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Non-Invasive Functional-Brain-Imaging with a Novel Magnetoencephalography System

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Mind Research Network, Albuquerque, NM

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U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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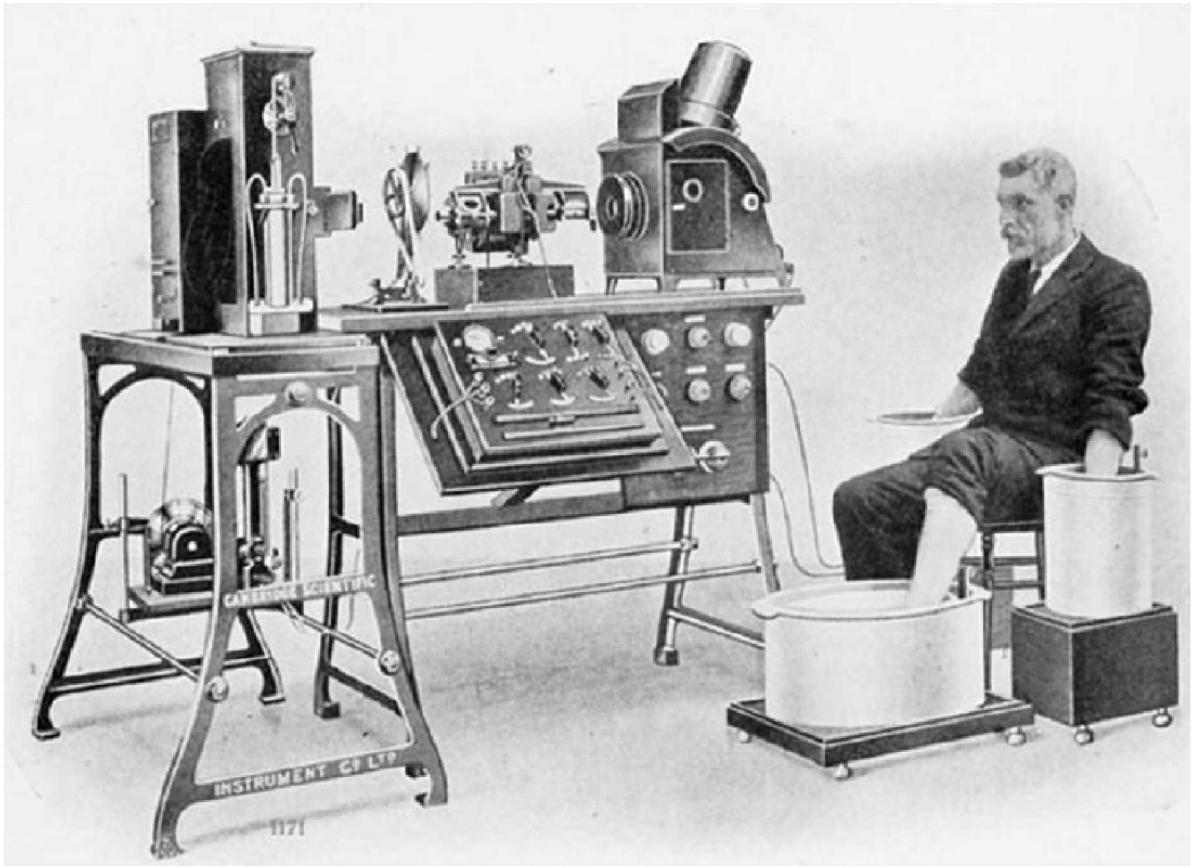
Outline

- ***Invasive Neural Telemetry Microsystems***
- Non-Invasive Functional Brain Imaging
  - OPM's Principle of Operation
  - OPM Sensor Design
  - OPM-Based MEG system
  - AEF/SEF Experiments
- Conclusion
- Future Work

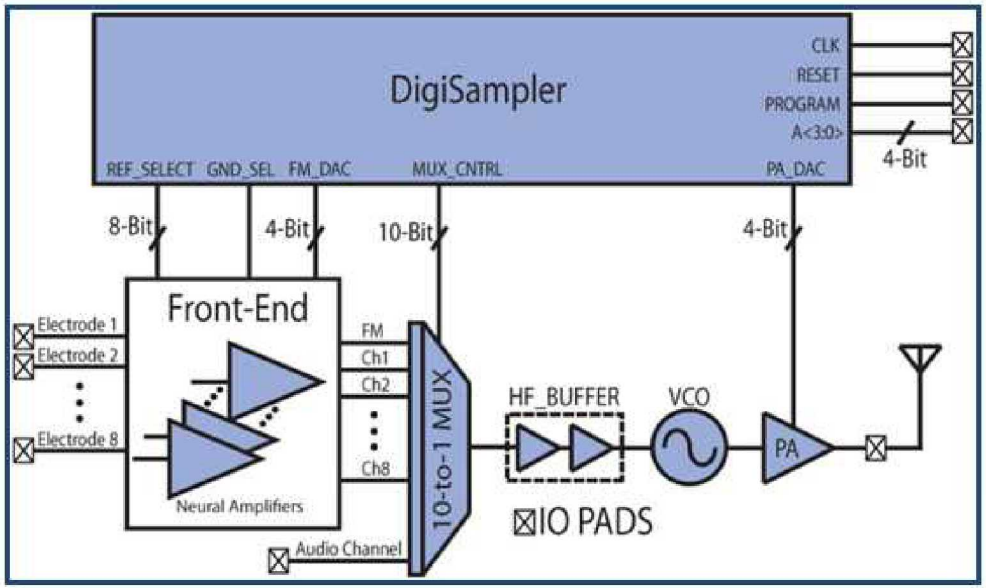
Invasive Neural Telemetry Microsystems

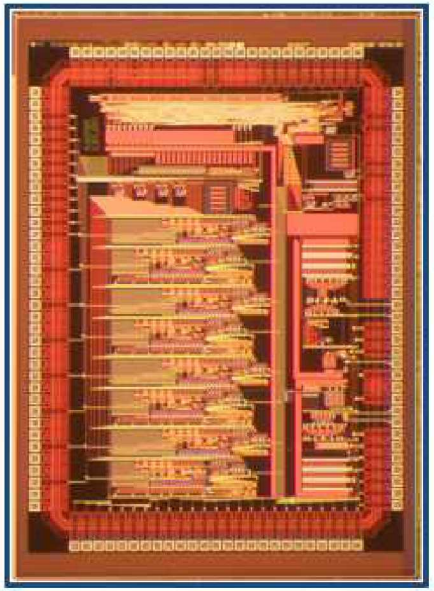


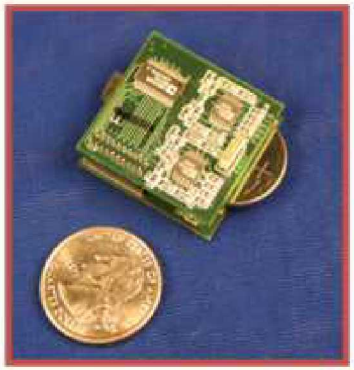
The first biotelemetry system pioneered by Professor Willem Einthoven (**1903**). In this setup built for Sir Thomas Lewis, immersion electrodes are used for **ECG** measurements and **telephones lines** are used to relay the biological information [1].

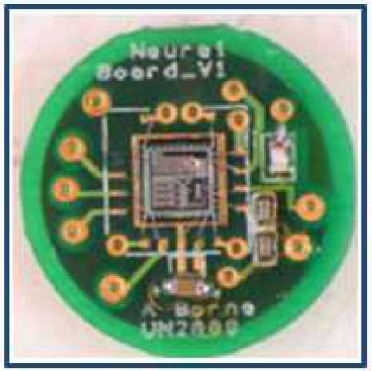
[1] Biomedical Instrumentation and Measurements, Leslie Cromwell, Fred J. Weibell, Erich A. Pfeiffer, Prentice Hall, 1980

