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Sandia National Laboratories

Toward an Optically Pumped Magnetometer Magnetoencephalography System with Full Head Coverage

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Introduction

Magnetoencephalography (MEG) is a non-invasive functional neuroimaging method with millisecond temporal and millimeter to centimeter spatial resolution. In MEG the magnetic fields of the brain are detected outside of the head using sensitive magnetometers. Traditional MEG scanners use superconducting quantum interference device (SQUID) sensors which are placed inside a cryogenic Dewar in a rigid, helmet-shaped configuration. The thermal insulation necessitated by the SQUIDs operating at around -269 °C sets the distance between the SQUID sensors and the subject's scalp to at least about 2 cm, limiting the spatial resolution of the SQUID-based MEG.

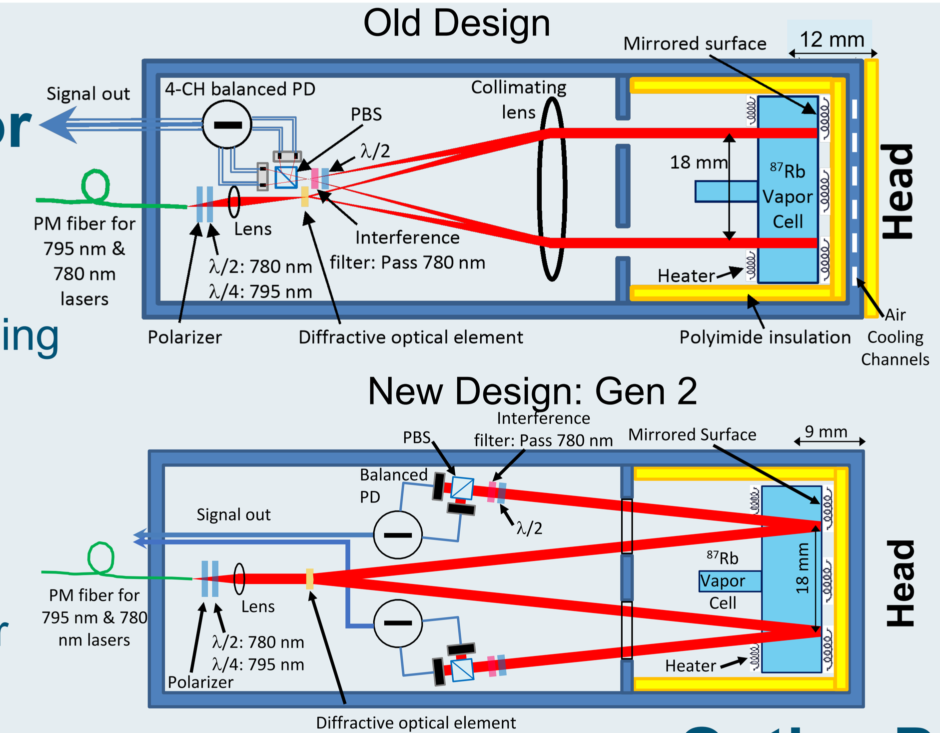
Recently, we have developed novel magnetometers for MEG that do not require cryogenic operation [1]. These optically pumped magnetometers (OPMs) enable positioning of the sensors directly on the subject's scalp in a flexible manner, increasing the spatial resolution of MEG as compared to SQUID-based scanners [2].

