Atomic Magnetometers for Magnetoencephalography
Design and Construction of a 36-Channel System

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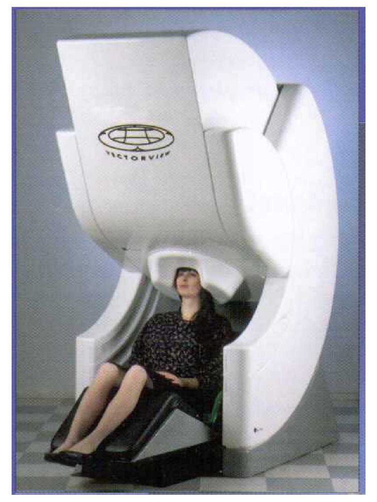
Conventional SQUID-based MEG

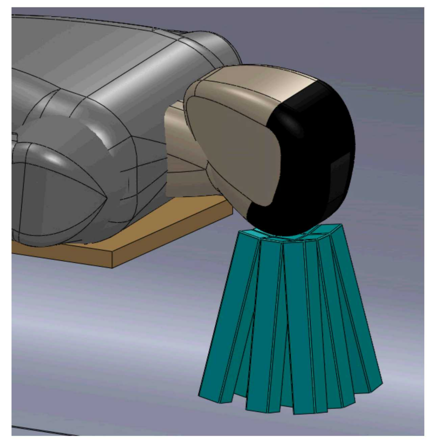


Elekta Neuromag® system

- **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 ºC.**
  - No cryogenic infrastructure and inflexible Dewar walls.
- **Our concept: 4-channel AM sensor modules that are arrayed around the head.**



Atomic Magnetometer Array

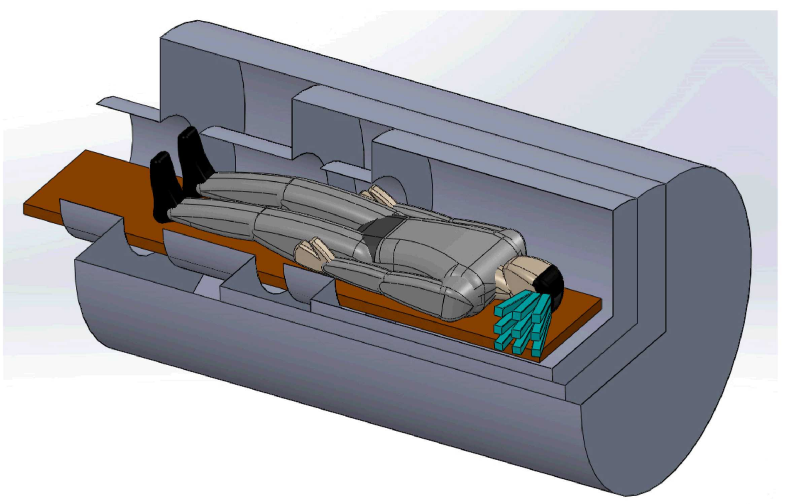
Advantages:
- Smaller and potentially much lower cost systems.
- Reconfigurable arrays to accommodate variable head size from small children to large adults.
- Minimize sensor-to-head distance, improve signal size.

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)
  - Operating at both high bandwidth and high sensitivity presents a challenge.

