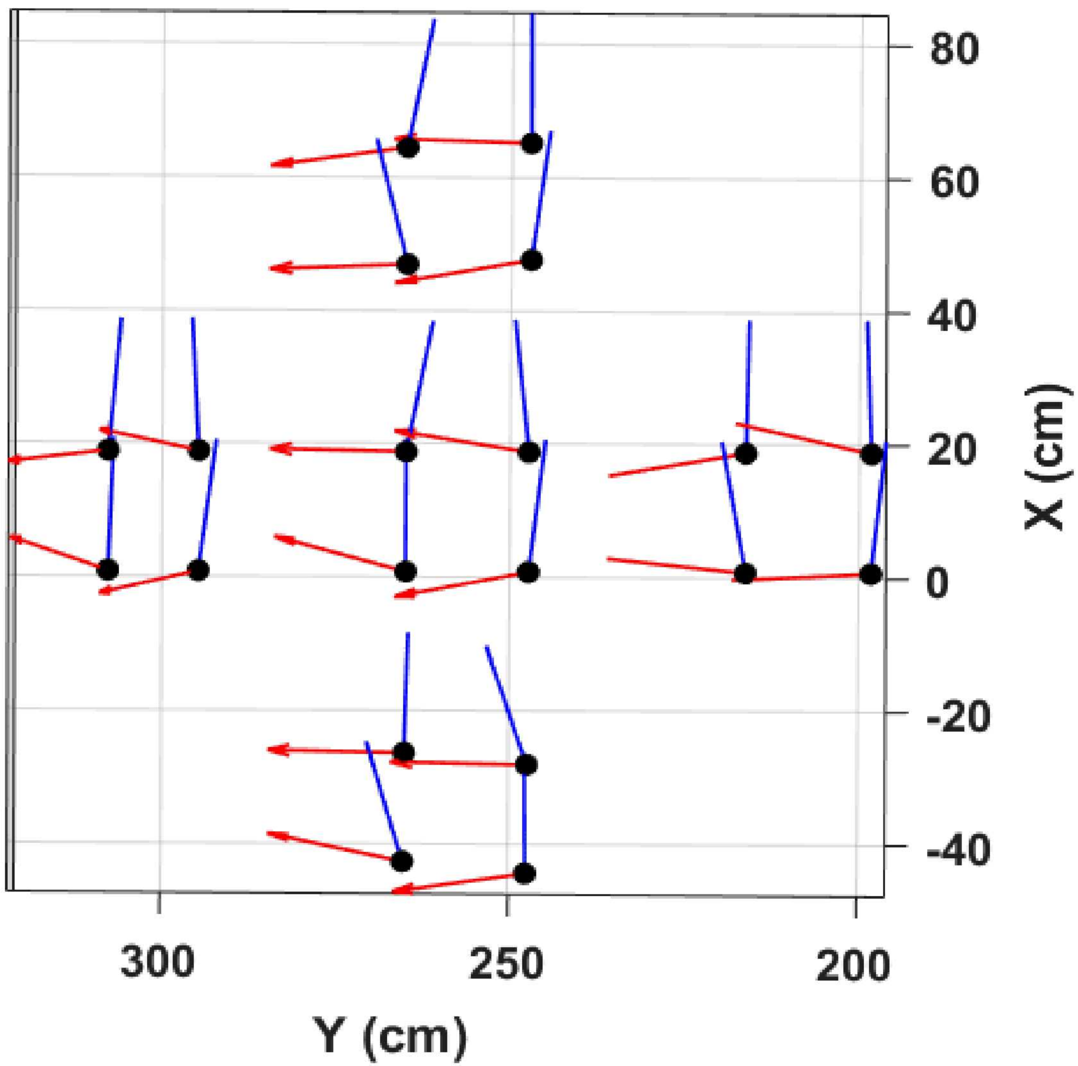
[1] R. Oostenveld, P. Fries, E. Maris, and J.-M. Schoffelen, "FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data," Computational Intelligence and Neuroscience, vol. 2011, p. 9, 2011.

[2] G. Nolte, "The magnetic lead field theorem in the quasistatic approximation and its use for magnetoencephalography forward calculation in realistic volume conductors," Physics in Medicine and Biology, Article vol. 48, no. 22, pp. 3637-3652, Nov 2003.

[3] Lutkenhoner B. "Dipole source localization by means of maximum likelihood estimation I. Theory and simulations,“ Electroencephalography and Clinical Neurophysiology, Volume 106, Issue 4, April 1998, Pages 314-321.

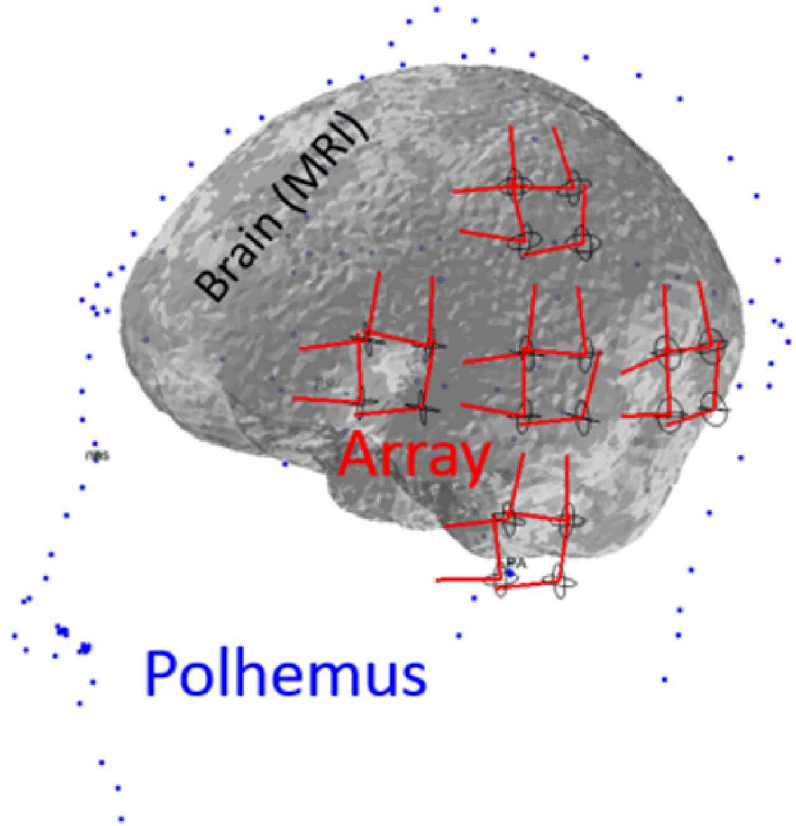
[4] B. D. Van Veen, W. van Drongelen, M. Yuchtman, and A. Suzuki, "Localization of brain electrical activity via linearly constrained minimum variance spatial filtering,“ IEEE Transactions on Biomedical Engineering, Article vol. 44, no. 9, pp. 867-880, Sep 1997.

20-Channels: 40 Measurements



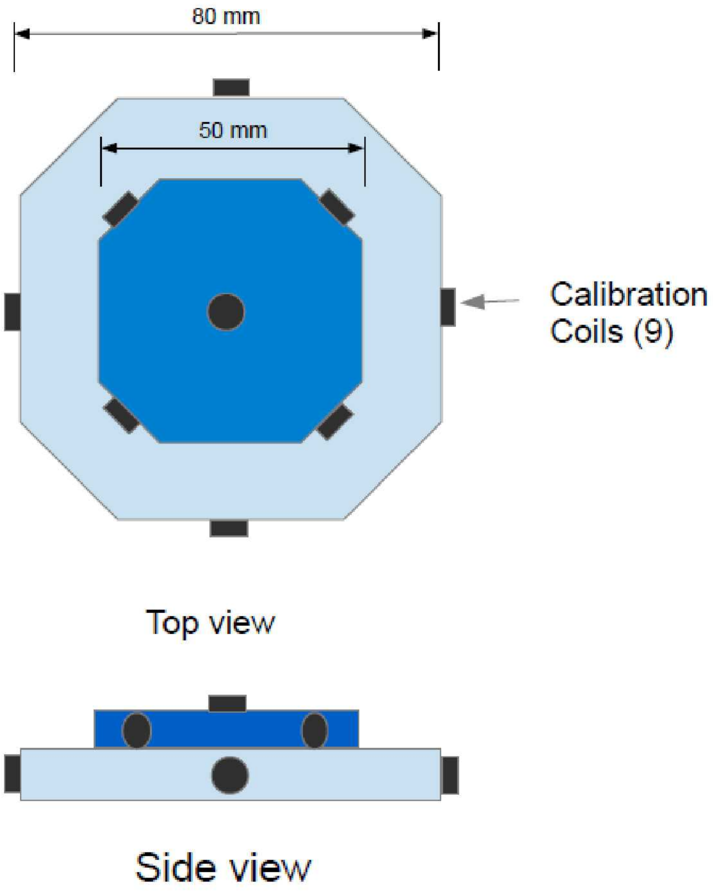
- Sequentially measure two components
- Calibrate each sensor to know its sensitive direction
- Neighboring sensors interfere to change sensitive direction