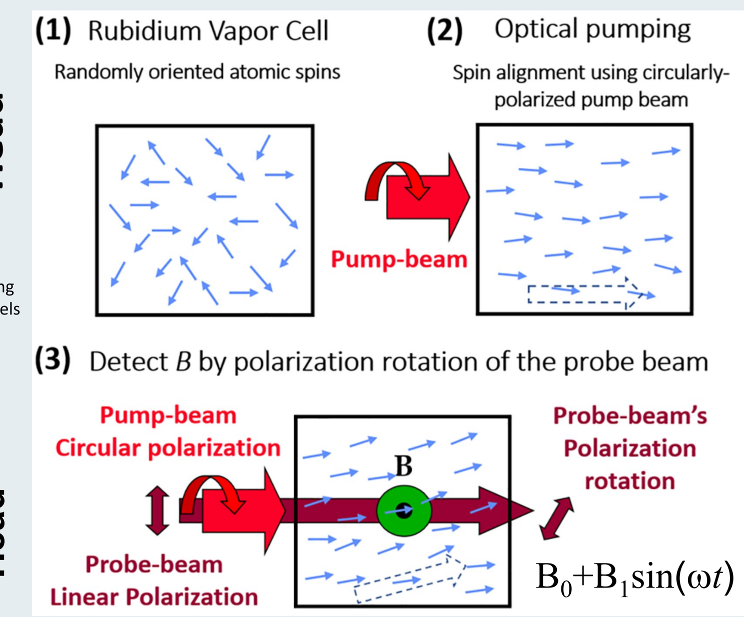
We are currently developing an OPM-based MEG scanner with a full-head coverage. **In this poster:**

- We describe our progress on the design and development of our next generation OPM sensor.
- We outline our plans for developing a complete MEG system with 108 channels in a shielded room.

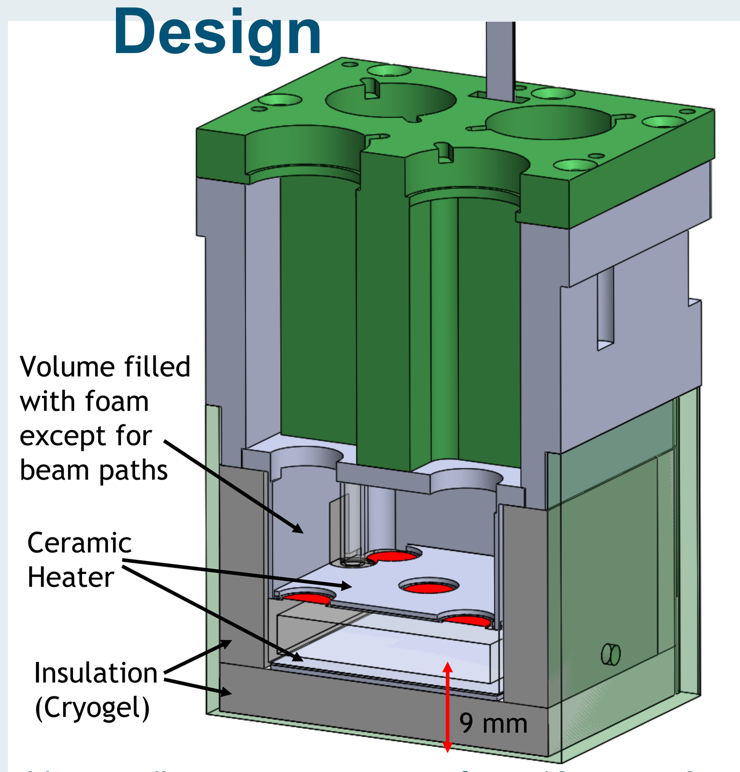
Redesign of the 4-channel sensor

- Reduce external temperature
- Reduce head to sensing volume distance
- Ease manufacturing
- Improve on-sensor magnetic field control
- Reduce optical power