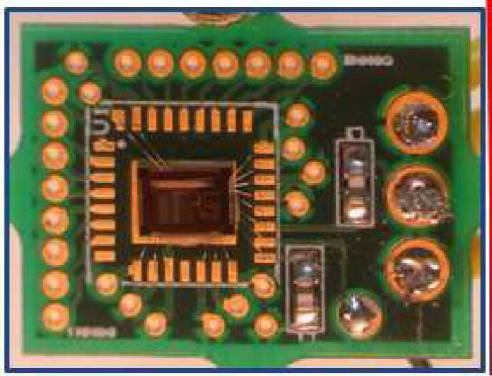
Invasive Neural Telemetry Microsystems

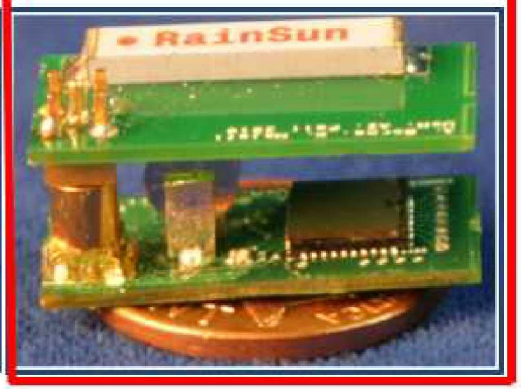






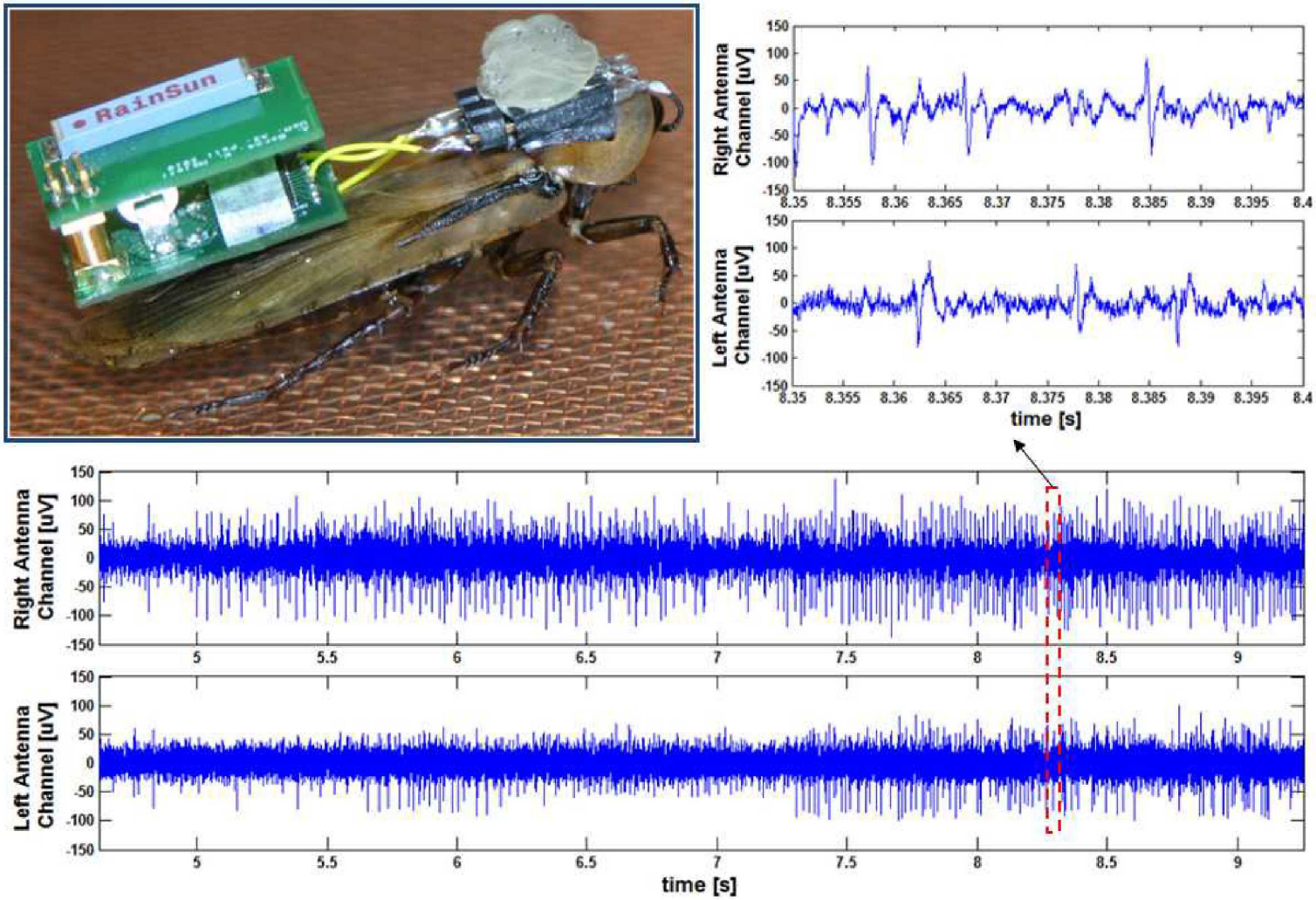






FMT_V1 NC_V1 NC_V2 NC_V3

Invasive Neural Telemetry Microsystems



In-vivo neural recordings from the antennas of a freely roaming South American cockroach (courtesy of Dr. Timothy Marzullo)

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Sandia National Laboratories

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Low-field Optically Pumped Magnetometers

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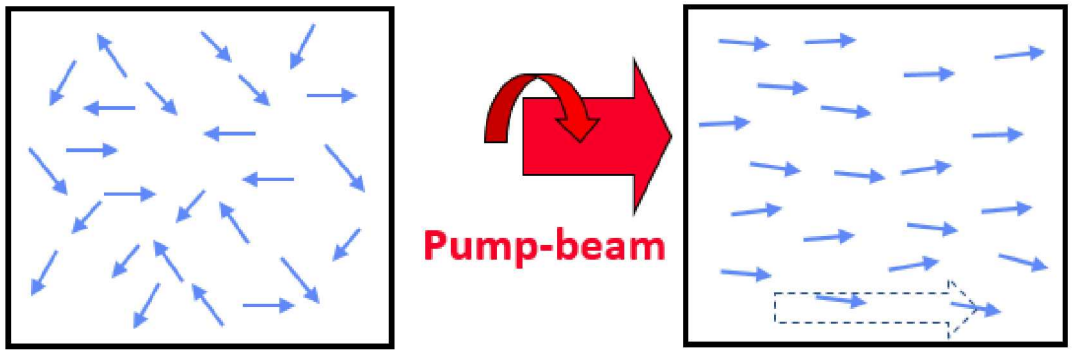
(1) Rubidium Vapor Cell

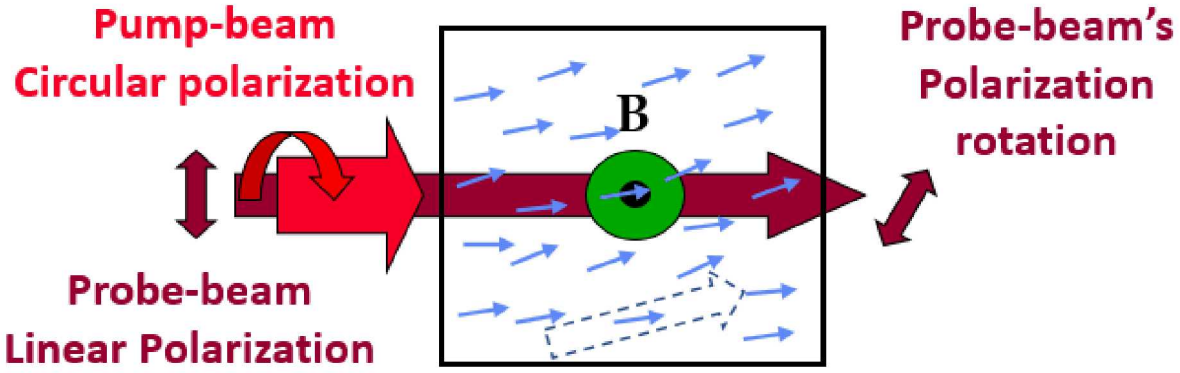
Randomly oriented atomic spins

(2) Optical pumping

Spin alignment using circularly-polarized pump beam



(3) Detect *B* by polarization rotation of the probe beam



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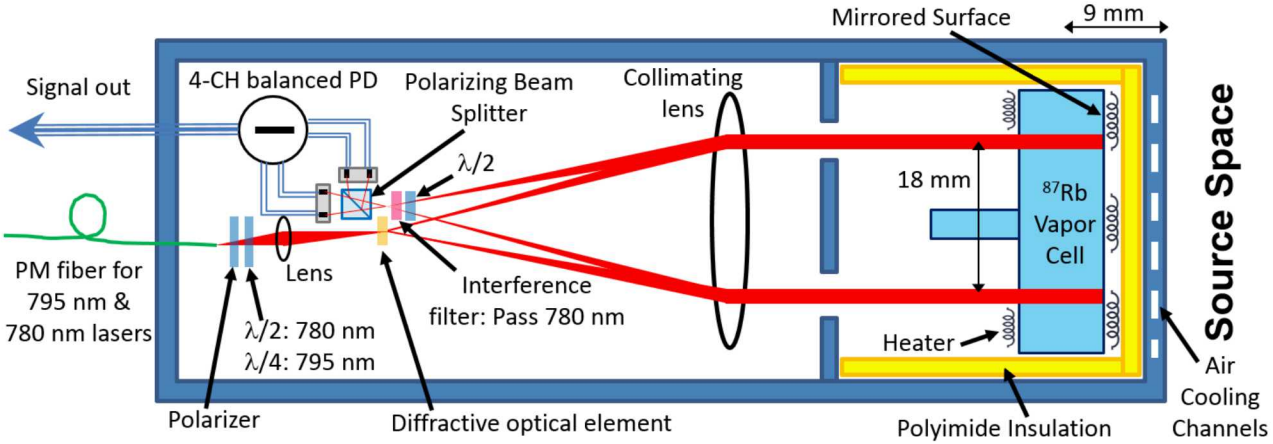
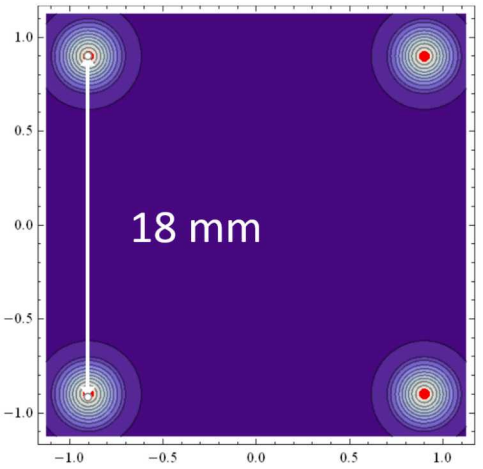
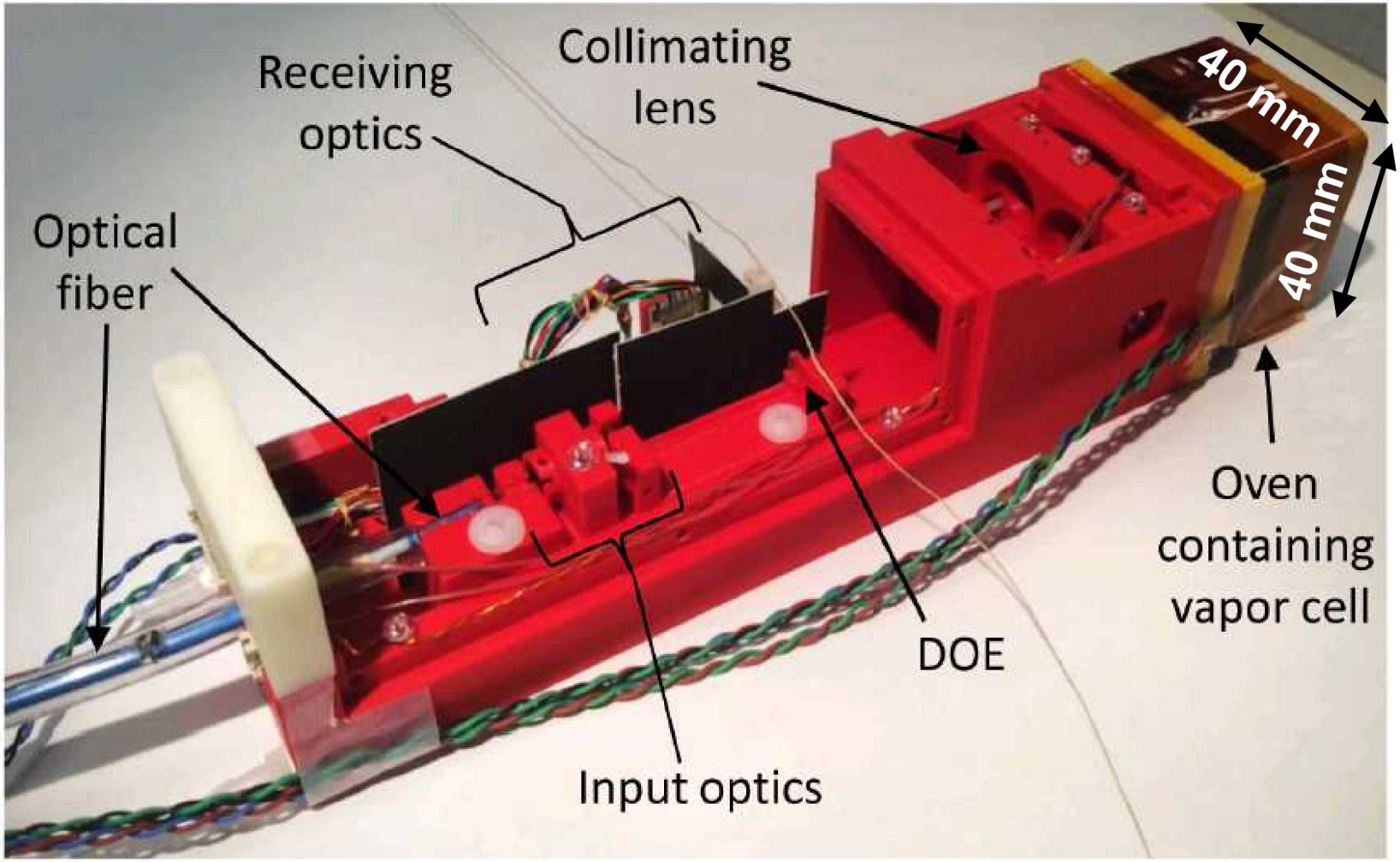
4-Channel OPM Sensor Design