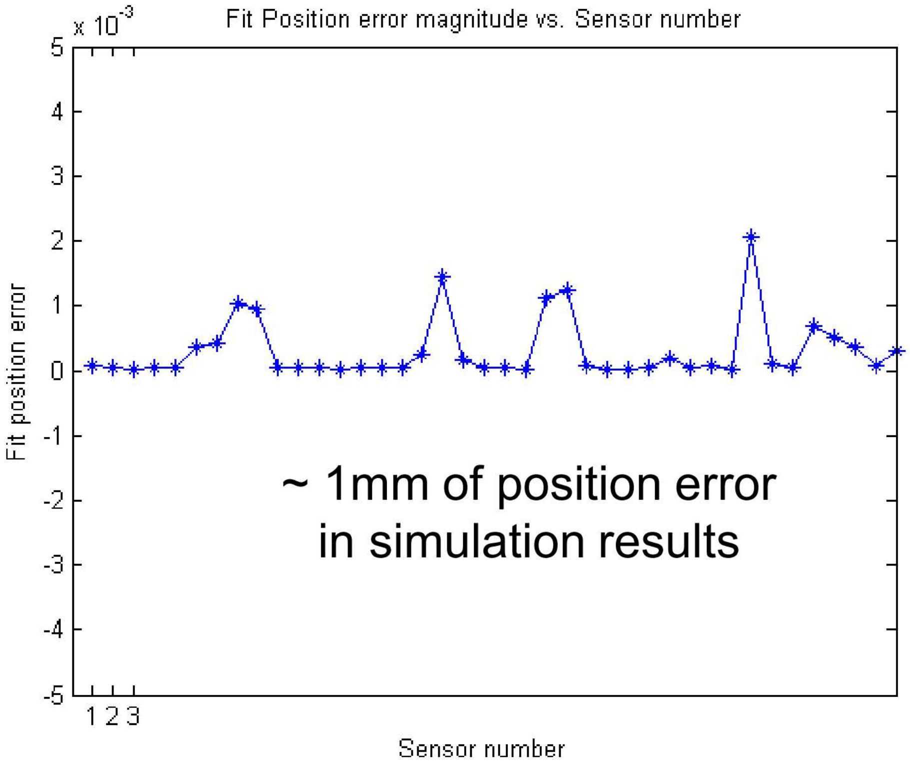
MRI Co-registration and Forward Model



- Four head localization coils close to the array
- Polhemus Fastrak system to digitize
- Relative sensor positions from CAD model

OPM Array Calibration: Simulation Results



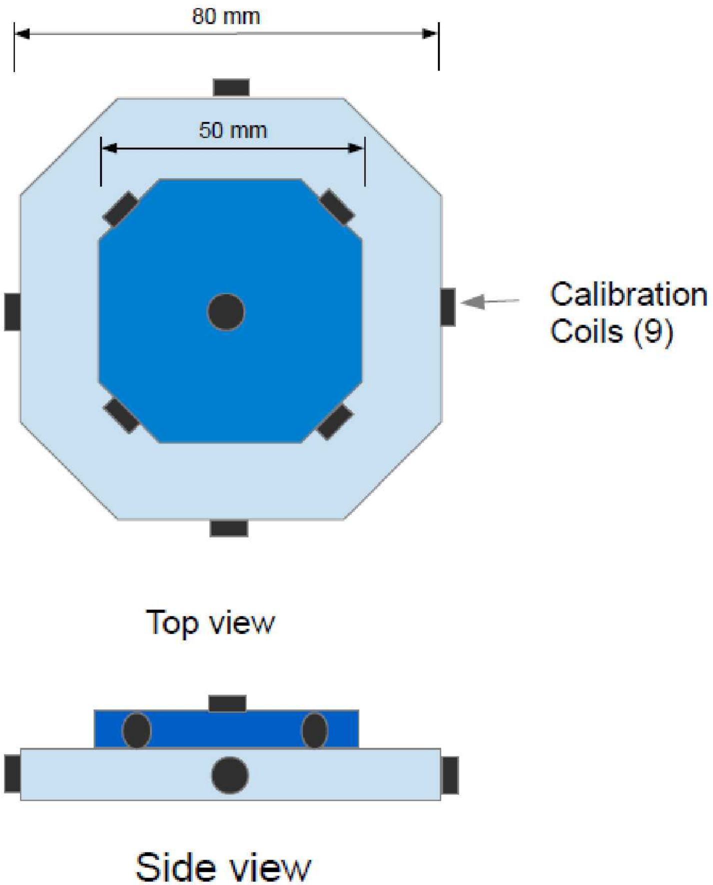


3D-printed magnetic dipole phantom used in array sensor position calibration

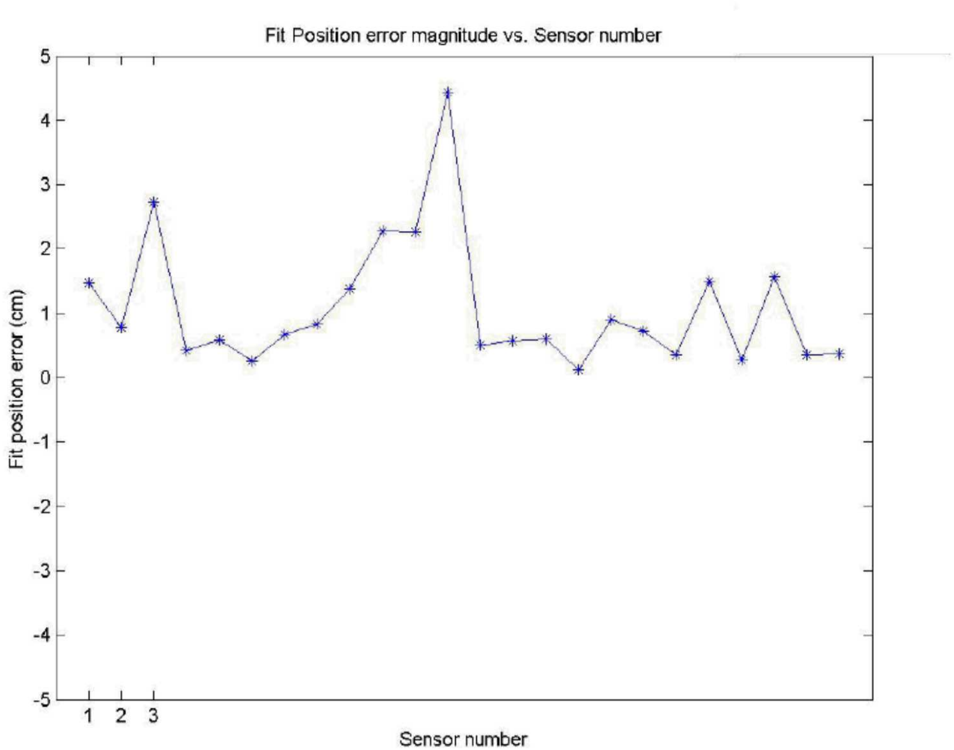
Simulated calibration: location error for 40 OPM sensors using 9 coil phantom

[1] Pfeiffer C, Andersen LM, Lundqvist D, Hämäläinen M, Schneiderman JF, Oostenveld R (2018) **Localizing on-scalp MEG sensors using an array of magnetic dipole coils**. PLoS ONE 13(5):e0191111. https://doi.org/10.1371/journal.pone.0191111