Oven Design



Vapor cell center to sensor surface: 12 mm → 9 mm

Optics Design

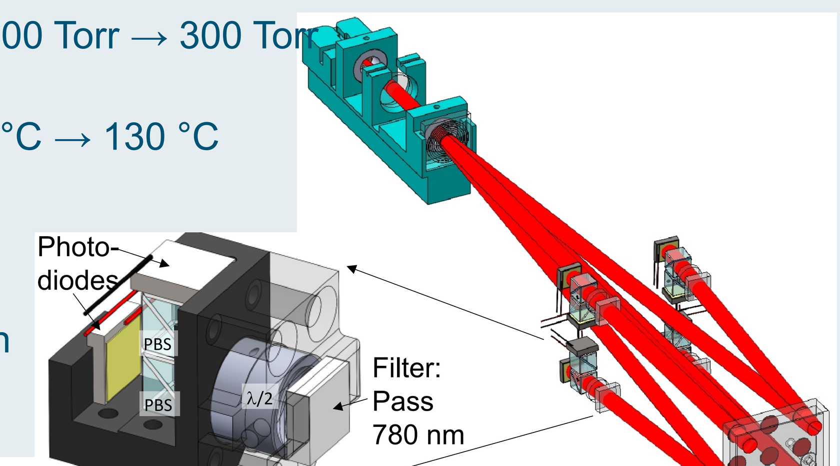
- Reduced beam size: 2.5 mm FWHM to 2 mm
- Reduced nitrogen buffer gas: 600 Torr → 300 Torr

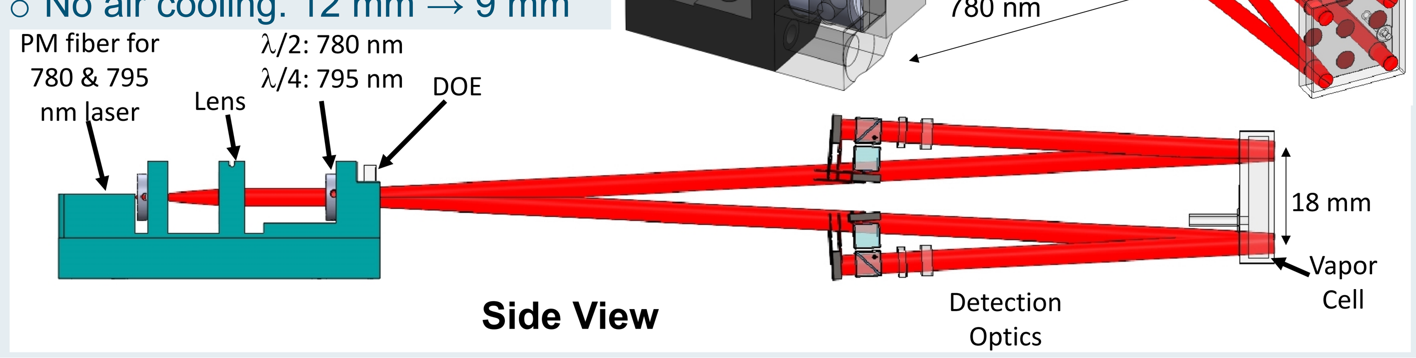
Result:

- Reduced cell temperature: 145 °C → 130 °C
- Reduced optical power:
  - Pump: 38 mW → 4 mW
  - Probe: 14 mW → 4 mW

