Magnetoencephalography with Cryogen-Free Atomic Magnetometers

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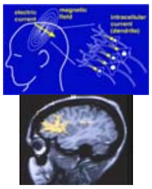
Magnetoencephalography (MEG)

- Magnetic fields produced by neural currents in the brain are detected
- Provides high quality, non-invasive spatial and temporal information of neural activity
- Typical field strength: ~100 fT
- Uses: localizing a pathology, understanding spatial and temporal brain function, brain-machine interface



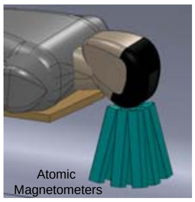
Elekta Neuromag® system

Conventional SQUID MEG

- Use superconducting quantum interference device (SQUID) magnetometer/gradiometer sensors
- SQUID Sensitivity: ~2-3 fT/Hz$^{1/2}$
- Multi-channel "helmet" arrangement enables millimeter spatial resolution
- Cryogenic liquid helium apparatus required to keep sensors at 4 Kelvin
  - High initial cost and substantial maintenance costs
  - Large size and not portable
  - Inflexible geometry of helmet

MEG with Atomic Magnetometers

- Atomic magnetometers (AMs) operate above room temperature, ~150 C
  - No cryogenic infrastructure and inflexible Dewar walls
- Our concept: 4-channel AM sensor modules that are arrayed around the head.

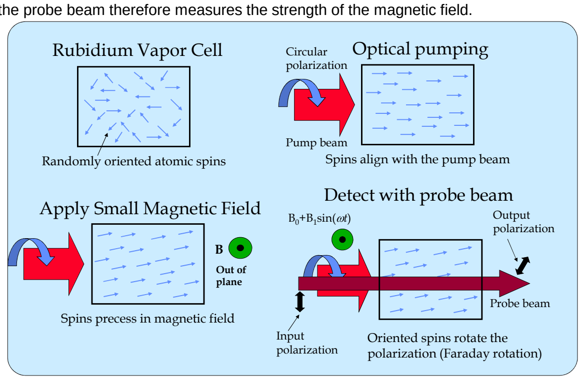


Advantages:
- Smaller and potentially much lower cost systems
- Reconfigurable arrays to accommodate variable head size from small children to large adults
- Minimize sensor to head distance, improved signal size

Disadvantages:
- High sensitivity only near zero magnetic field, < 10 nT; magnetic coils must be used to cancel ambient fields
- Lower bandwidth than SQUIDs, ~100 Hz
  - It is challenging to operate at both high bandwidth and high sensitivity

Low-field Atomic Magnetometers

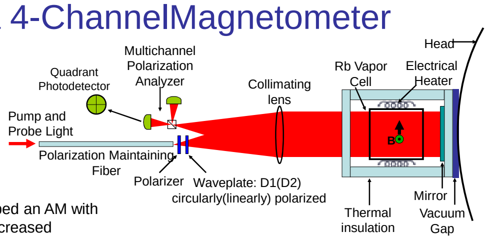
Electron spins in an atomic alkali vapor are oriented via process called optical pumping. In optical pumping, laser light, which is resonant with an electronic transition (795 nm for rubidium) and is circularly polarized, transfers spin angular momentum to the atoms via absorption and re-emission of photons. In a small magnetic field $\boldsymbol{B}$, the atomic magnetic moments are polarized by an amount $\boldsymbol{P}$ and precess around the magnetic field vector according to $\dot{\boldsymbol{P}} = \gamma \boldsymbol{P} \times \boldsymbol{B}$, where γ is the gyro magnetic ratio. A linearly polarized probe laser (780 nm) passing through the spin polarized atomic sample experiences Faraday rotation in an amount proportional to the angle of the atomic magnetic moments. Polarization analysis of the probe beam therefore measures the strength of the magnetic field.

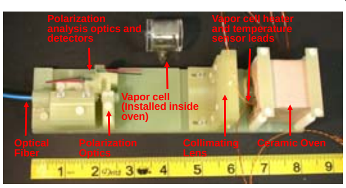


Sandia 4-ChannelMagnetometer

The first atomic magnetometer MEG demonstration used a large vapor cell and free-space pump and probe laser beams [1], an approach that is not easily scaled to replicate a whole-head MEG system. We have developed an AM with the features needed for increased scalability:

- Fiber-optic coupling: one laser for multiple sensors
- Co-linear pump/probe beams: compact construction
- Small footprint on head: whole-head coverage
- Head to vapor cell center distance: 3 cm

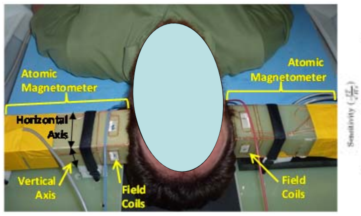


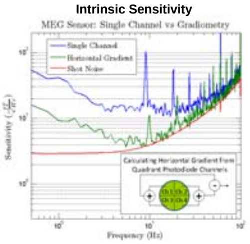


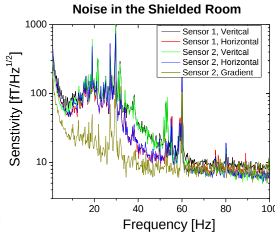
[1] H. Xia, A. Ben-Amar Baranga, D. Hoffman, and M. V. Romalis, Appl. Phys. Lett. 89, 211104 (2006).