OPM Array Calibration: Experimental Results



3D-printed magnetic dipole phantom used in array sensor position calibration



Fit position error (distance from given sensor location) for sensors 1-24 (y-mod) using the time domain dipole fit at 0.02 sec (sensors 25-48 (x-mod) have similar results)

[1] Pfeiffer C, Andersen LM, Lundqvist D, Hämäläinen M, Schneiderman JF, Oostenveld R (2018) **Localizing on-scalp MEG sensors using an array of magnetic dipole coils**. PLoS ONE 13(5):e0191111. https://doi.org/10.1371/journal.pone.0191111

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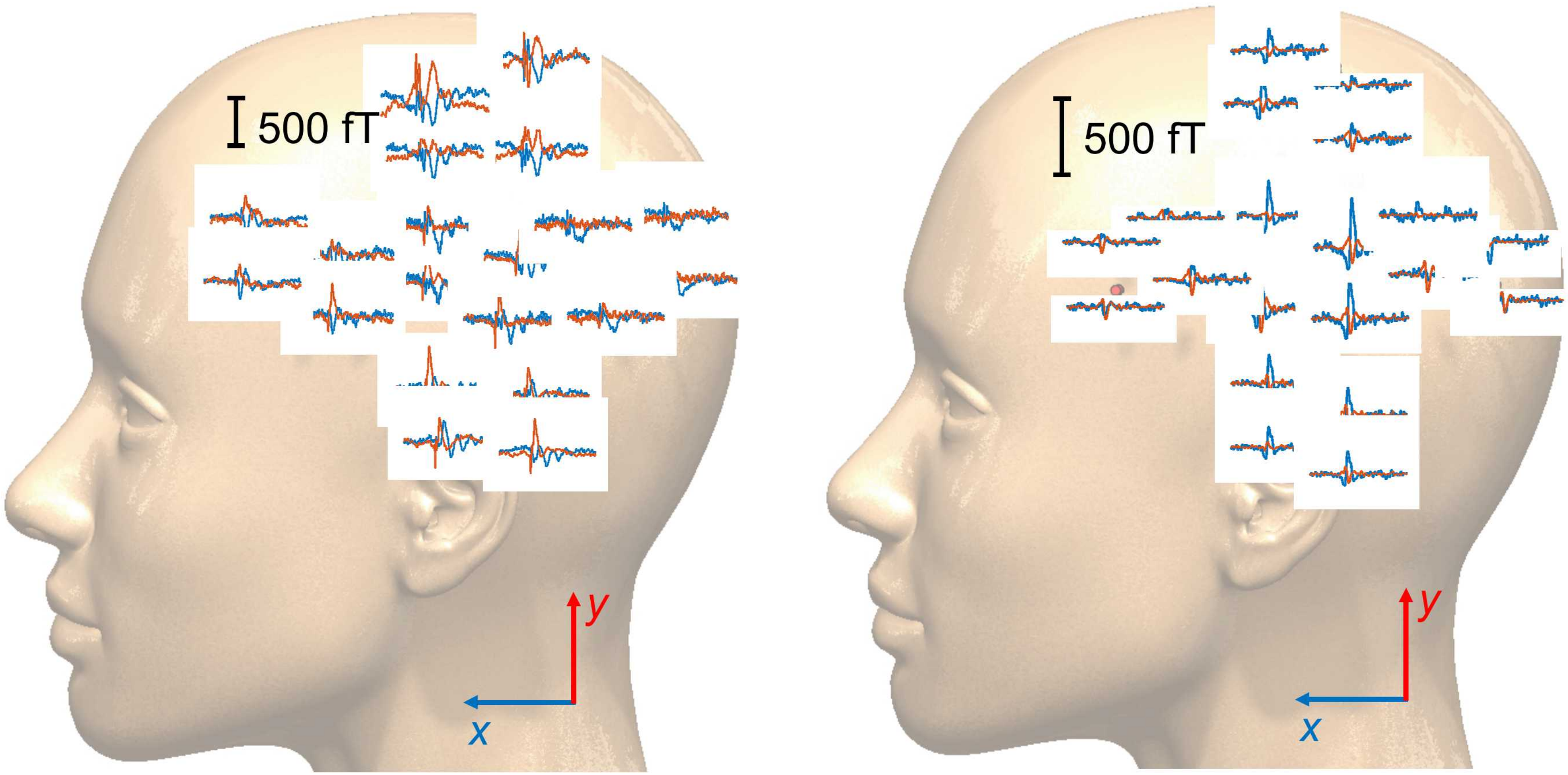
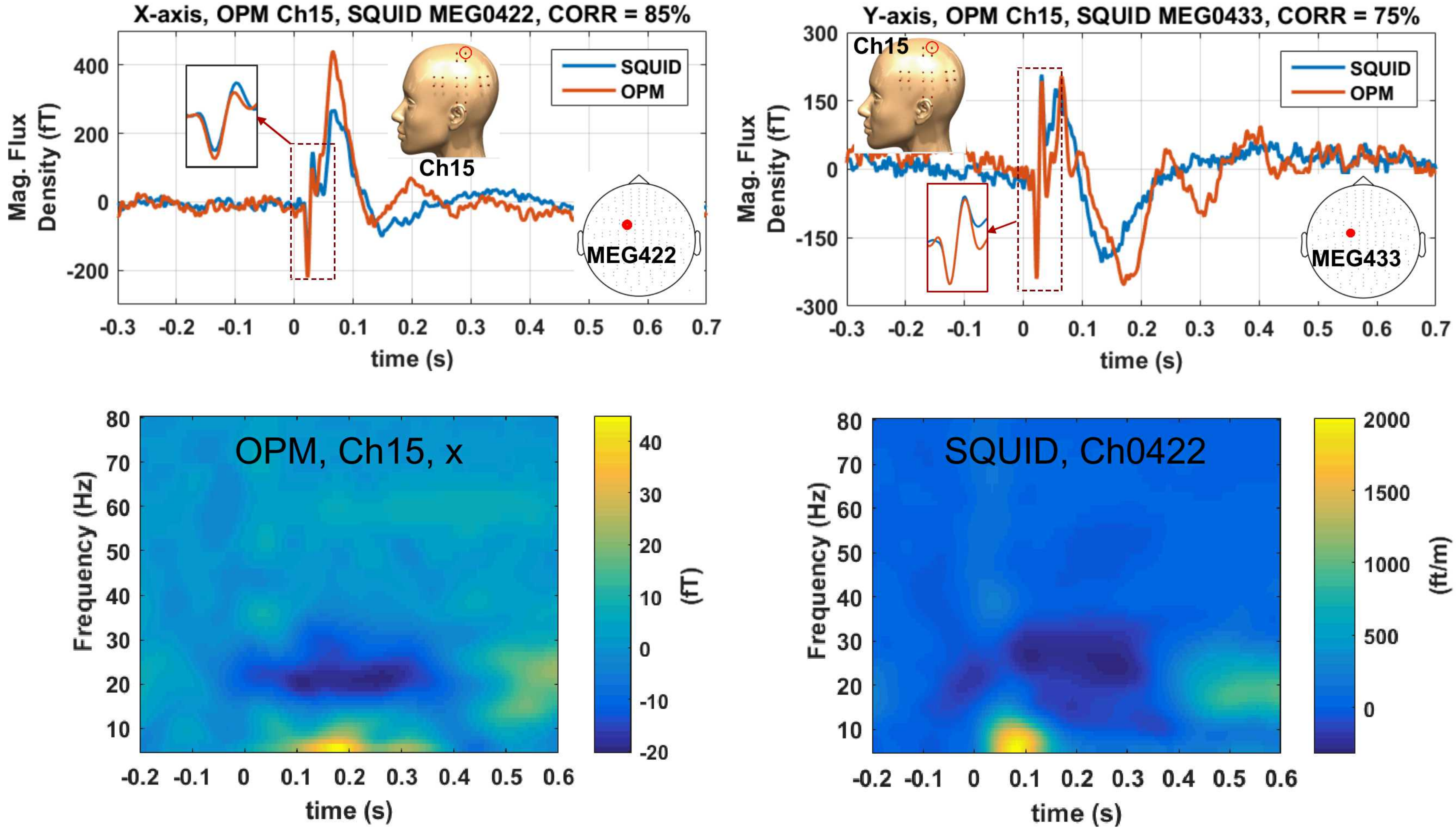
Somatosensory/Auditory Evoked Magnetic Fields: Spatial Topographies