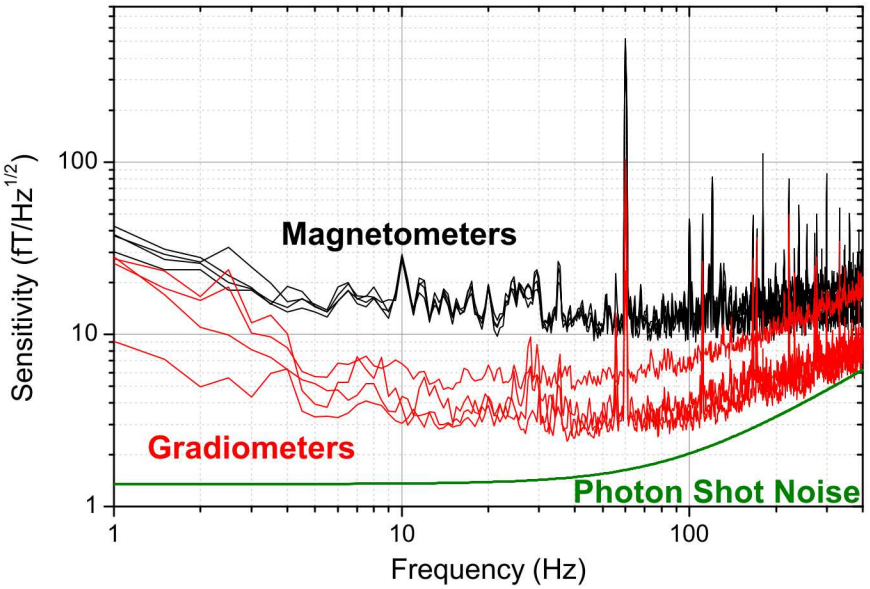
- Four separated beams:
  - 18 mm baseline
  - 2.5 mm FWHM beam diameter
- Vapor cell:
  - 4 mm long
  - 600 Torr N_2
- Sensing volume: 4 mm × π × (1.25 mm)^2 ≈ 20 mm^3
- Distance from the source space to the sensing volume: 12 mm

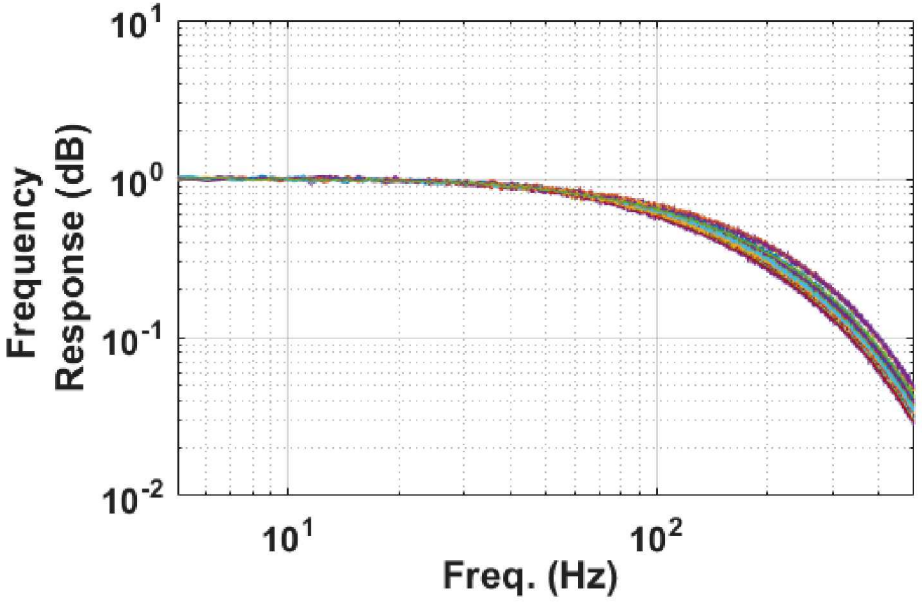
4-Channel OPM Sensor Design



4-Channel OPM Sensor Performance

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)	13.38	13.16	13.09	12.1
Grad. Noise (fT/cm/rt-Hz)	5.23	4.14	4.42	3.5

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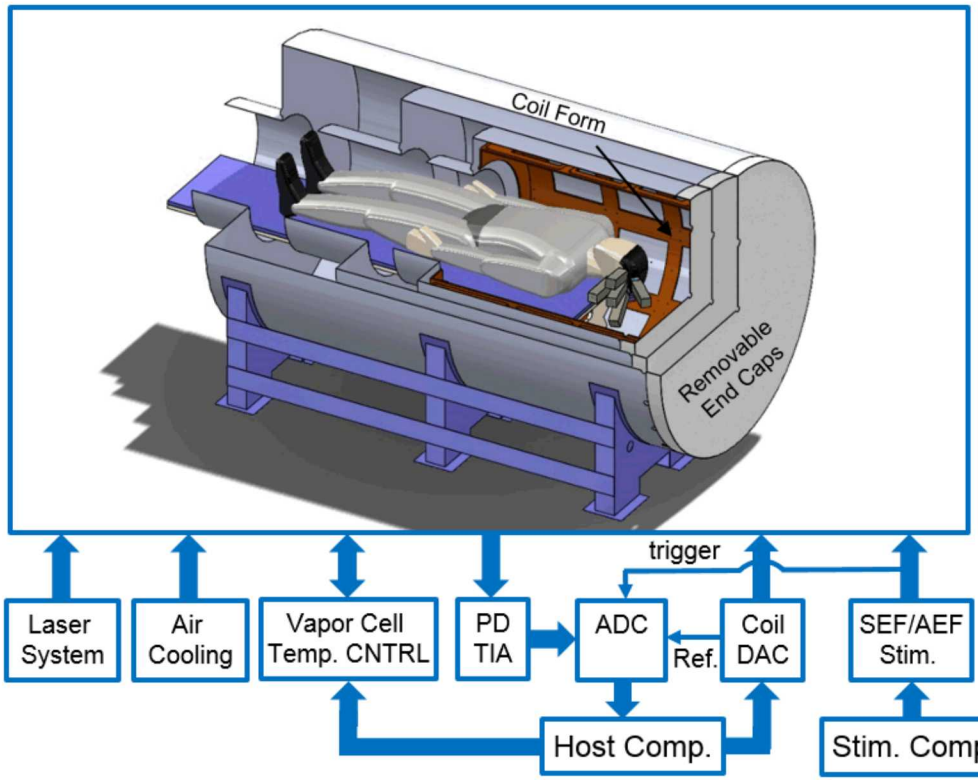
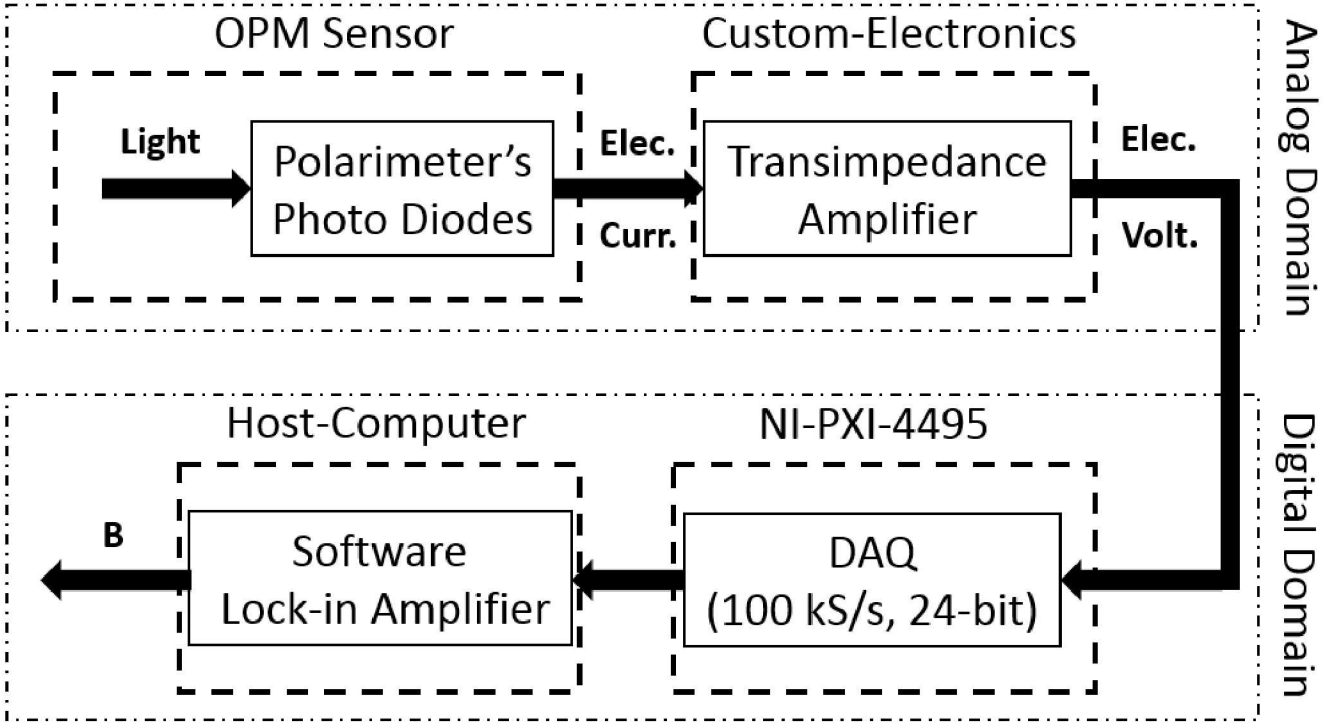
MEG System: Block Diagram



- 24-ch, 6 sensor, OPM array
- Human-sized magnetic shield, measured shielding factor ~ 1600
- Custom laser source
- Custom electronics
- Custom LabView-based data acquisition and control software
- Custom Matlab-based MEG data analysis pipeline

MEG System: Signal Path



- The probe beam's polarization is converted into electrical current by the sensor's polarimeter.
- the amplified electrical current is digitized by a sampling rate of 100 kS/s and a resolution of 24-bit.
- Using custom-designed software lock-in amplifier (LIA), the sensed magnetic flux density is calculated and stored on the host computer's hard drive.