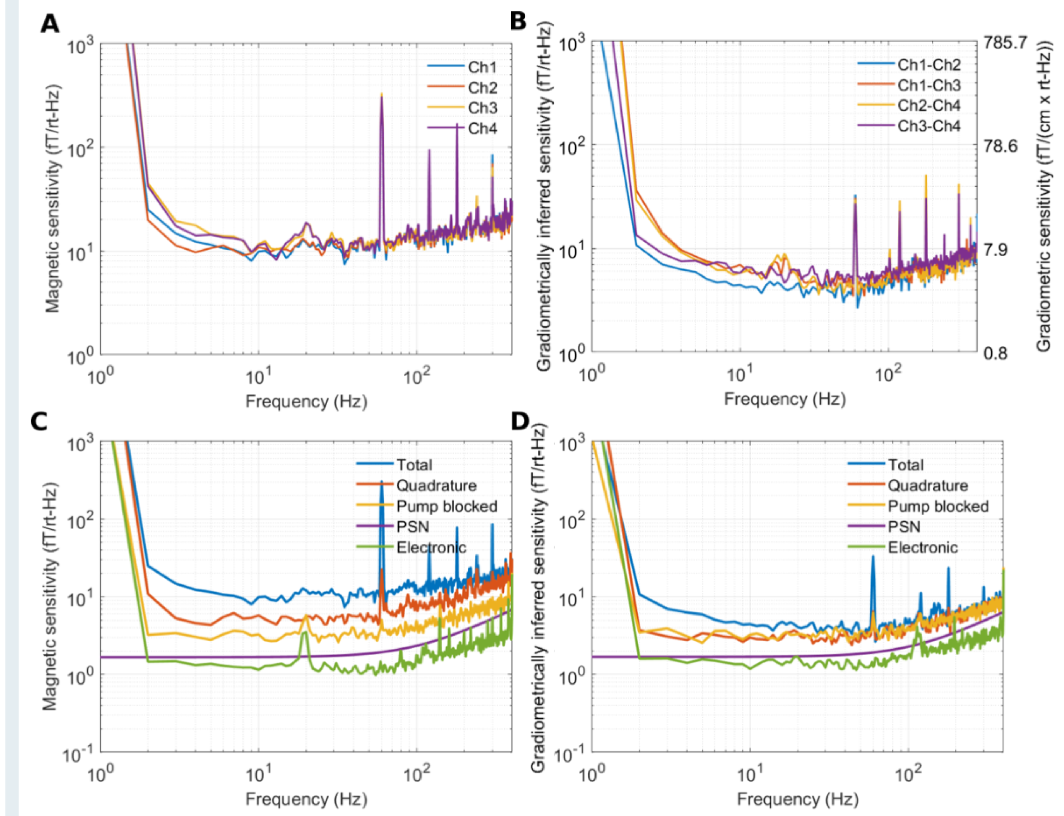
Increase 3 mm → 5 mm insulation

- Oven power: 6.1 W → 3 W
- No air cooling. 12 mm → 9 mm





Sensor Performance [5]



