Diamond Quantum Sensors for Magnetoencephalography

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Outline

- Magnetoencephalography (MEG)
  - Motivation
  - MEG Origin
  - Clinical Brain Imaging

- Diamond-Based MEG
  - The Nitrogen-Vacancy Center in Diamond
  - The MIT Lincoln Lab MEG System
The human brain is the most complicated biological structure in the known universe. We’ve only just scratched the surface in understanding how it works – or, unfortunately, doesn’t quite work when disorders and disease occur.

- NIH Director Francis S. Collins, M.D., Ph.D.
Brain Science

- Neuroscience
- Psychology
- Computer Science
- Medicine
- Biology
- Physics
The Magnetoencephalography Signal

**Neurons**

- Neurons exist in complex networks throughout the brain.
- Neurons communicate via transient electrical signals.
- Bulk neuronal activity creates detectable signals.

**Magnetic Field**

**Electric Field**

Electrodes pick up voltage fluctuations

Electroencephalography

Sensitive magnetometers detect magnetic fields

Magnetoencephalography
Clinical Brain Imaging Methods

- (Functional) Magnetic Resonance Imaging (fMRI/MRI)
- X-ray Computed Tomography (X-ray CT)
- Single-Photon Emission Computed Tomography (SPECT)
- Positron Emission Tomography (PET)
- Electroencephalography (EEG)
- Magnetoencephalography (MEG)
## Brain Imaging Method Comparison

<table>
<thead>
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<th>(f)MRI</th>
<th>X-ray CT</th>
<th>SPECT</th>
<th>PET</th>
<th>EEG</th>
<th>MEG</th>
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</tbody>
</table>

MEG Visualized

Data and visualization from MNE software package using sample data (citation below).

Inferred dipole sources

Courtesy of S. Pursiainen, Inverse Problems research group at Tampere University of Technology. Created using Zeffiro Interface ©.
The History of Magnetoencephalography (at MIT)

Dr. David Cohen, MIT
“The Father of Biomagnetometry”

Early magnetoencephalography (1971) seen by Cohen et al.


Superconducting quantum interference device (SQUID)

Fig. 1. Topology of a weakly connected superconducting ring. The inductance of the ring is $L$ and the weak link has a length $l$, cross section $a$, and maximum supercurrent $I_c$. 

Reprinted from: 11 February 1972, Volume 175, pgs. 664-666
Less than 200 clinical MEG facilities exist worldwide.

SQUID: Superconducting Quantum Interference Device
Clinical MEG

Epilepsy
- Localization of Epileptic Spikes within the Brain

Post-Traumatic Stress Disorder
- Disease Identification and Localization

Presurgical Functional Mapping
- Identification of Abnormally Functioning Areas

- Brain Scan Offers First Biological Test in Diagnosis of Post-Traumatic Stress Disorder

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Magnetic Field Scales

Superconducting MRI\(^1\) magnet

Earth’s (core) magnetic field

Urban magnetic noise

Magneto-cardiology

Magneto-encephalography

Magnetic Field (Tesla)

10^0, 10^-1, 10^-2, 10^-3, 10^-4, 10^-5, 10^-6, 10^-7, 10^-8, 10^-9, 10^-10, 10^-11, 10^-12, 10^-13, 10^-14, 10^-15

Commercially available magnetometers by minimum detectable field

Hall Effect Sensor

Magnetoresistor

Atomic Vapor Cell

SQUID\(^3\)

1MRI: Magnetic Resonance Imaging; 2NV: Nitrogen Vacancy; 3SQUID: Superconducting Quantum Interference Device
Quantum Sensors: Nitrogen-Vacancies in Diamond

Diamond

Carbon atoms

$\text{N}\text{V}^-$

$e^-$

$\text{N}$
Advantages of a Solid State Device

- No Vacuum
- No Fancy Lasers
- No Cryogenics

Sub-centimeter Scale

Measurements Tied to Fundamental Constants

Superb Precision Measurement Capability

Mature Semiconductor Processes

Fixed Crystallographic Axes (Reliable Vector Sensitivity)

MIT LL Unique Diamond Technology Platform

- **RF Engineering**
- **Pulse Sequence Design**
- **Quantum State Preparation & Measurement**
- **Selective Isotopes**: $^{12}$C, $^{14}$N, $^{15}$N
- **Enhanced Quantum Coherence**
- **Tailored Diamond Growth**
Diamond Engineering

In-House Characterization Capabilities

- EPR\(^1\)
- Raman
- PL\(^2\)
- Profillmeter
- FTIR\(^3\)
- NV confocal

Commercial Diamond

Inhomogeneous Strain Degrades Sensor Performance

- Optimized growth and processing

MIT LL chemical vapor deposition reactor

MIT LL Diamond

\(^1\)EPR: Electron paramagnetic resonance spectroscopy; \(^2\)PL: Photoluminescence spectroscopy;
\(^3\)FTIR: Fourier-transform infrared spectroscopy
MIT LL Shield System

Shielded Room: $1M

MIT LL Shields: < $50k

Technology Outlook

NV Diamond Biomagnetometry

- Single-sensor MEG
- Magneto-cardiography

Potential New Applications

- Navigation via Magnetic Maps
- Space Weather Sensing
- Geomagnetic Storm
- By
- Bz

Technology Outlook
Acknowledgements

MIT LL Quantum Sensing Team

Back: John Barry, Alex Zhang, Erik Eisenach, Matt Steinecker, Mike O'Keeffe
Front: Linh Pham, Jonah Majumder, Erik Thompson, Danielle Braje, Alexandra Day, Chuck Wuorio
Not pictured: Christopher Foy, Scott Alsid, Reggie Wilcox

Mass General Hospital

Matti Hämäläinen
Seppo Ahlfors
Energy Levels of the Nitrogen-Vacancy Center

Excited states

Green optical excitation

Red fluorescence

Intersystem crossing

Ground states

Ground states

|0⟩

2.87 GHz

±1⟩

Zeeman splitting

Zero-field splitting

Electric field

Magnetic field

Temperature

|+1⟩

|−1⟩

Intersystem crossing

2.87 GHz

|0⟩
Inherent Vector Sensitivity

Magnetic field splitting

\[ |\pm 1\rangle \]

Microwave Frequency

2.82 GHz 2.92 GHz 2.92 GHz
Pushing the Nitrogen-Vacancy’s Sensitivity

\[ B_{\text{min}} = \frac{\hbar}{g_e \mu_B} \left( \frac{1}{\Delta m_s \sqrt{N \tau}} \right) \times \frac{1}{e^{\left( \frac{\tau}{T_2} \right)^p}} \times \frac{1}{\mathcal{F}_R} \times \sqrt{\frac{t_{\text{over}} + \tau}{\tau}} \]

- Spin-projection noise
- Inhomogeneous dephasing
- Readout fidelity
- Measurement overhead

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**Graphs:**

- **Left Graph:**
  - Title: Integrated PL Noise (mV)
  - X-axis: Detector Collection Time (μs)
  - Y-axis: Integrated PL Noise (mV)
  - Data points show a linear increase.

- **Right Graph:**
  - Title: Fluorescence Signal (V)
  - X-axis: Precession Time (μs)
  - Y-axis: Fluorescence Signal (V)
  - Two curves: COTS Diamond (red), MIT LL Diamond (blue)
  - Inset shows variations in signal over time.