MEG System: The 20-Channel Array

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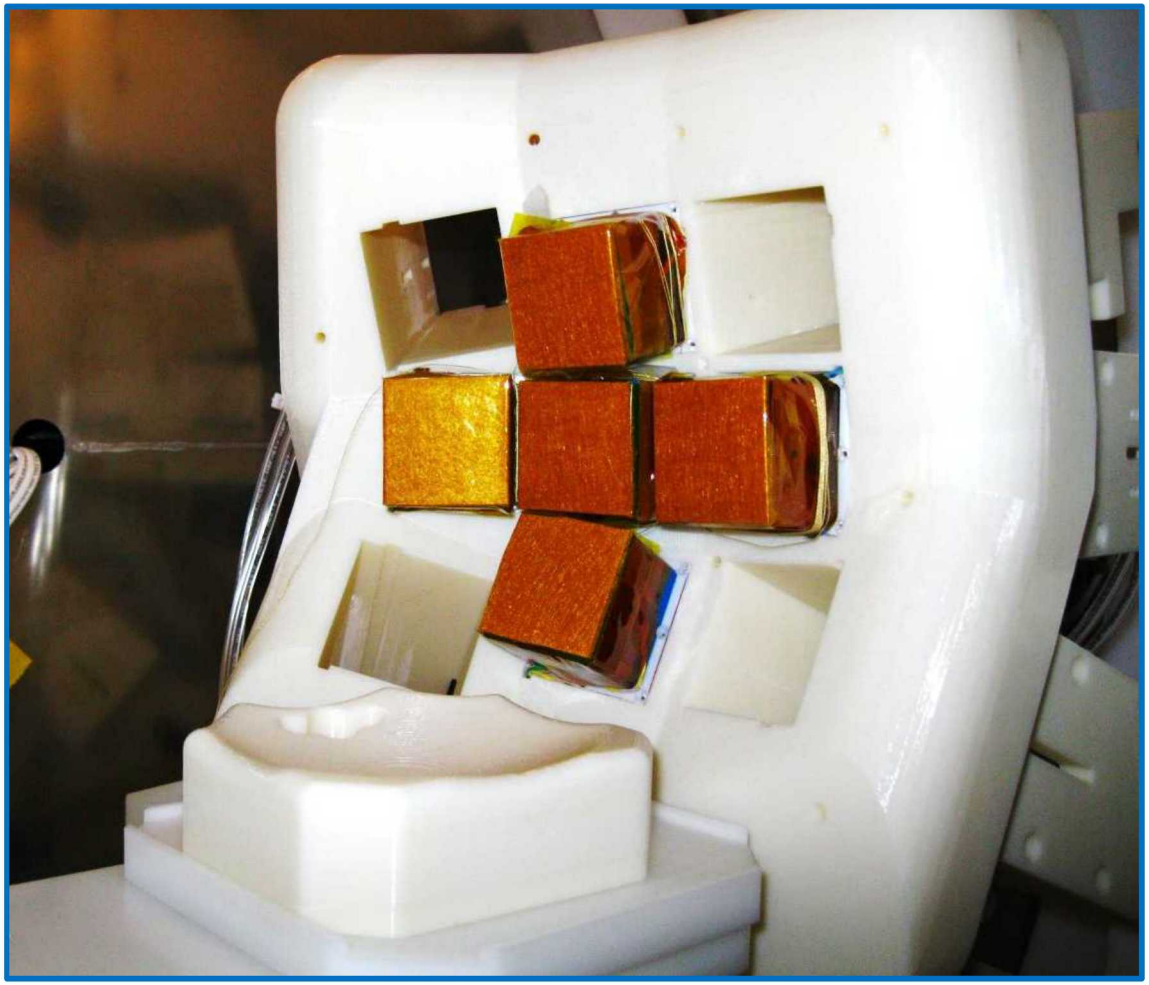
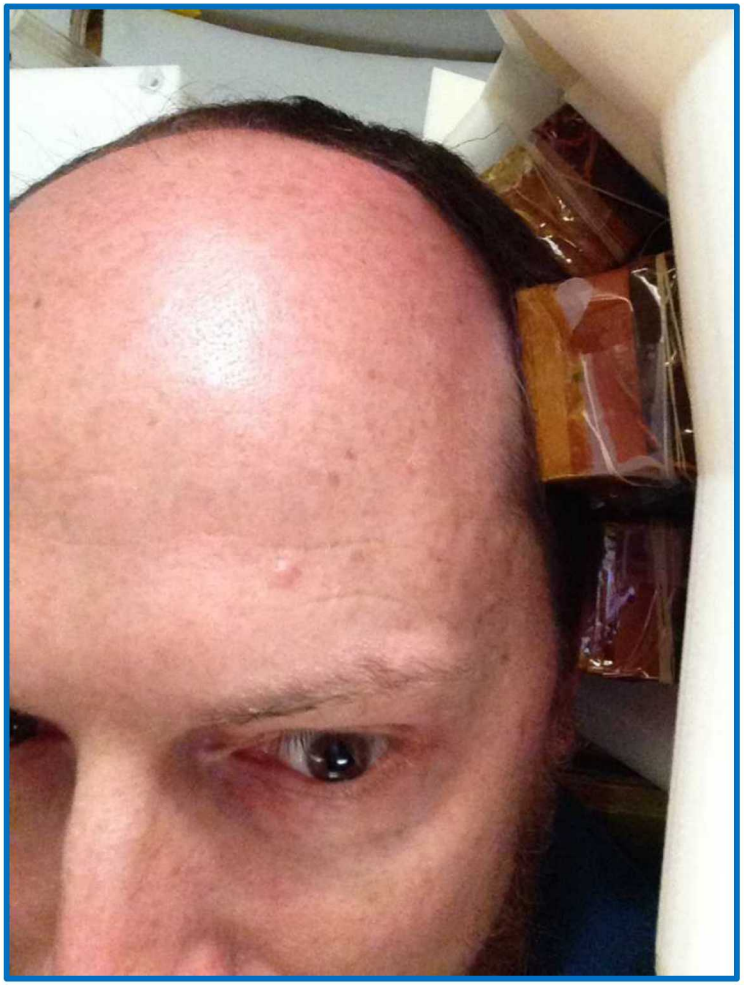
5-sensor, 20-channel array