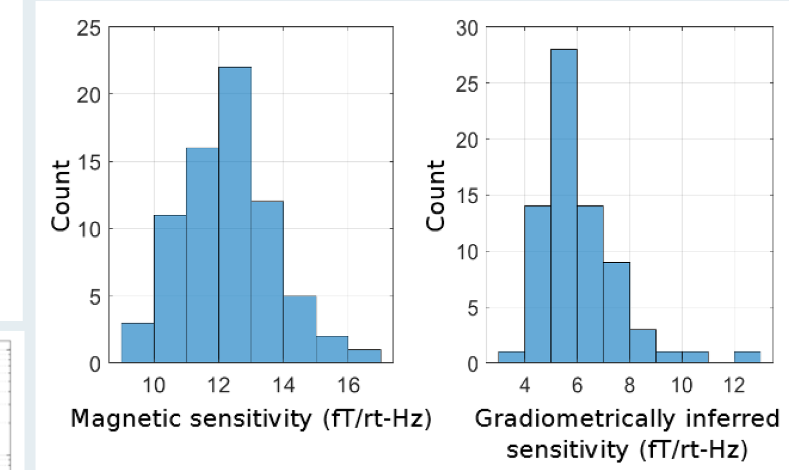
Single sensor noise and bandwidth

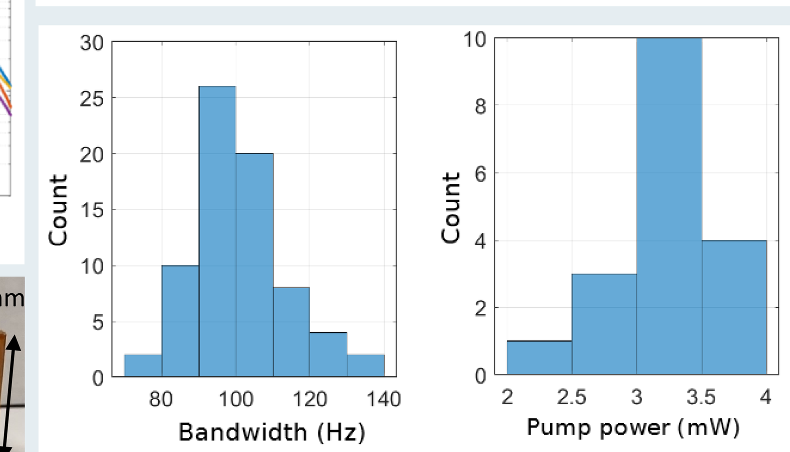
Gen 1 Channel Avg.
92
17.3
4.3

	Ch 1	Ch 2	Ch 3	Ch 4
3-dB BW (Hz)	92	88	98	87
Mag. Noise (fT/rt-Hz, 10-44 Hz)	10.5	10.9	12.5	12.3
Grad. Noise (fT/rt-Hz, 10-44 Hz)	4.1	5.5	5.4	5.6

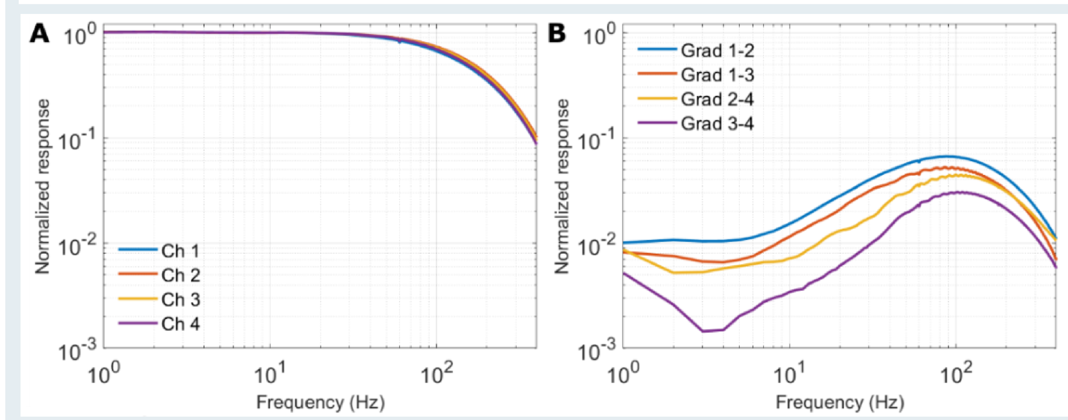
Histograms for 18 sensors

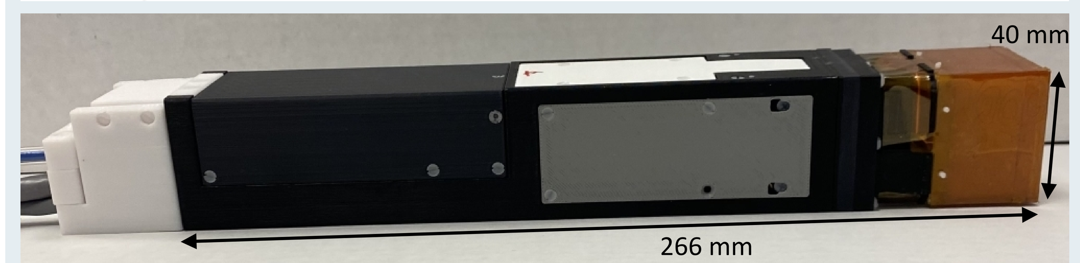
-72 Channels





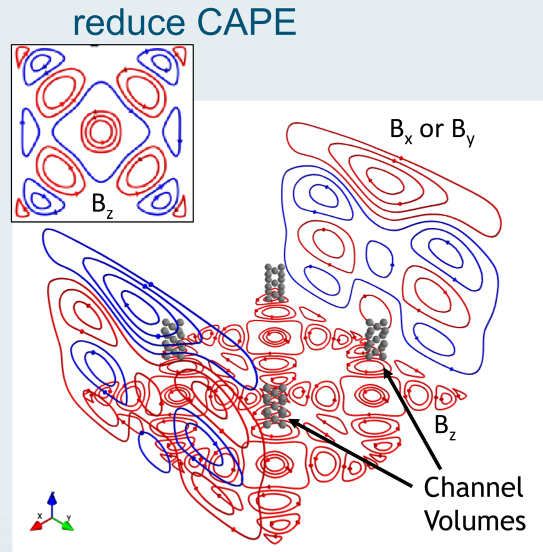
Probe power typically 3-3.5 mW





On-Sensor coils

- Designed by Joonas Iivanainen with *bfieldtools* [4]
- Coils: X Y Z
  2 coils 2 coils 4 coils
- Control B_z for each channel to reduce CAPE