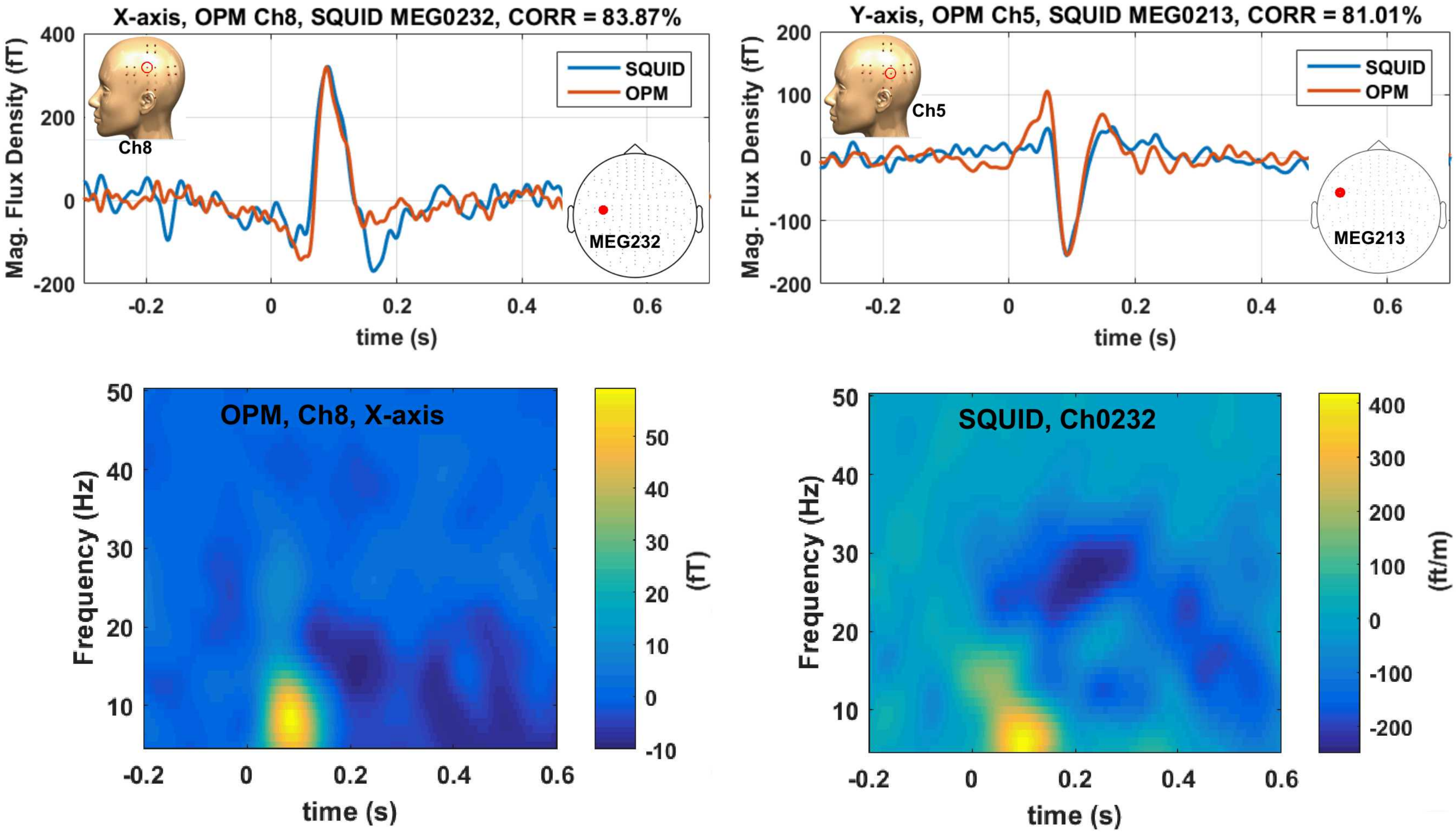
SEF AEF

Somatosensory Evoked Magnetic Fields: OPM vs. SQUID



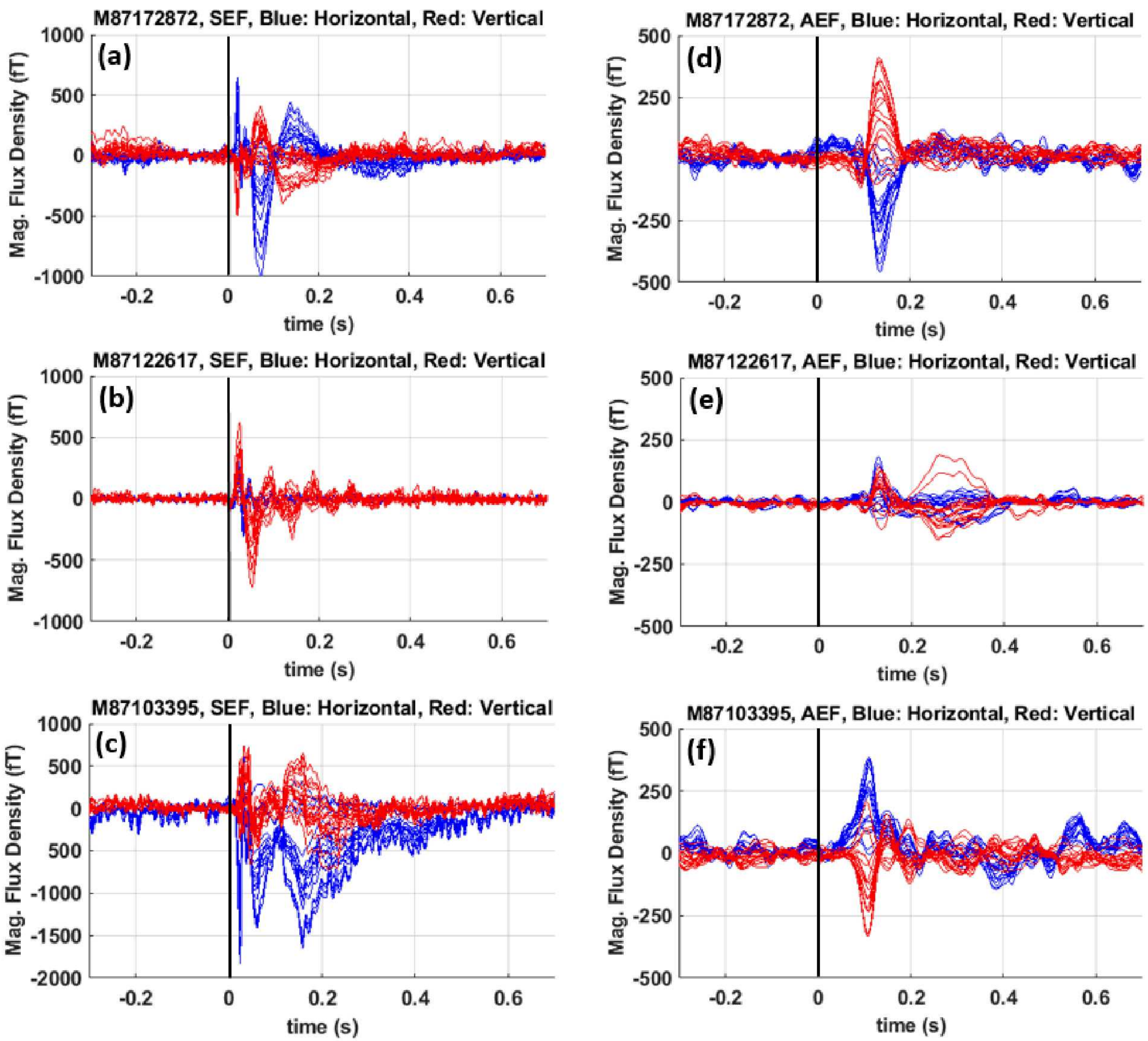
- More than 75% correlation for both x and y component
- Beta suppression is observed with both SQUID and OPM array