Partially covers the left hemisphere



MEG System: Inside the Magnetic Shield

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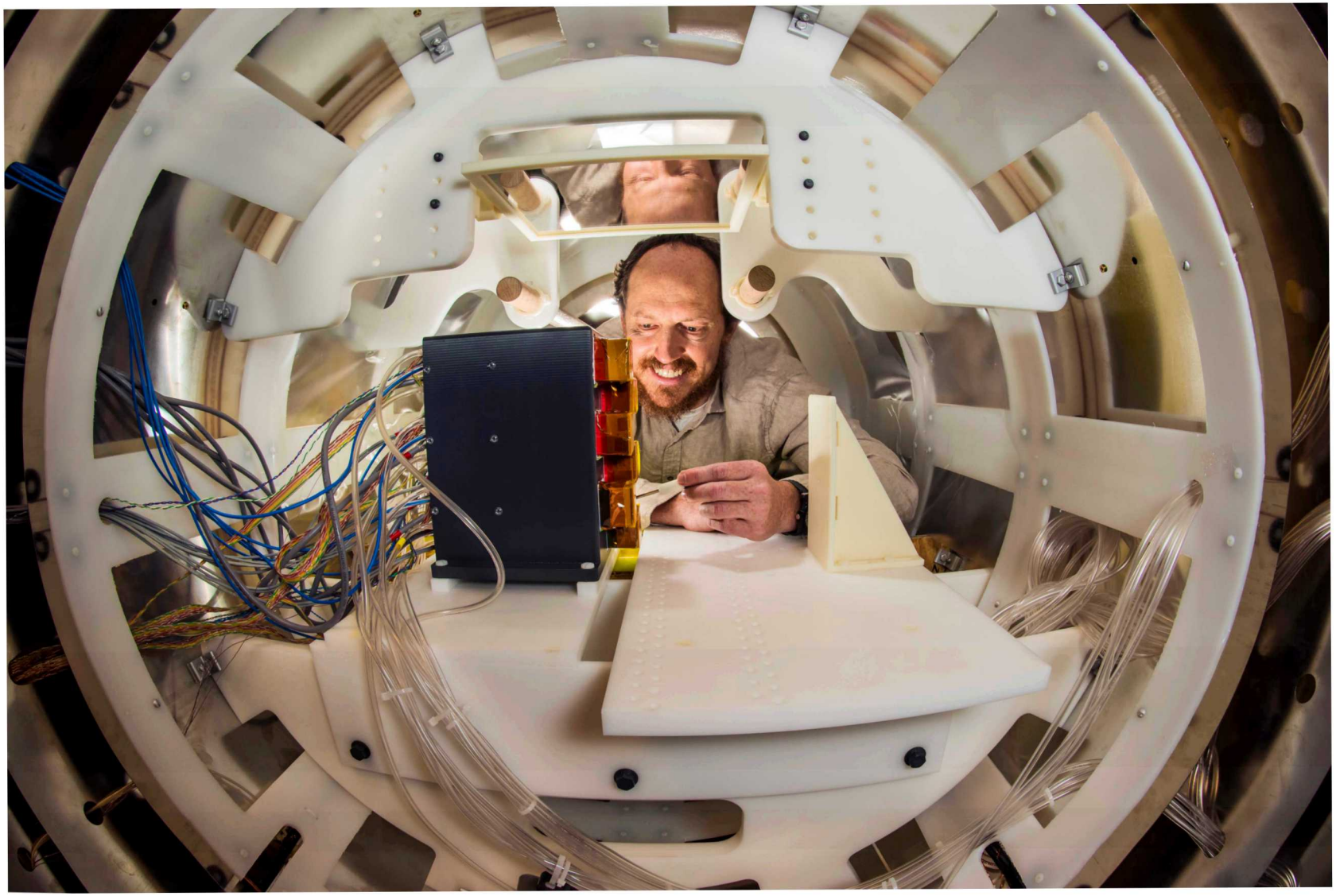
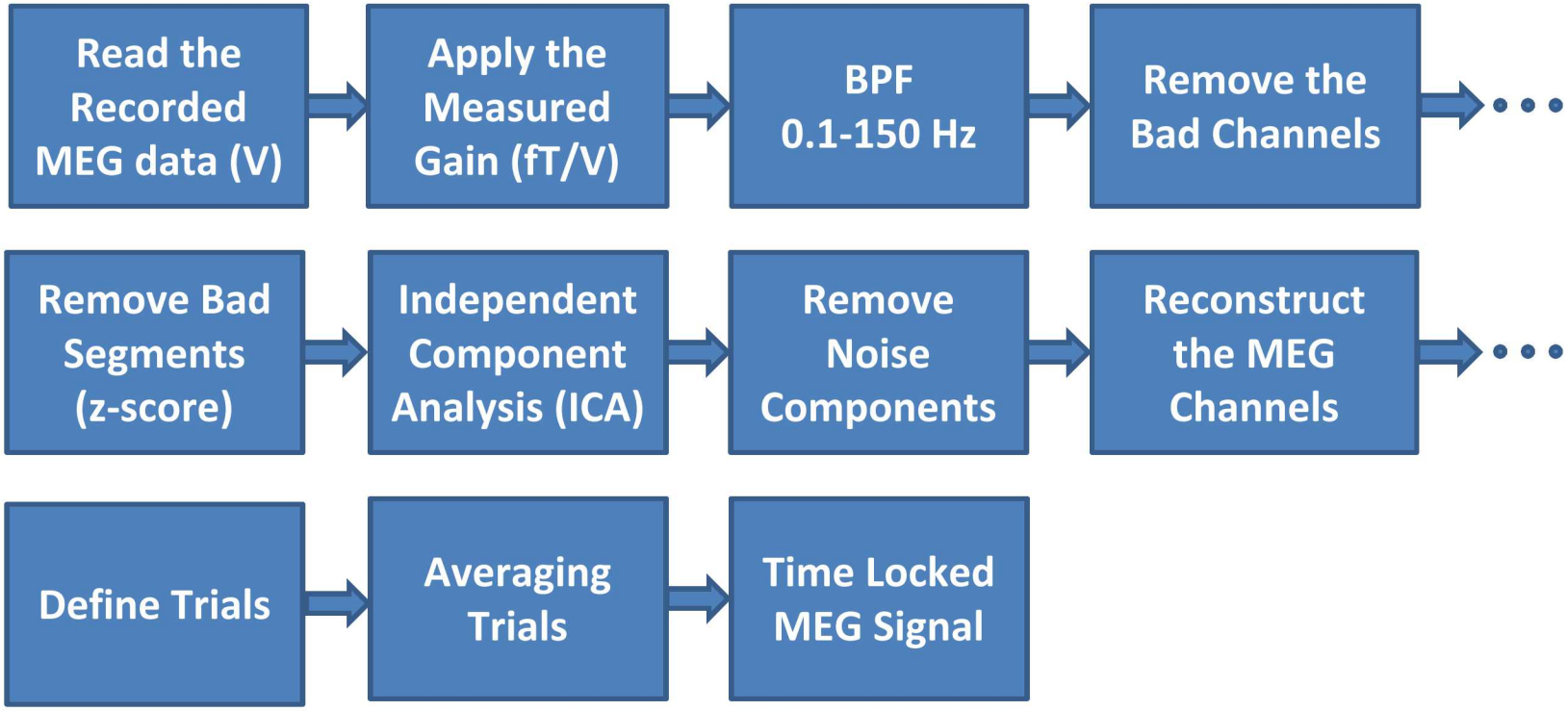


MEG System: Signal Processing Pipeline (1)



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.

MEG System: Signal Processing Pipeline (1)

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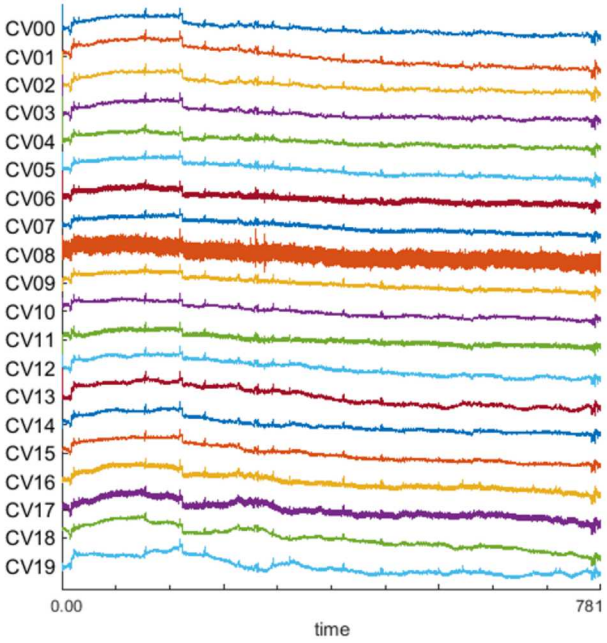
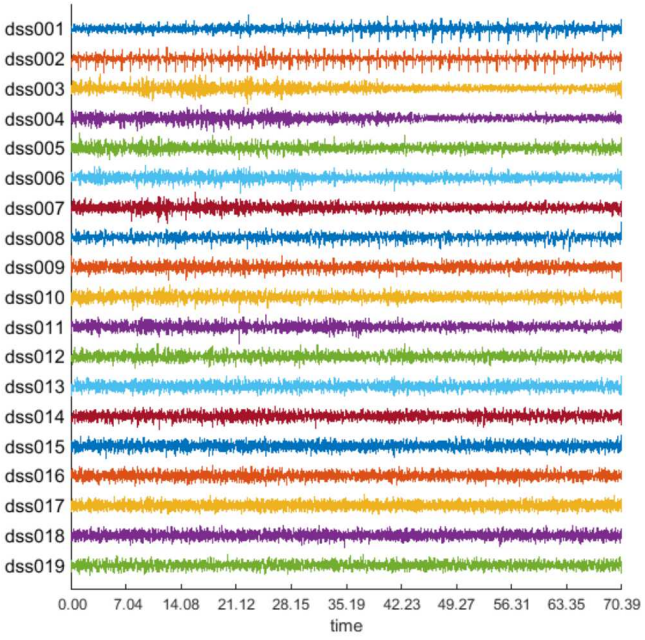
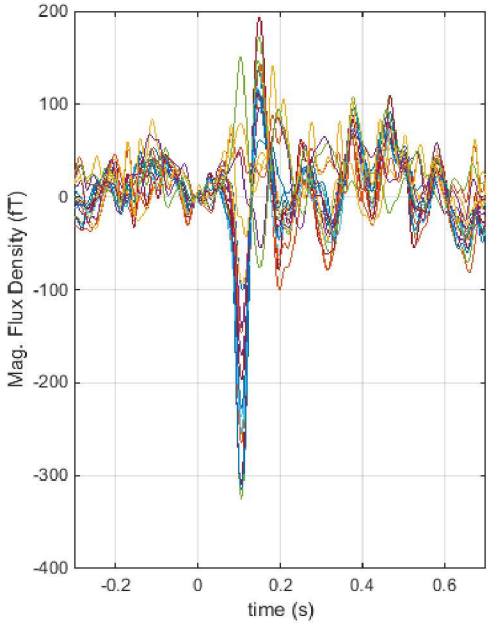
Recorded MEG data



Denoising Source Separation (DSS) Channels [1]



Time-Locked MEG Channels

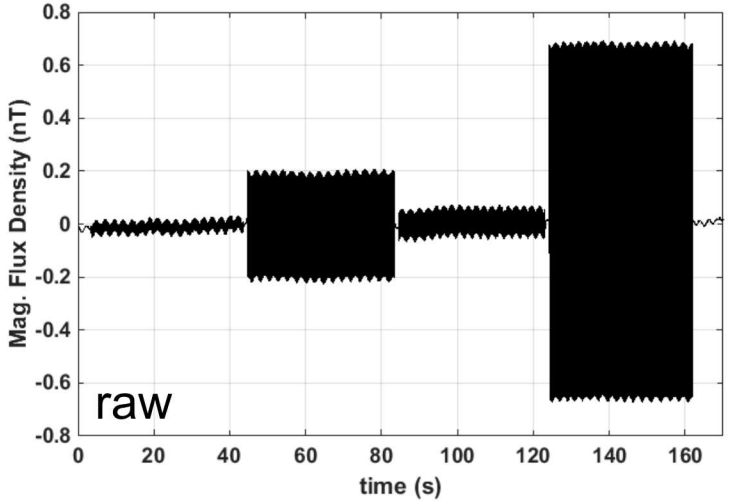


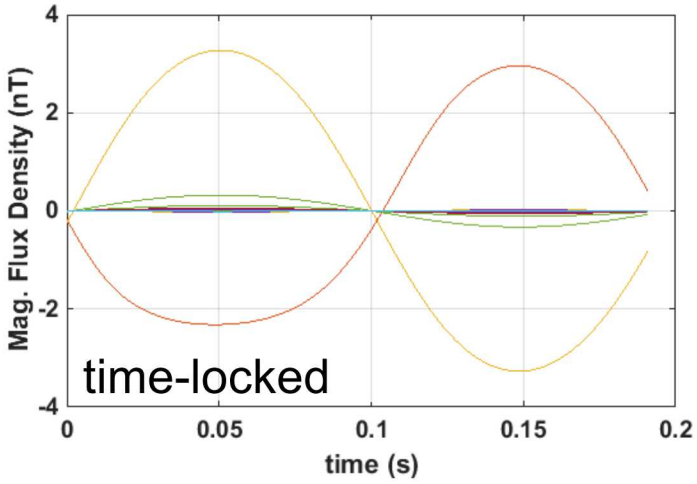
[1] Jaakko Särelä, Harri Valpola, “Denoising Source Separation,” Journal of Machine Learning Research, Vol. 6, pp: 233-272, 2005.

[2] 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.

MEG System: MRI Coregistration

- Place four head position indicator (HPI) coils on the subject's scalp
- Use a Polhemus Fastrak system to digitize the subject's scalp and the HPI coils
- Energize the HPI coils sequentially and measure the magnetic field generated by the coils (5-6 Hz) using the OPM array.
- Using the measured magnetic field and the equivalent current dipole (ECD) method provided by the Fieldtrip [1], HPI coils are localized.