- Field inhomogeneities
  - On-sensor Bx: 9.0%
  - On-sensor By: 8.9%
  - On-sensor Bz: 14.1%
- Bz cross-channel leakage < 12.4%
- Gen 1 coil: 26%

Broadening due to gradients

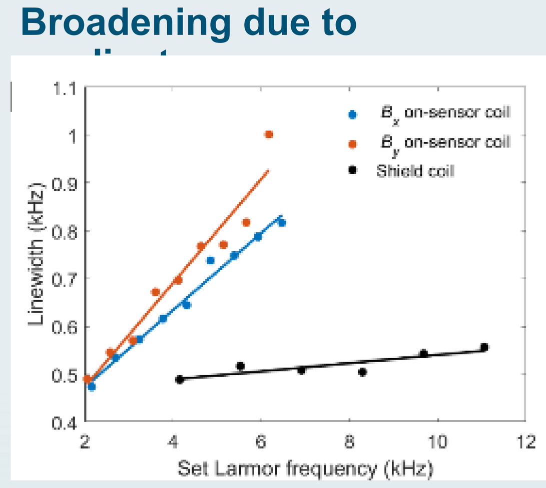
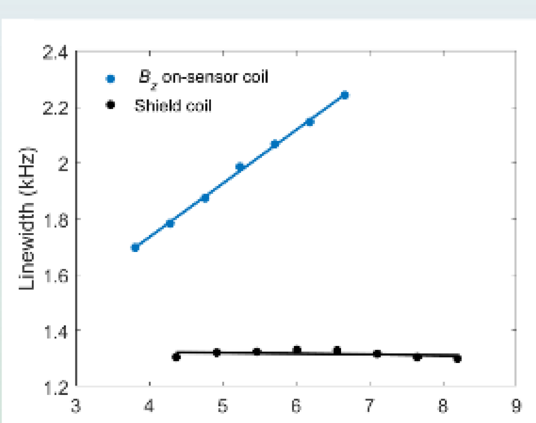
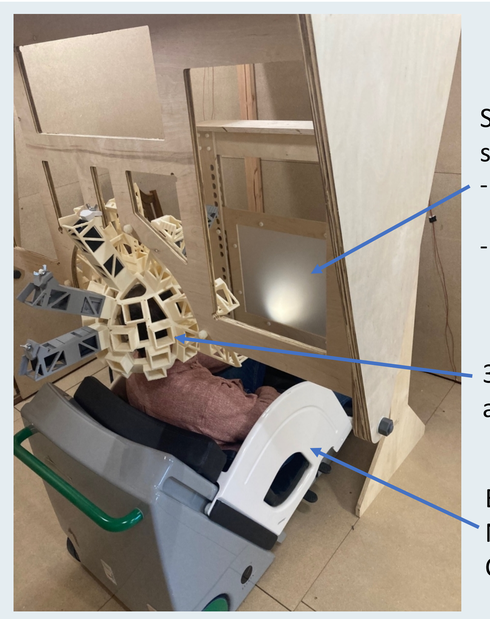


Photo of the On-Sensor Coil



OPM-Based MEG system

- Plan 27 sensors: 108 (216) channel single (dual) axis
- Position in a magnetically shielded room (MSR)
- Field cancellation coils in the MSR
- Allow modest movement



Control Electronics

Each daughterboard contains analog circuits and FPGA board for:

- Temperature control
- Laser monitoring (possible active power control)
- Signal detection and demodulation
- Arbitrary waveform generator for on-sensor coils
- Communication with host computer