Auditory Evoked Magnetic Fields: OPM vs. SQUID

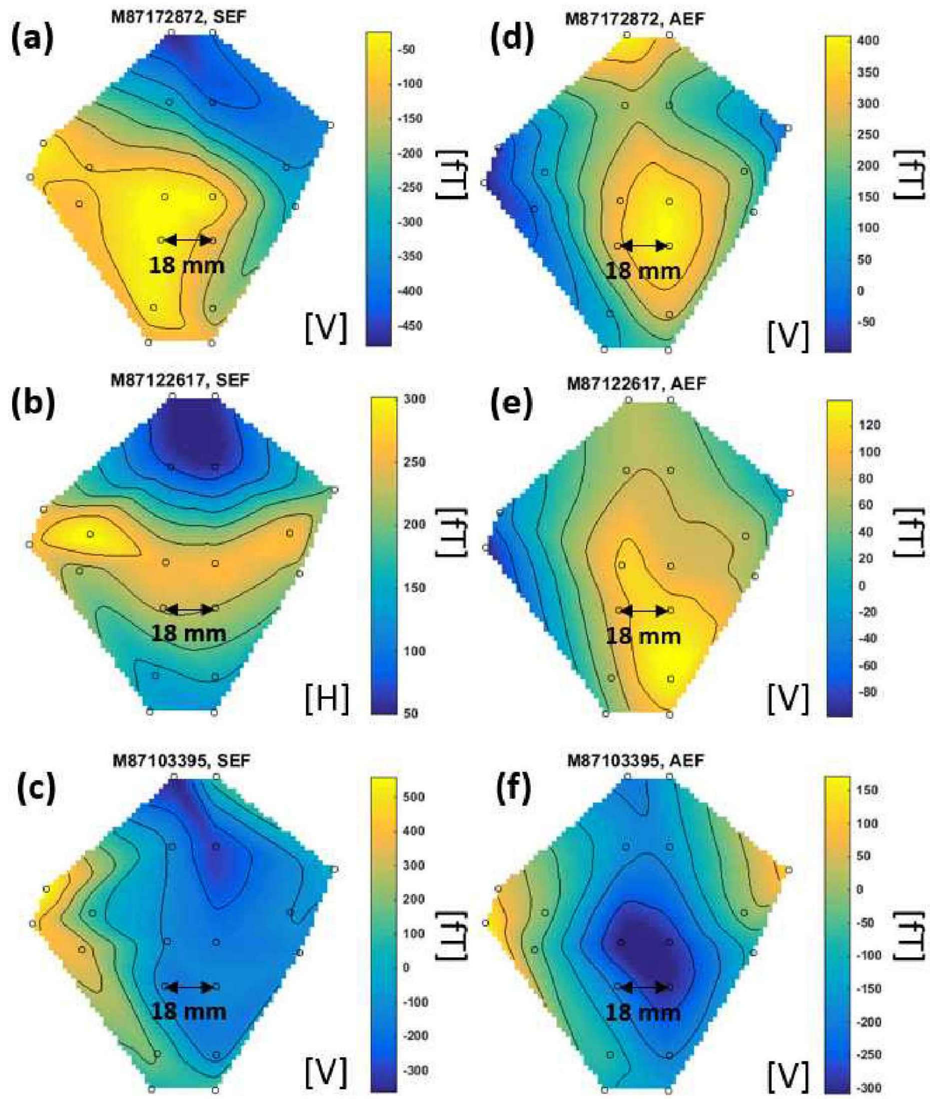


- More than 80% correlation for both x and y component

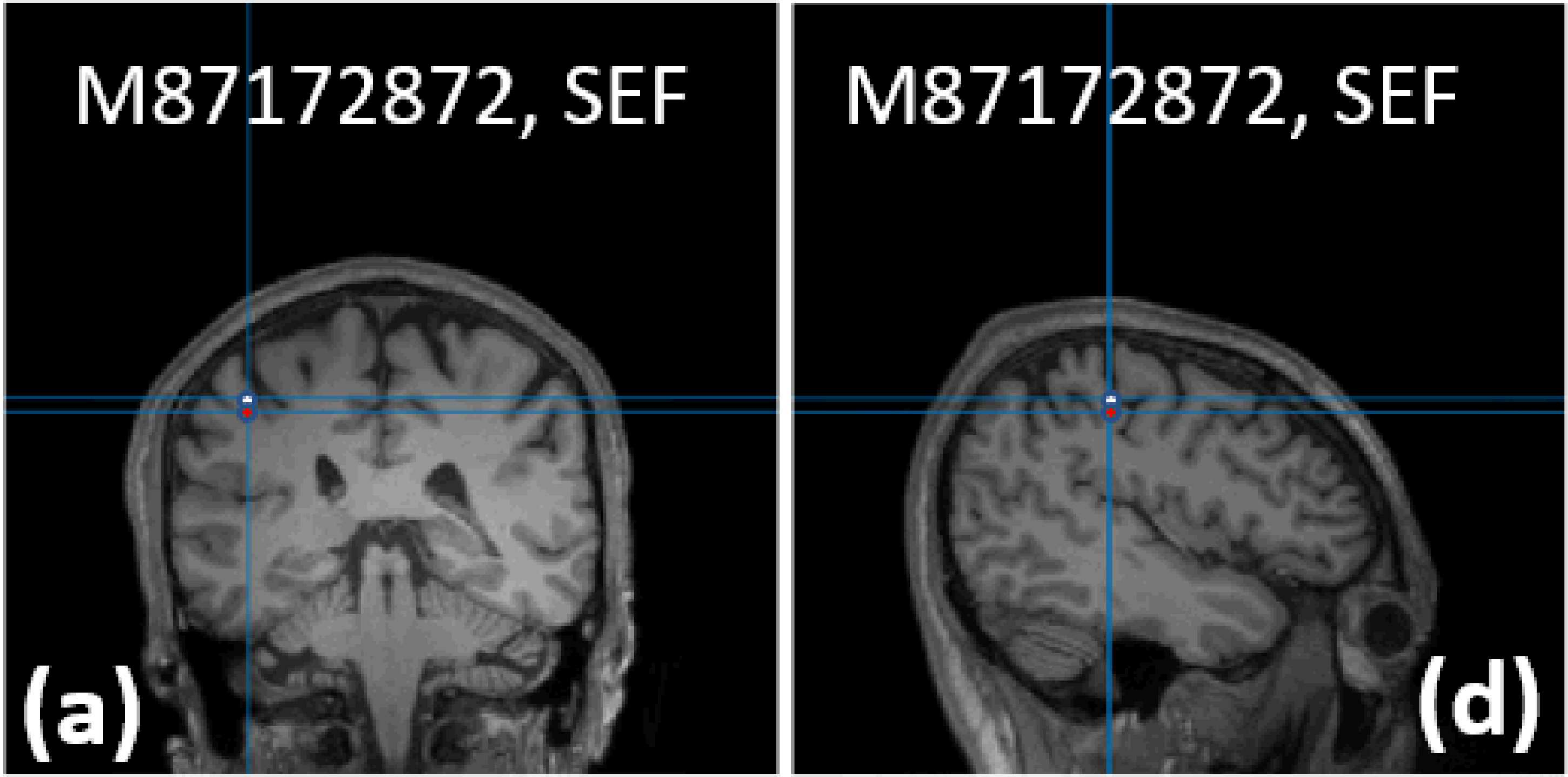
OPM time-domain SEF/AEF data



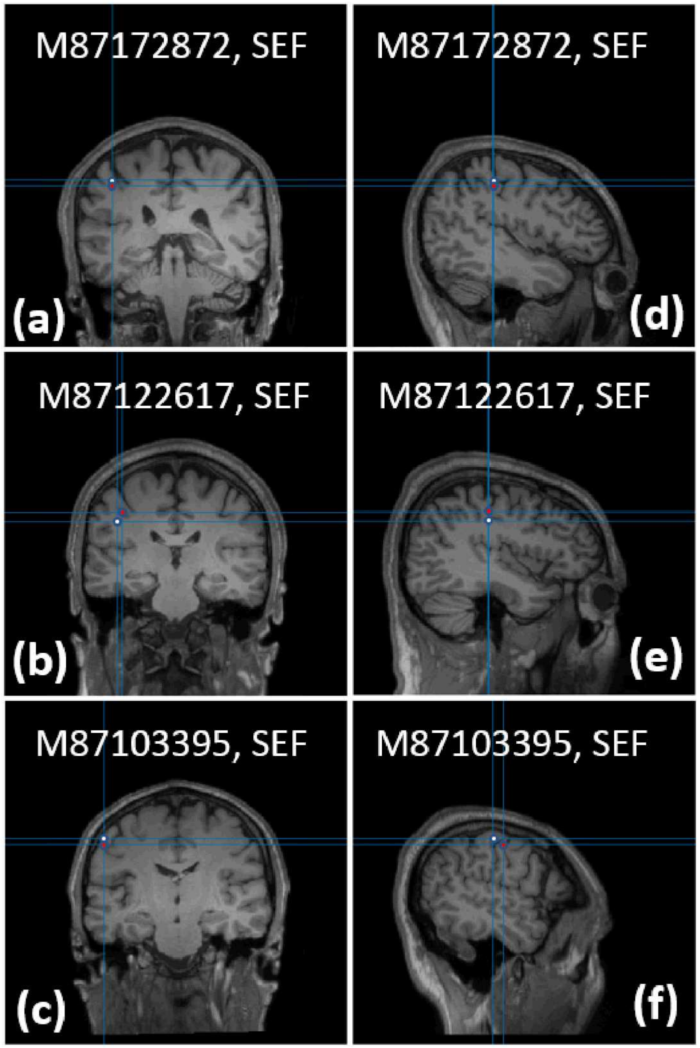
OPM SEF/AEF Spatial Topography

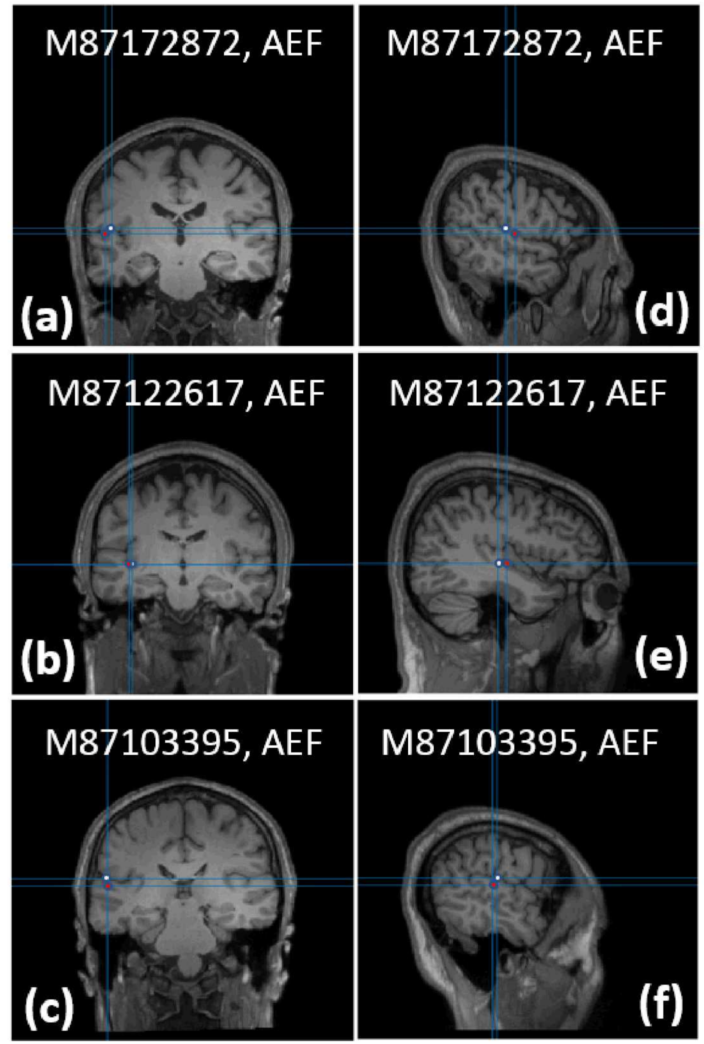


Source Localization: SEF



OPM vs. SQUID Localization





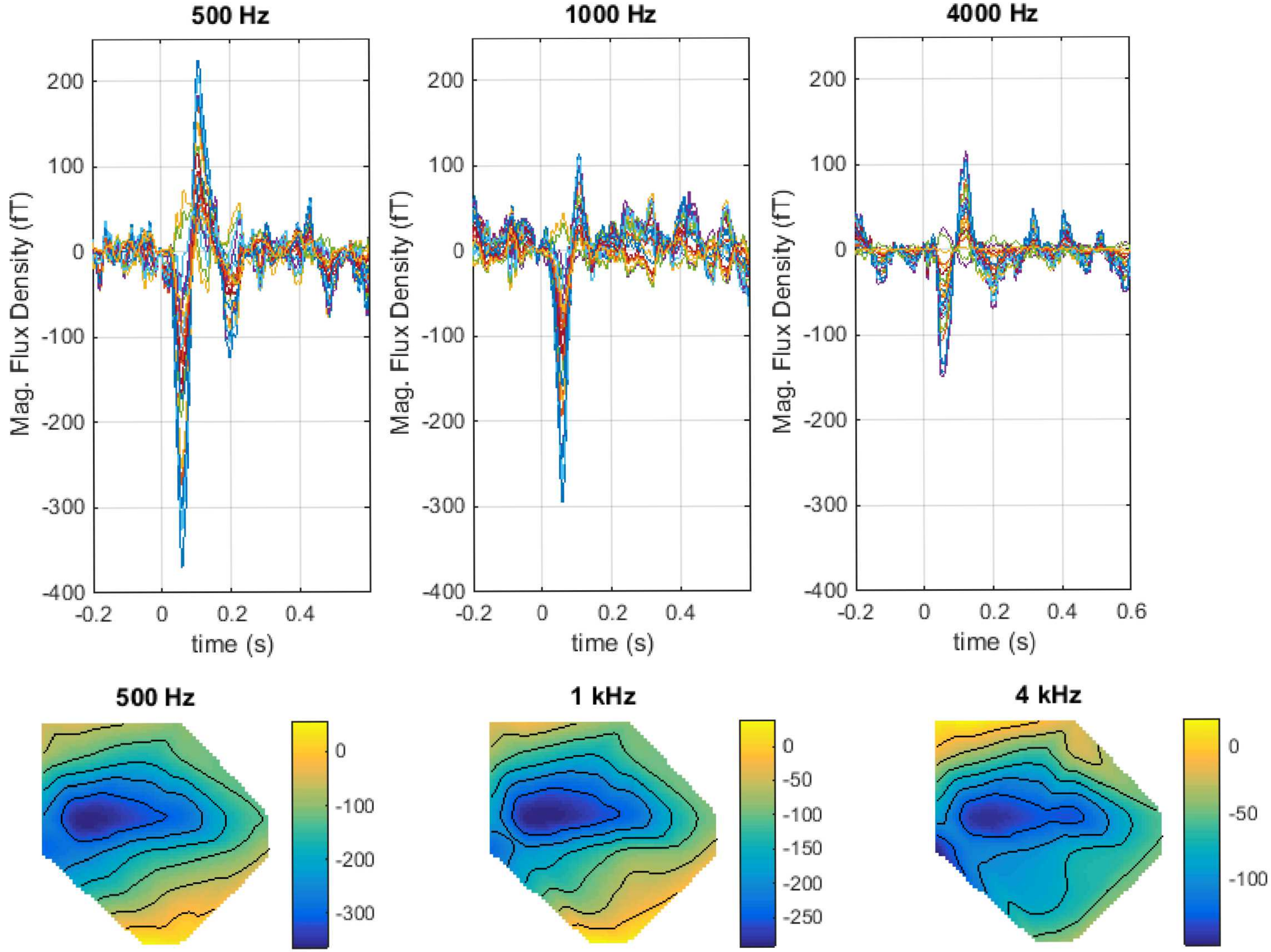
OPM vs. SQUID Localization

Table 1. Comparison of the OPM- and SQUID-based MEG system performance

Subject ID	**Experiment Type**	**Error (*mm*)**	**OPM *rv***	**SQUID *gof* (%) (26)**	**OPM/SQUID SNR**
M87172872	SEF	3.9	0.0249	86.3	14.6/17.5
	AEF	9.5	0.0381	97.1	26.6/15.4
M87122617	SEF	7.5	0.0144	58.5	24.9/7.4
	AEF	7.1	0.0059	79.2	26.7/16.6
M87103395	SEF	9.7	0.0212	87.9	16.1/13.3
	AEF	6.2	0.0193	86.3	35.5/15.6