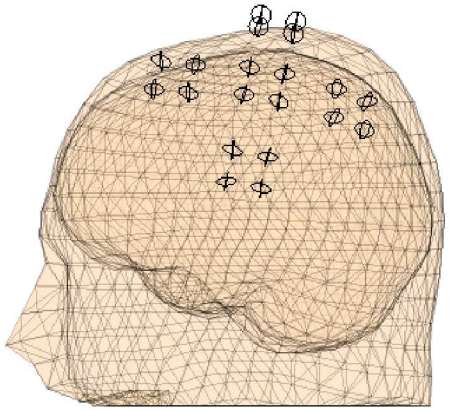




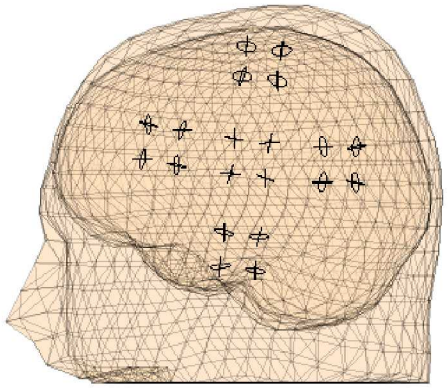
[1] R. Oostenveld, P. Fries, E. Maris, and J.-M. Schoffelen, "FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data," Computational Intelligence and Neuroscience, vol. 2011, p. 9, 2011.

MEG System: Forward Model

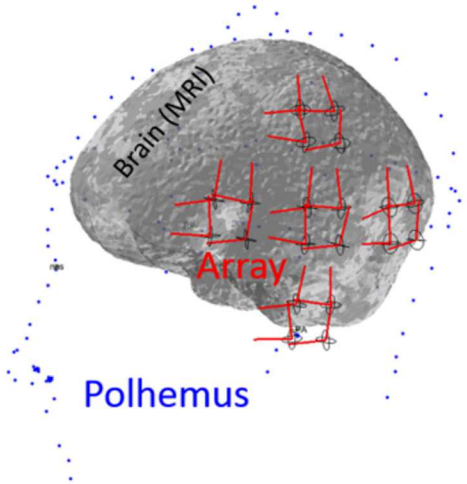
- Subject‘s MR images measured using a 3-T MRI scanner located at the MRN, Albuquerque, NM.
- Before each experiment the positions of the HPI coils were adjusted to cover the cortex of interest (auditory vs. somatosensory)
- The subject was asked to tilt his/her head such that the targeted neuronal cortex was covered by the array.
- The brain tissue, extracted by segmenting the MRI, is used to generate a single-shell forward model [1].



SEF



AEF



Coregistered MRI

[1] G. Nolte, "The magnetic lead field theorem in the quasi-static 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.

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Auditory/Somatosensory Evoked Magnetic Fields: Spatial Topographies

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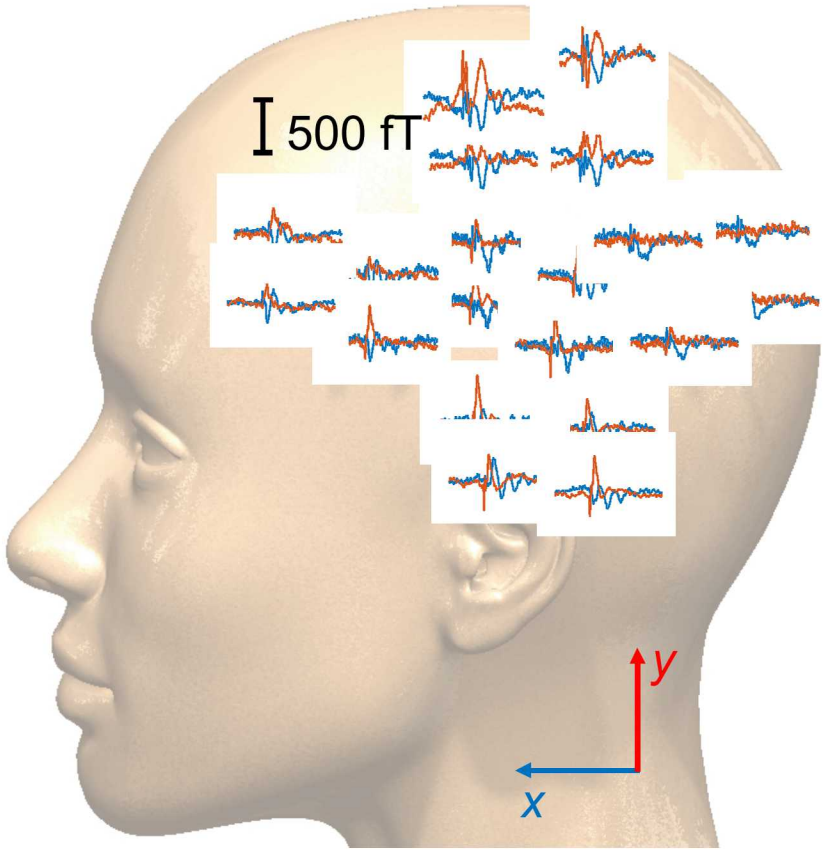
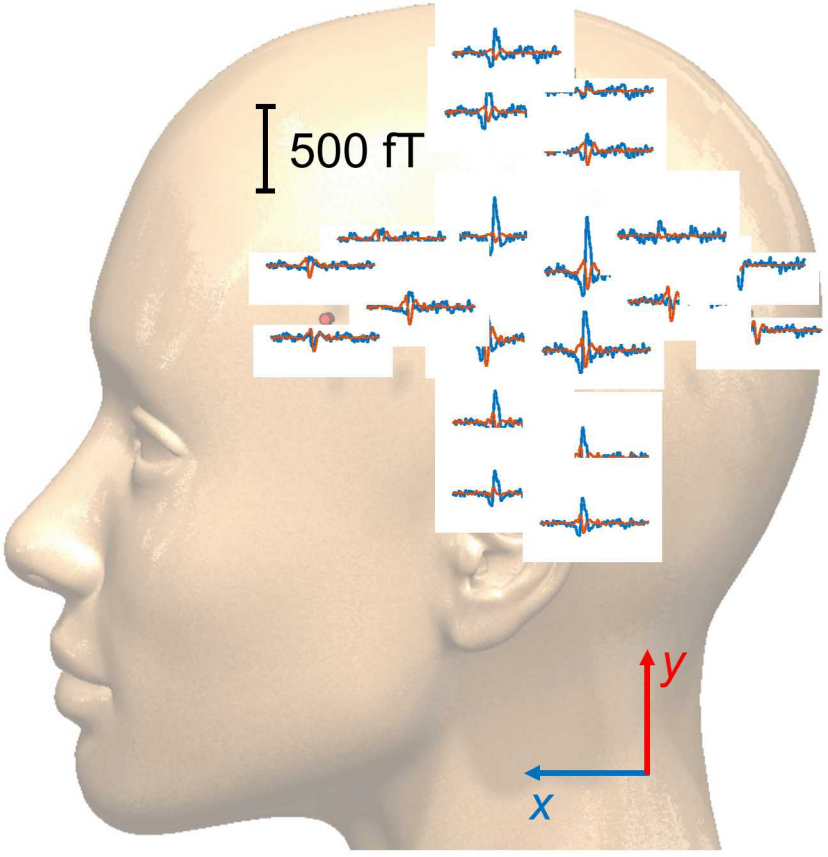
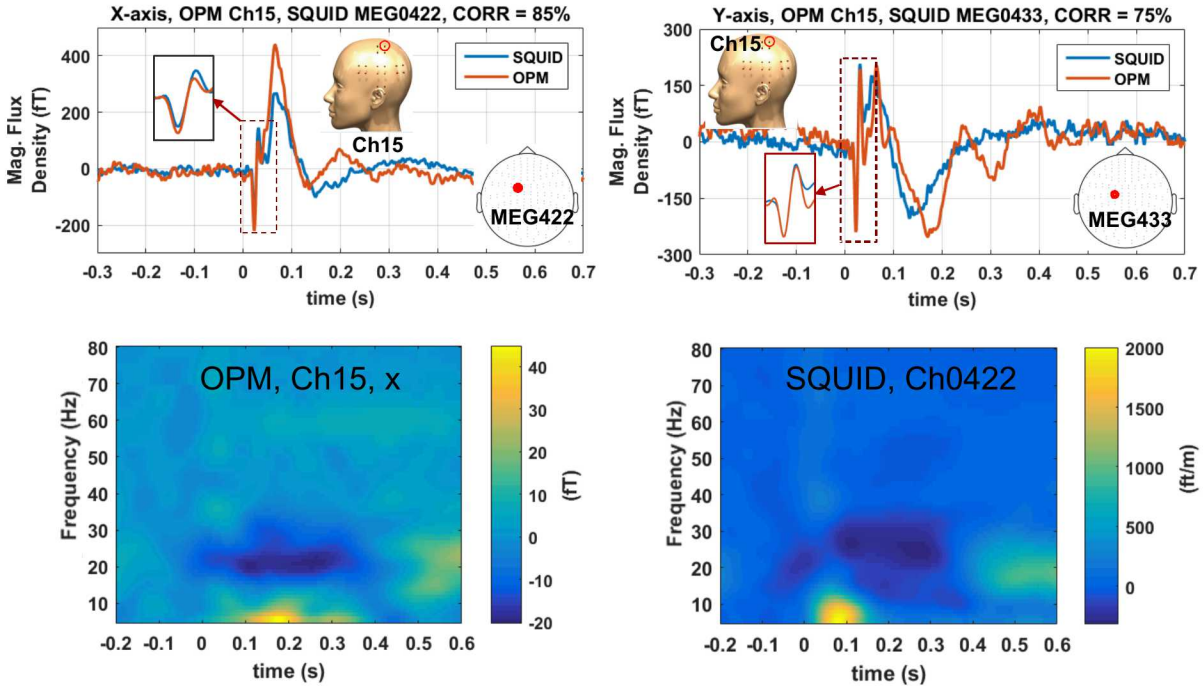