Laser system

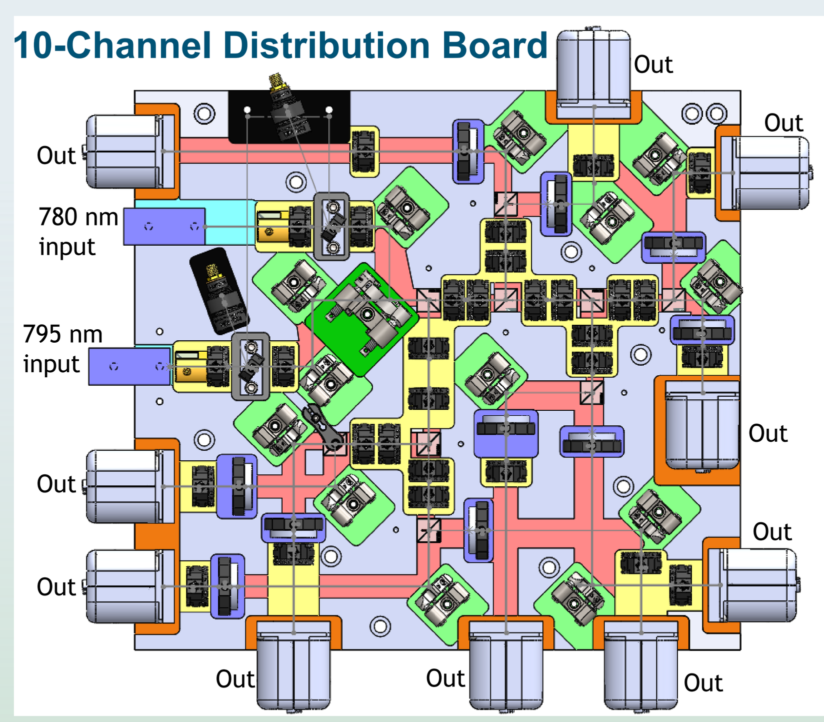
Laser Sources:

- Probe: Toptica amplified DFB laser: 4 W
- Pump: Moglabs amplified cateye laser: 3.5 W
  - Two seed lasers separated by ~10 GHz

Light distribution boards:

- Solid aluminum construction
- Commercial optical mounts
- Distribute 780 and 795 nm light
- Actively stabilize power onto the board

10-Channel Distribution Board



Magnetically Shielded Room and Cancelation Coils

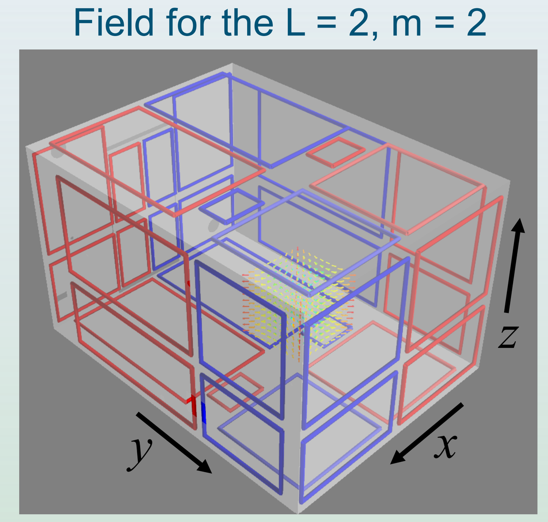
IMEDCO housed the 1st US-based whole-head MEG system installed at the New Mexico VA Medical Center in Albuquerque, NM

- 3-layer (heavy) room - Outer and inner layer of mu metal and a middle layer of aluminum
- Interior: 4 m × 3 m × 2.4 m

Simulated error from cancelation coils

Spherical component	Relative Error
Homogeneous x	2.7%
Homogeneous y	7.1%
Homogeneous z	5.6%
L = 2 m=-2 gradient	8.7%
L = 2 m=-1 gradient	5.5%
L = 2 m=0 gradient	2.5%
L = 2 m=1 gradient	10.3%
L = 2 m=2 gradient	13.4%

