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.
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

(Functioanal) Magnetic Resonance Imaging (fMRI/MRI)

X-ray Computed Tomography (X-ray CT)

Single-Photon Emission Computed Tomography (SPECT)

Positron Emission Tomography (PET)

Electroencephalography (EEG)

Magneetoencephalography (MEG)
Brain Imaging Method Comparison

<table>
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<tr>
<th></th>
<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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<td>Spatial Localization</td>
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Data and visualization from MNE software package using sample data (citation below).

Inferred dipole sources

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

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.

Magnetoencephalography Today

Elekta Neuromag® TRIUX™

SQUID Sensor Array

Magnetically Shielded Room

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

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Magnetic Field Scales

Superconducting MRI\(^1\) magnet

Earth’s (core) magnetic field

Urban magnetic noise

Magneto-cardiology

Magneto-encephalography

Commercially available magnetometers by minimum detectable field

Hall Effect Sensor

Magnetoresistor

Atomic Vapor Cell

SQUID\(^3\)

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

Diamond

Carbon atoms

Nitrogen-Vacancies (NV-)

$\text{NV}^-$
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

Pulse Sequence Design

RF Engineering

Quantum State Preparation & Measurement

Selective Isotopes
$^{12}\text{C}, ^{14}\text{N}, ^{15}\text{N}$

Enhanced Quantum Coherence

Tailored Diamond Growth
Diamond Engineering

In-House Characterization Capabilities

- EPR\(^1\)
- Photoluminescence spectroscopy
- Raman
- FTIR\(^3\)
- NV confocal
- Profilometer

Commercial Diamond

- MIT LL Diamond

Optimized growth and processing

Inhomogeneous Strain Degrades Sensor Performance

\(^1\)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
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

- **Zero-field splitting**:
  - $|0\rangle$
  - $|\pm 1\rangle$
  - $2.87 \text{ GHz}$

- **Zeeman splitting**:
  - $|+1\rangle$
  - $|-1\rangle$

- **Intersystem crossing**

- **Green optical excitation**

- **Red fluorescence**
Inherent Vector Sensitivity

\[ \left| -1 \right\rangle \rightarrow \left| 1 \right\rangle \]

Microwave Frequency

- 2.82 GHz
- 2.92 GHz

Magnetic field splitting
Pushing the Nitrogen-Vacancy’s Sensitivity

$$B_{\text{min}} = \frac{\hbar}{g_e \mu_B} \left( \frac{1}{\Delta m_s \sqrt{N \tau}} \right) \times \frac{1}{e^{-\left(\frac{\tau}{T_2^*}\right)^p}} \times \frac{1}{F_R} \times \frac{t_{\text{over}} + \tau}{\tau}$$

(optical shot noise) Spin-projection noise Inhomogeneous dephasing Readout fidelity Measurement overhead

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Integrated PL Noise (mV)

Detector Collection Time (µs)

Fluorescence Signal (V)

Precession Time (µs)

- COTS Diamond
- MIT LL Diamond

MIT LL Unpublished 2019