MEG Measurements

Atomic magnetometer installed in the magnetically shielded room at the Mind Research Network
- Conventional magnetically shielded room has large DC and AC fields.
- Ambient DC field of ~100 nT is canceled with large cancellation coils surround the subject.
- AC fields can be removed to some degree with signal processing (gradiometry, signal space projection, *etc*.).
- Coils installed on the magnetometer provide the required field modulation and define the sensitive axis.
- Magnetometer enclosed in an insulating vessel to protect human subject from 160ºC cell.



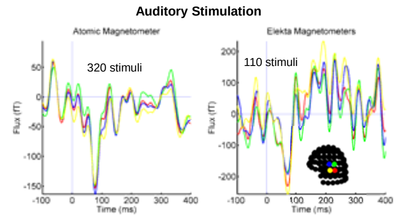


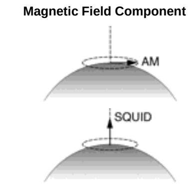


Atomic Magnetometer to SQUID Comparison

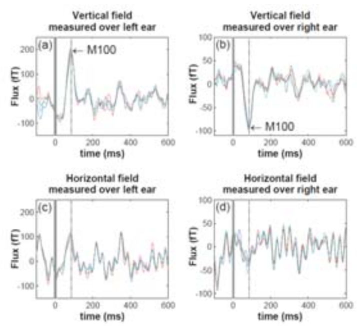
- Comparisons of brain activity recorded with the AM and the Elekta-Neuromag MEG instrument are quite favorable.
- 1000 Hz tones presented for 250 ms presented at intervals of either 0.9 s, 1.0 s, or 1.1 s. Data averaged and filtered 1-40 Hz.
- Differences in the waveforms are likely due to the differences in the measurement of field components.

C. Johnson, P.D.D. Schwindt, and M. Weisend, *Appl. Phys. Lett.* **101**, 253518 (2012)

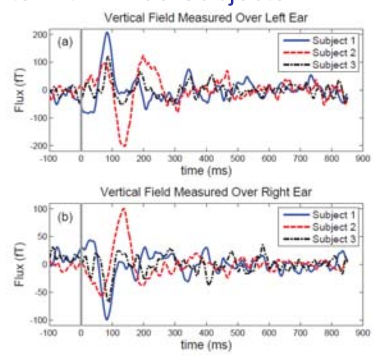




Two Sensor Measurements with Three Subjects



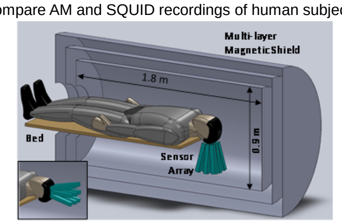
Subject 1 auditory stimulation showing two field components, 330 stimuli averaged, filter: 2-55 Hz, signal space projection.



Scaling up to Larger Arrays

Project Goals

- 36 channel AM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation
- Compare AM and SQUID recordings of human subjects

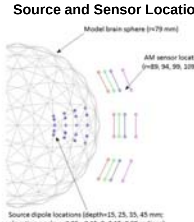


Major tasks

1. Redesign, miniaturize sensor (4 cm X 4 cm area on head)
   - <10 fT/Hz1/2, >100 Hz bandwidth
2. Carefully model human-sized shield performance
3. Design/model array for minimum interference
   - Modulation coil fields are seen by neighboring sensors
4. Adapt source localization codes for AM geometry
   - Brainstorm for localization and Fieldtrip for modeling
5. Construct array; source localization with phantom
6. Auditory/somatosensory recordings on human subjects with AM/SQUID systems
   - Coregistration, source localization comparison

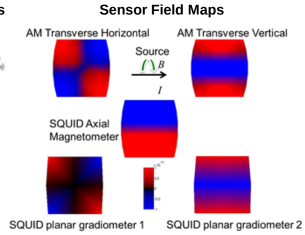
Atomic Magnetometer Array Simulations

Source and Sensor Locations



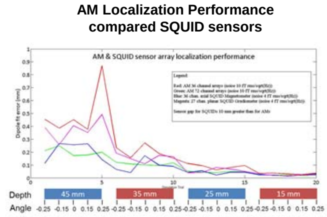
Simulations study a 3 x 3 array of 4-channel atomic magnetometers, looking at source localization performance.

Sensor Field Maps



An AM array measuring the field components transverse to the scalp gives similar signals to planar gradiometers measuring the radial component of the field.

AM Localization Performance compared SQUID sensors



These simulations show that the localization of the AM array is similar to that of SQUID-based systems covering a similar area of the head. Only sensor noise is taken into account.

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