SEF



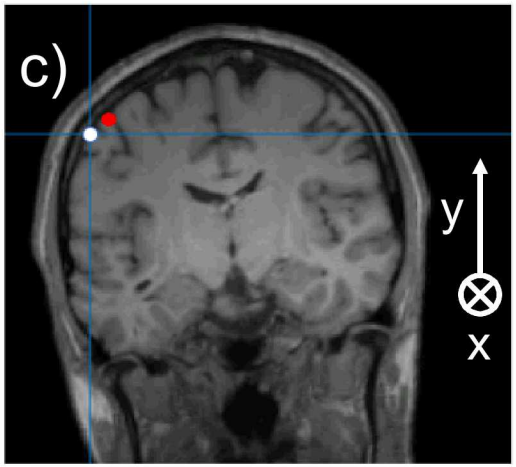
AEF

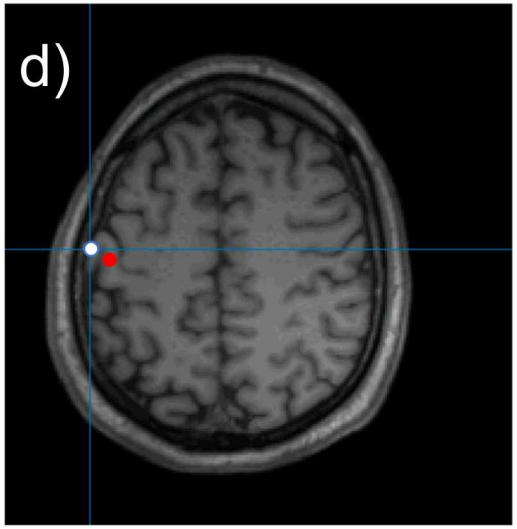
Somatosensory Evoked Magnetic Fields: OPM vs. SQUID

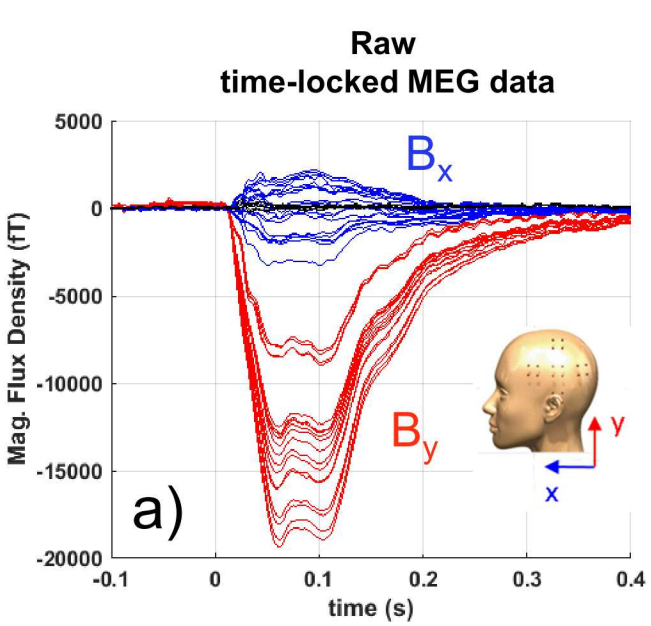


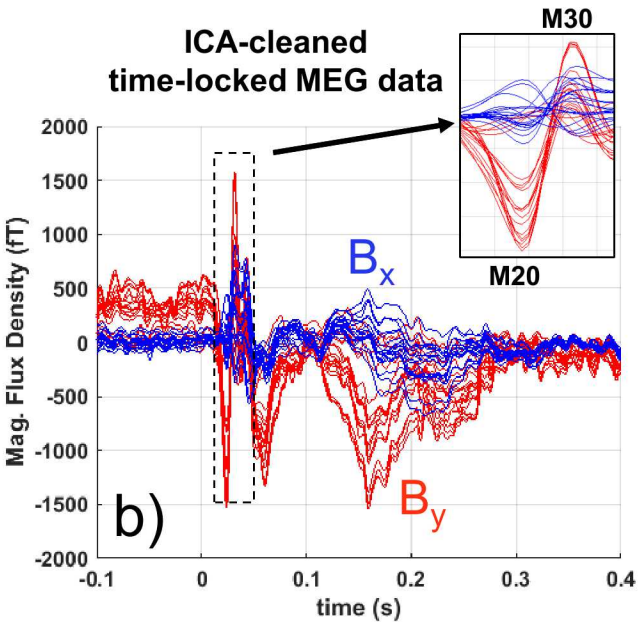
- Comparing OPM and SQUID SEF data in time domain shows more than 75% correlation for both x and y component
- Time-frequency spectra of the OPM and SQUID SEF data are compared for the x-axis modulation
  - They both have similar frequency spectrum.
- Beta suppression is observed with both SQUID and OPM array

Somatosensory Evoked Magnetic Fields: Localization







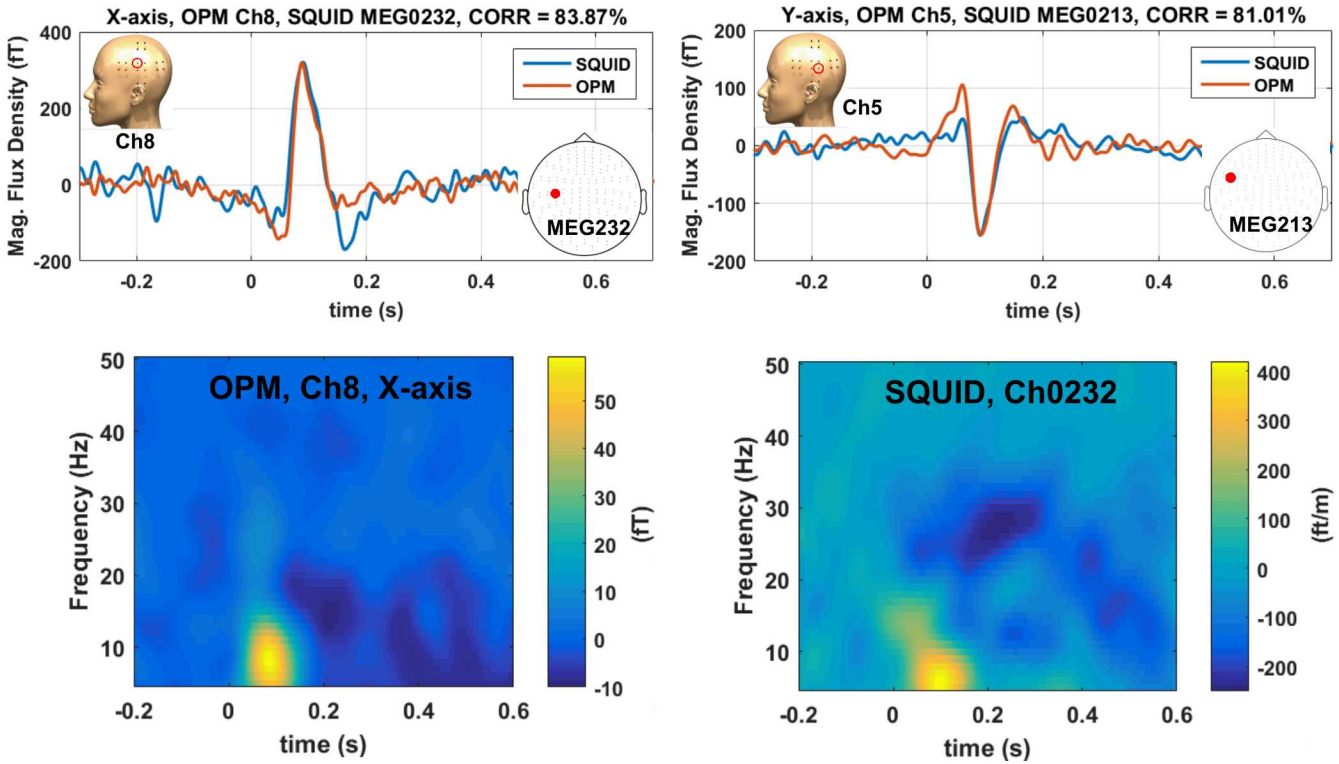


- The raw SEF amplitude reached 20 pT as depicted in (a).
- The ICA successfully removes the large low frequency component at M100 as shown in (b); the inset in (b) depicts the M20 and M30 components. This component is attributed to the shield's in-phase response.
- Control experiment in which the electrode's are slightly off the median nerve is shown in (a) by black traces.

c) Positions of the fitted dipoles overlaid on the **coronal** MRI slice. The white dot is the location of the OPM fit dipole. The red dot is the location of the dipole located by the SQUID MEG data.

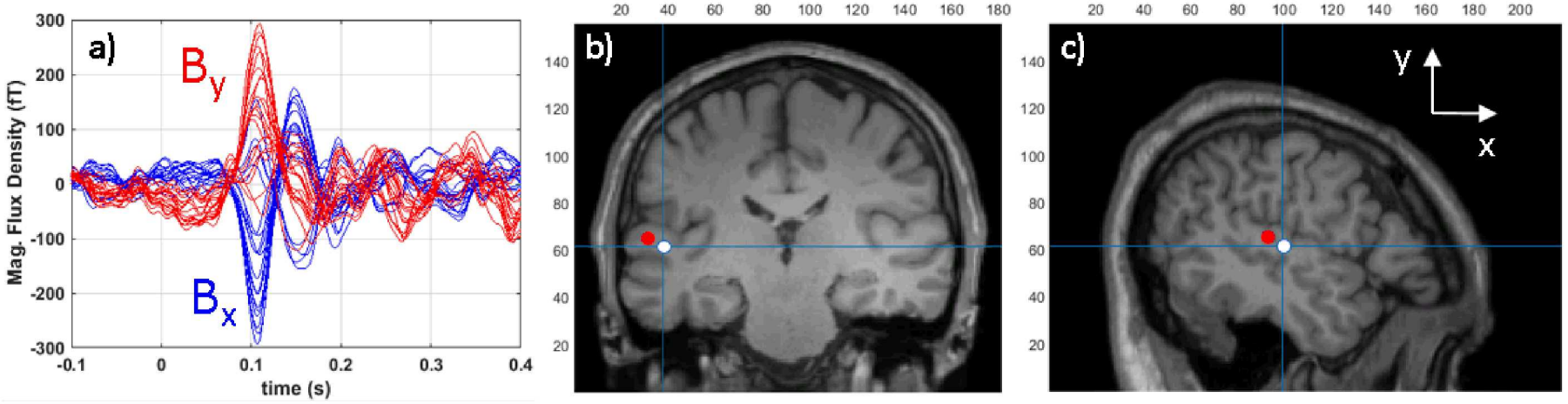
d) Positions of the fitted dipoles overlaid on the **axial** MRI slice. The distance between the two dipoles is sub-centimeter for all the subjects.

Auditory Evoked Magnetic Fields: OPM vs. SQUID



- Comparing OPM and SQUID AEF data in time domain shows more than 80% correlation for both x and y component
- Time-frequency spectra of the OPM and SQUID AEF data are compared for the x-axis modulation
  - They both have similar frequency spectrum

Auditory Evoked Magnetic Fields: Localization



a) Evoked response due to auditory stimulation as measured by the OPM array. A 1000 Hz tone is played every 1 to 1.5 s for 456 trials

b) Positions of the fitted dipoles overlaid on the coronal MRI slice. The white dot is the location of the OPM fit dipole. The red dot is the location of the dipole located by the SQUID MEG data

c) Positions of the fitted dipoles overlaid on the sagittal MRI slice. The distance between the two dipoles is sub-centimeter.