Field for the L = 2, m = 2



Fluxgate measurements

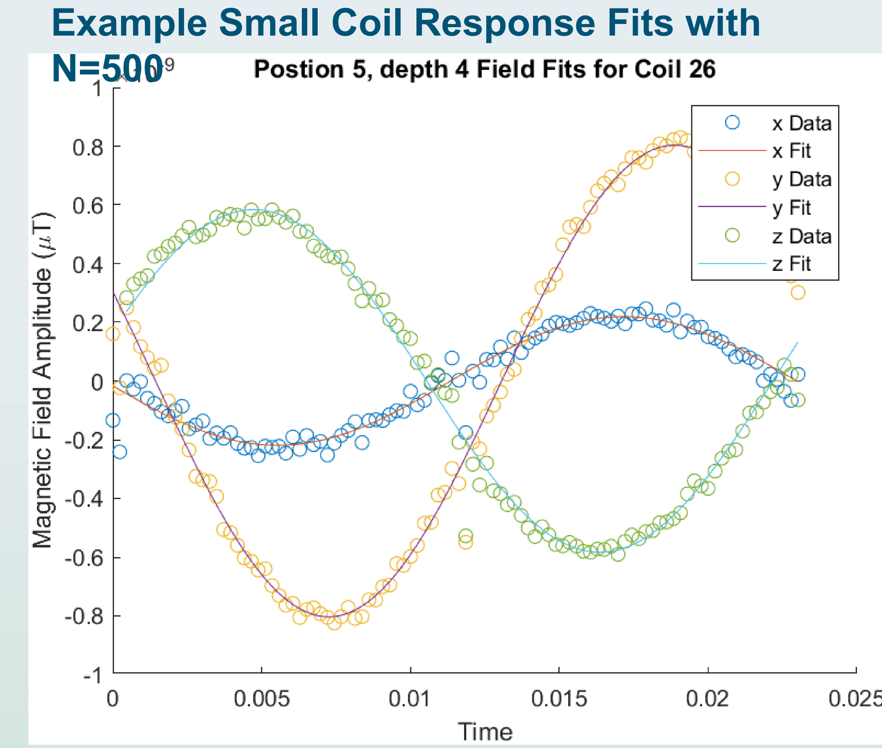
Field component	Strength
x	-9.0 nT
y	-16.2 nT
z	-0.82 nT
dB_x/dx	3.4 nT/m
dB_y/dy	-4.0 nT/m
dB_x/dy	-3.0 nT/m
dB_x/dz	4.9 nT/m
dB_y/dz	4.4 nT/m

Coil Calibration

- For each sample point, all 32 coils sequentially driven with 500 periods of sinusoid at 43 Hz.
  - Average many periods for good SNR on small coils. (Fig. at right)
- Sensys fluxgate mounted at 31 MEG array positions, 8 depths 2 cm apart per holder position for 248 sample points within MEG volume .
- Minimum of 25.6 hours to gather data, not including time to re-position sensor! Real data gathering took weeks.
- Data are being processed to produce calibrations
  - Response along fluxgate x,y,z fit with sinusoid to extract field amplitudes at each point.
  - Results at each point have coordinates calculated from CAD model and amplitudes are rotated into subject frame.

To do: Fit each coil response over MEG volume with vector spherical harmonics (VSH). Use VSH model fit results to calculate 3 sets of 32 currents that produce most uniform x,y,z fields across MEG volume.

Example Small Coil Response Fits with N=500



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[1] A. P. Colombo, *et al.*, Optics Express, **24**, 15403 (2016)
[2] A. Borna, *et al.*, Phys Med Biol, **62**, 8909 (2017). Amir Borna, *PLoS One*,**15**(1), e0227684 (2020).
[3] Amir Borna, *NeuroImage*, **247**, 118818 (2022).
[4] *https://bfieldtools.github.io/*
[5] Joonas Iivanainen, Opt. Express **32**, 18334-18351 (2024)