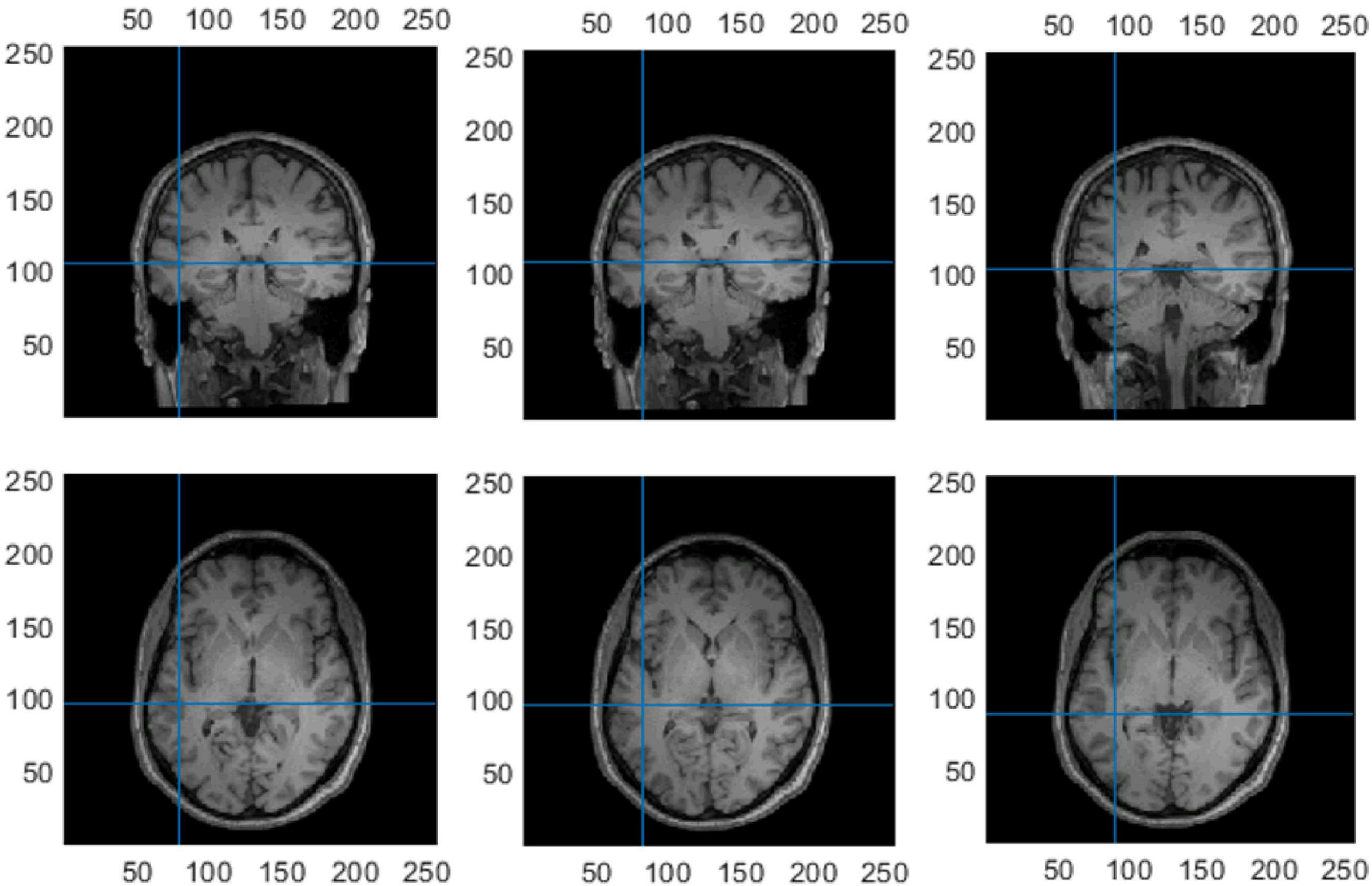
Ground truth is the source location provided by the commercial Elekta-Neuromag SQUID-based MEG system; the distance between the locations of the equivalent current dipole calculated by the OPM-based MEG system and that of the commercial SQUID-based MEG system is shown in the Error column. OPM *rv* refers to the residual variance between the measured data and the reconstructed data from the localized sources; goodness of fit for the SQUID data is shown in the column labeled SQUID gof (%); last column compares the signal to noise ratio of both systems.

Preliminary: Studying Auditory Frequency Response



Source Localization

500 Hz　　　　1000 Hz　　　　4000 Hz



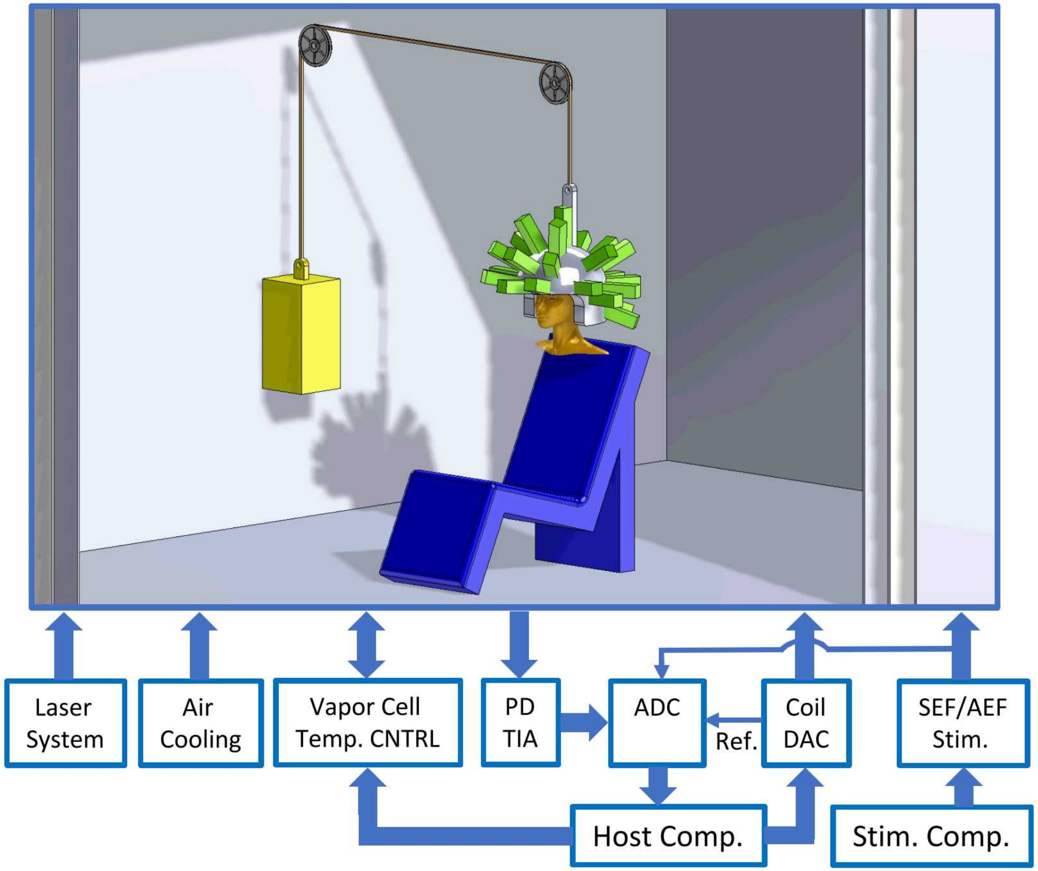
Outline

- Introduction
- Non-Invasive Functional Brain Imaging
    - Sensor Design
    - The Magnetoencephalography System
    - Auditory/Somatosensory Experiments
- **Conclusion**