COMPARISON OF THE AEF/SEF SOURCE LOCALIZATION ACCURACY IN THREE DIFFERENT MALE ADULT SUBJECTS

Subject ID	AEF Err. (mm)	SEF Err. (mm)
M87172872	9.5	3.9
M87122617	7.1	7.5
M87103395	6.2	9.7

Ground truth is the source location provided by the commercial Elekta-Neuromag SQUID-based MEG system.

Conclusion

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MEG System

- Constructed a fully functional Magnetoencephalography system using optically pumped magnetometers.
- Achieved results comparable to the commercial SQUID-based MEG systems for both AEF and SEF.
- 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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Full-head, On-scalp MEG System Using Commercial OPM

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Metric	Gen-1	Gen-2
Sensitivity	15 fT/√Hz	7-10 fT/√Hz
Bandwidth	135 Hz	135 Hz
Max background	50 nT	200 nT
Standoff	6.0 mm	6.5 mm
Size (sensor)	13.0×19.0x110 mm	12.4×16.6×24.4 mm
Weight (sensor)	20 g	4 g
Cable Weight	10 g/ft	1 g/ft
Surface Temp.	~45 °C	~41 °C

Gen-1

Pricing per sensor (USD):

Qty 1-3: $10,000
Qty 4-7: $8,500
Qty 8+: $8,000

QuSpin Inc., Louisville, CO, US

Biomedical Advanced Research and Development Authority
BAA-18-100-SOL-00018
In-Vivo Vagus Sentinels to Detect and Prevent Infection

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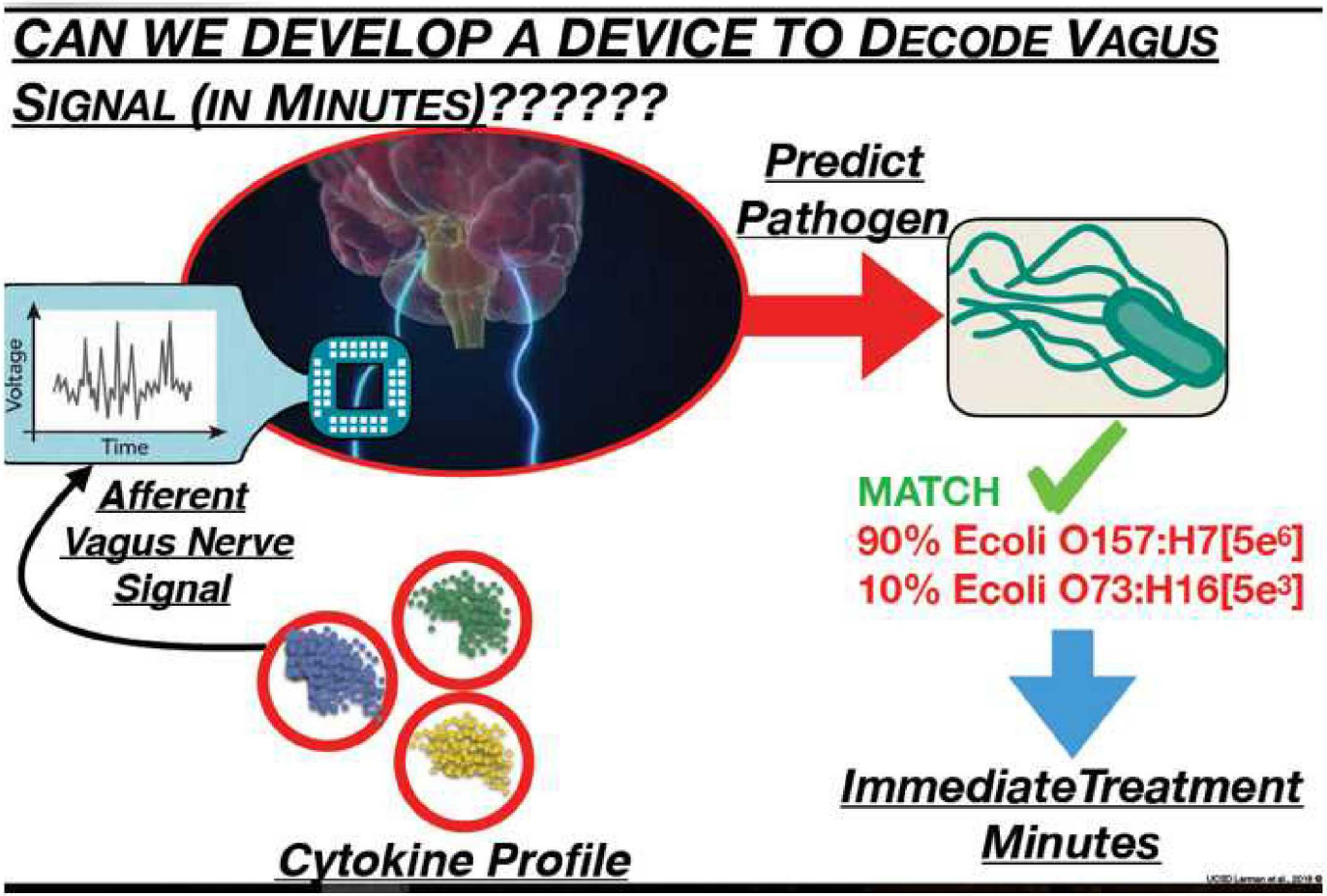
- Recently funded project
- Partnered with UCSD (Dr. Mingxiong Huang, Dr. Imanuel Lerman)



Biomedical Advanced Research and Development Authority
BAA-18-100-SOL-00018
In-Vivo Vagus Sentinels to Detect and Prevent Infection

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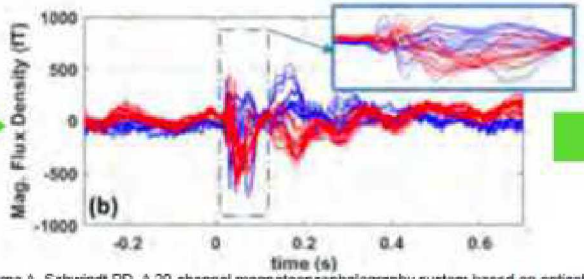
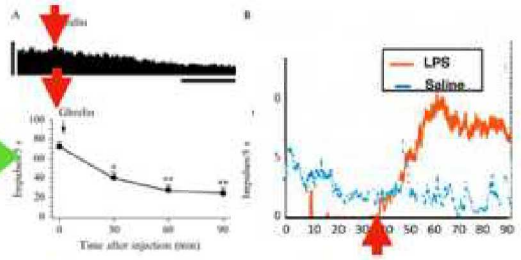
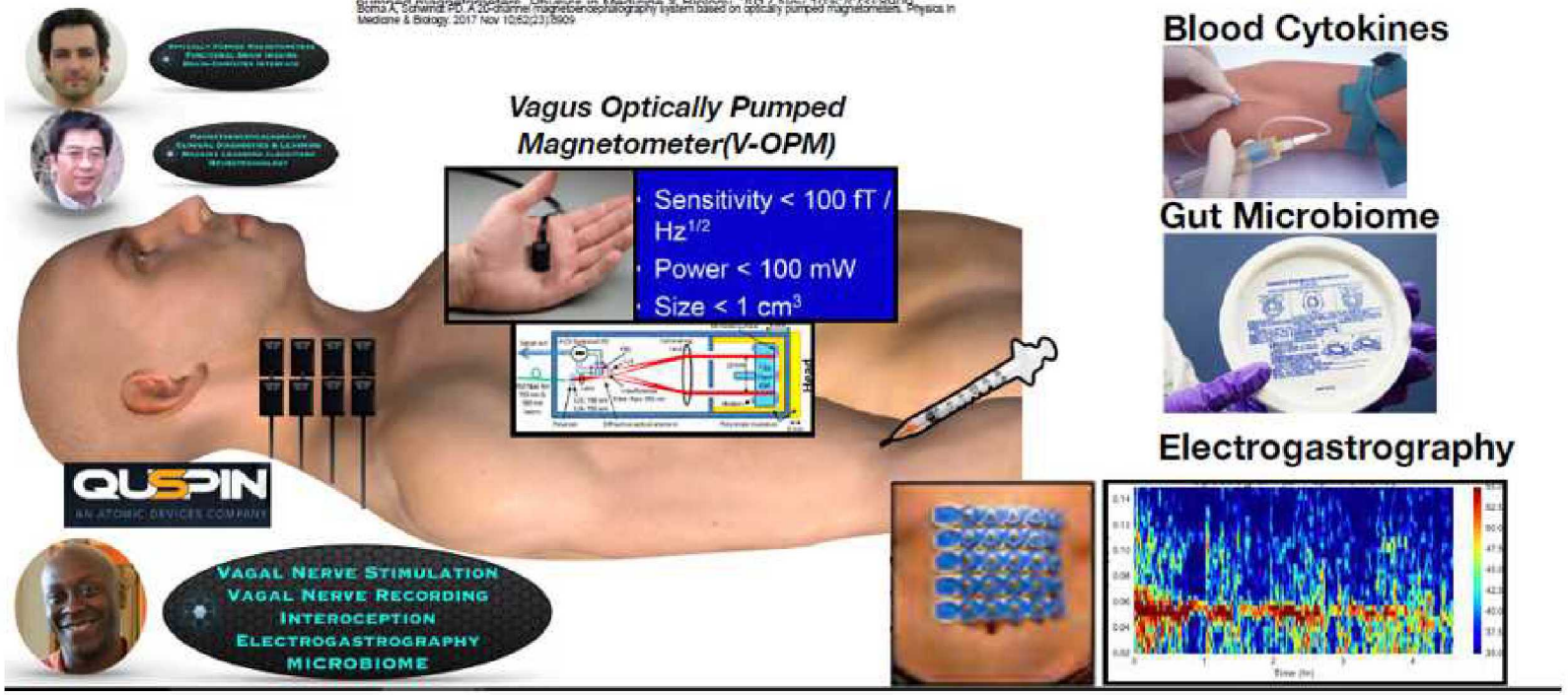


Borna A, Schwindt PD. A 20-channel magnetoencephalography system based on optically pumped magnetometers. Physics in Medicine & Biology. 2017 Nov 10;62(23):8909.



LPS AND Grhelin Effect on Vagal Firing



Blood Cytokines

Gut Microbiome

Electrogastrography

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