Future Directions: Scaling Up

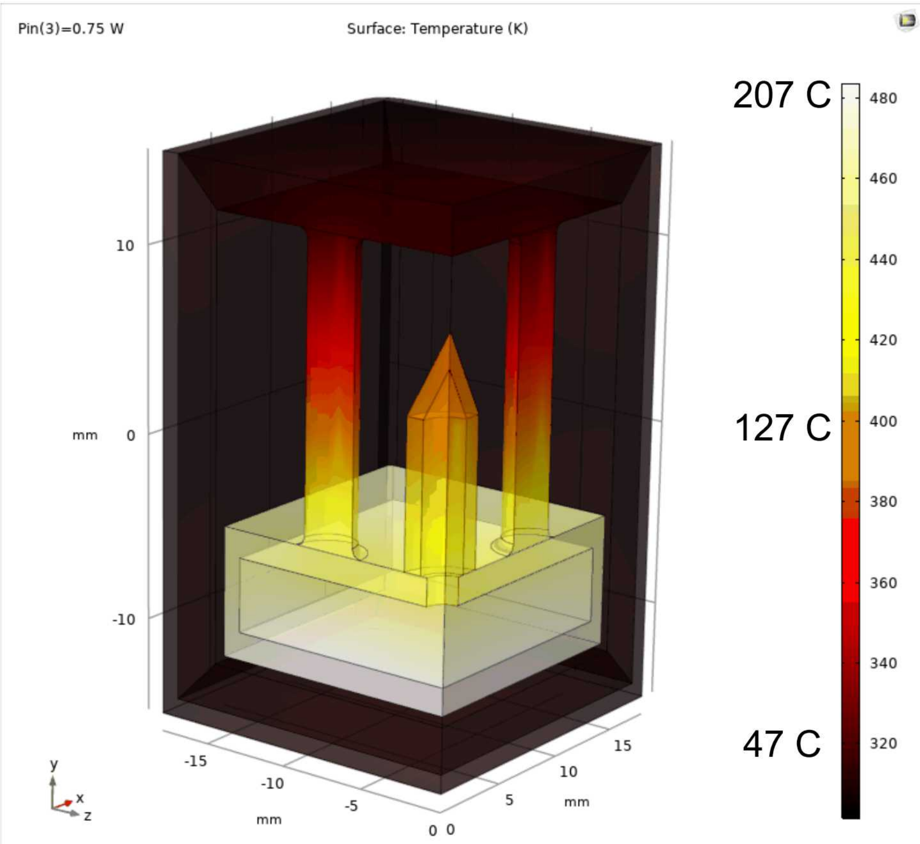
A 108-channel OPM MEG system

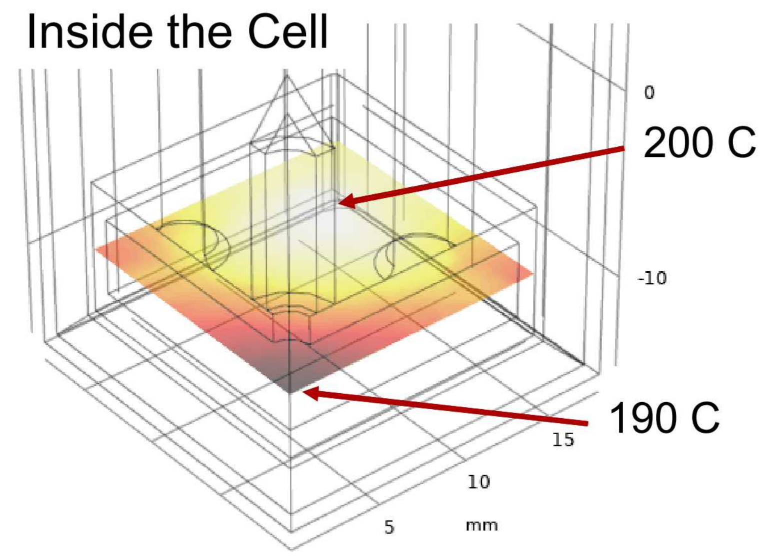
- Redesign the OPM and build 27 sensors
  - Improve performance
  - Simpler manufacture
  - Higher reliability
- Install inside a magnetically shielded room
  - Implement magnetic field control à al Nottingham

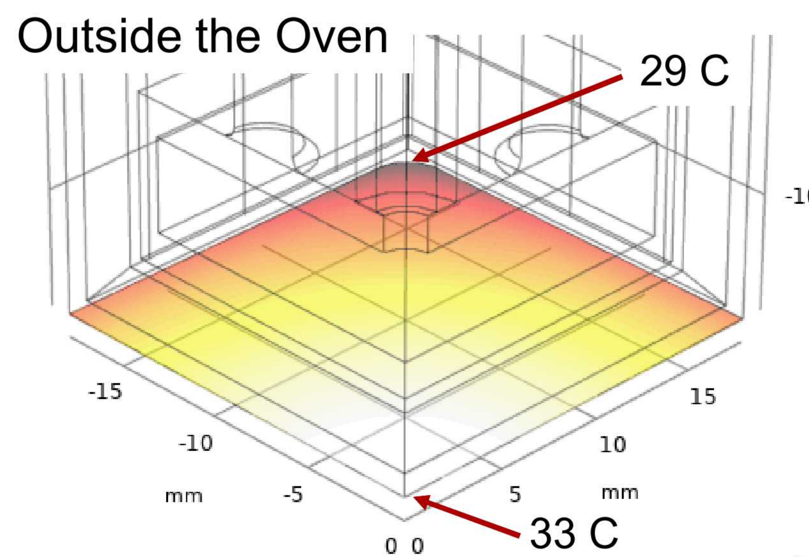


Vacuum Packaging the Vapor Cell

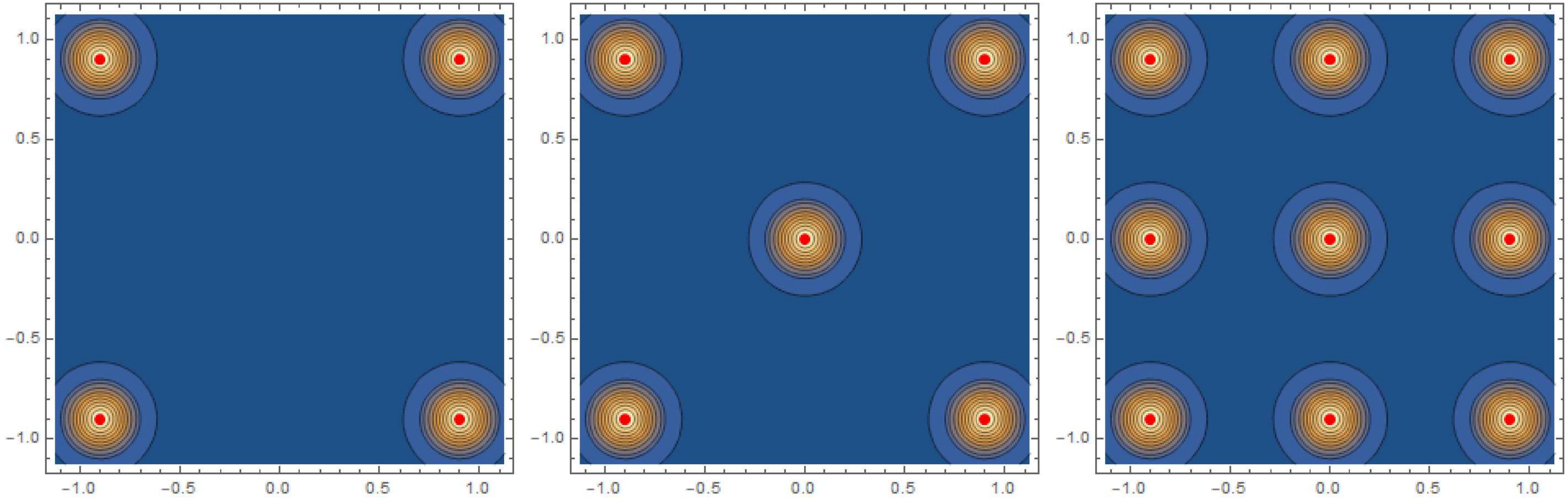
- Reduce power consumption
  - 6-10 W → 2-3 W
- Move closer to the head
  - 12 mm → 6 or 7 mm
- Minimize sensor footprint on the head
  - 40 mm × 40 mm → 36 mm × 36 mm







Adding More Channels



4 Channels 5 Channels 9 Channels

- Spacing is arbitrary

Conclusion

MEG System

- Constructed a fully functional Magnetoencephalography system using Optically Pumped Magnetometers (OPMs).
- Demonstrated source localization results for both AEF and SEF with sub-centimeter accuracy.

OPM Sensor

- Compact, 4-channel sensor design
- 12 mm standoff
- 18 mm channel separation
- 13 fT/rt-Hz mag. sensitivity and 5 fT/rt-Hz/cm grad. sensitivity
- 80-90 Hz bandwidth

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