Scaling up to Larger Arrays

Project Goals

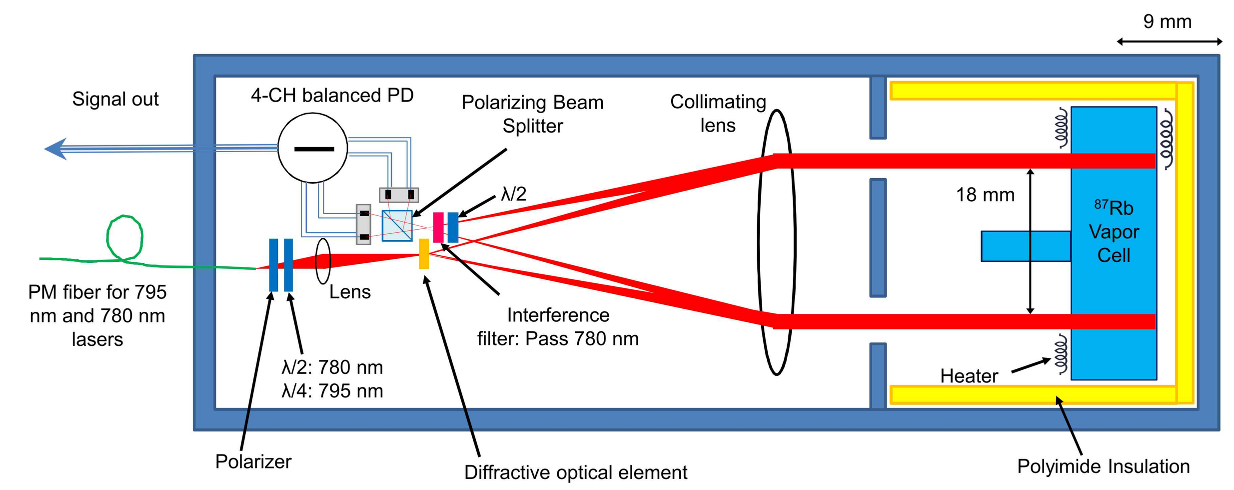
- 36 channel AM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation
- Compare AM and SQUID recordings of human subjects



Major tasks

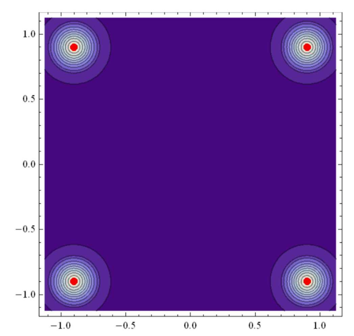
1. Redesign, miniaturize sensor (4 cm X 4 cm area on head)
   - < 10 fT/Hz$^{1/2}$ sensitivity, > 100 Hz bandwidth
2. Carefully model human-sized shield performance
3. Design/model array for minimum interference
   - Modulation coil fields are seen by neighboring sensors
4. Adapt source localization 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 and SQUID systems
   - Coregistration, source localization comparison

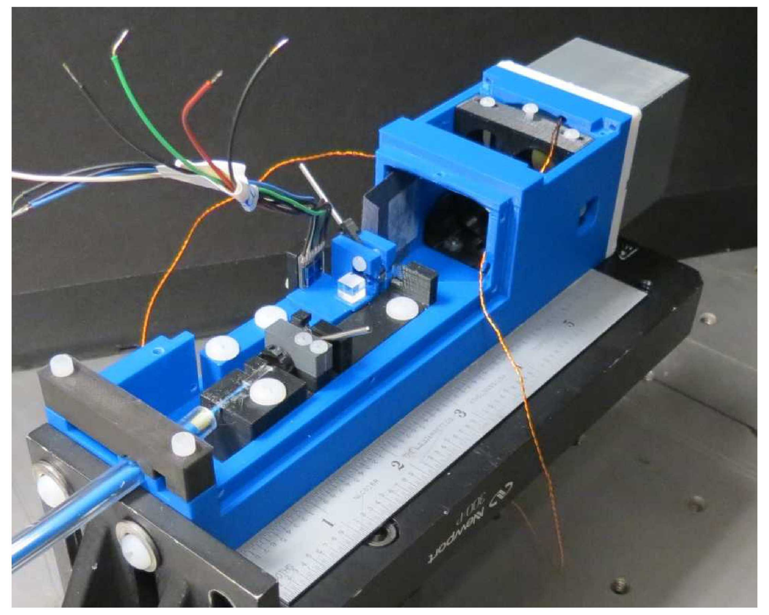
2nd Generation 4-Channel Magnetometer



Features:
- Switch to 4 separate beams, ~18 mm baseline.
- Change vapor cell composition
  - Previous: 10 mm long, 600 Torr He, 30 Torr N_2.
  - Current: 4 mm long, 600 Torr N_2.
- Minimize distance from the head to the vapor cell: 9 mm.
- Air cooling for oven housing instead of vacuum insulation.

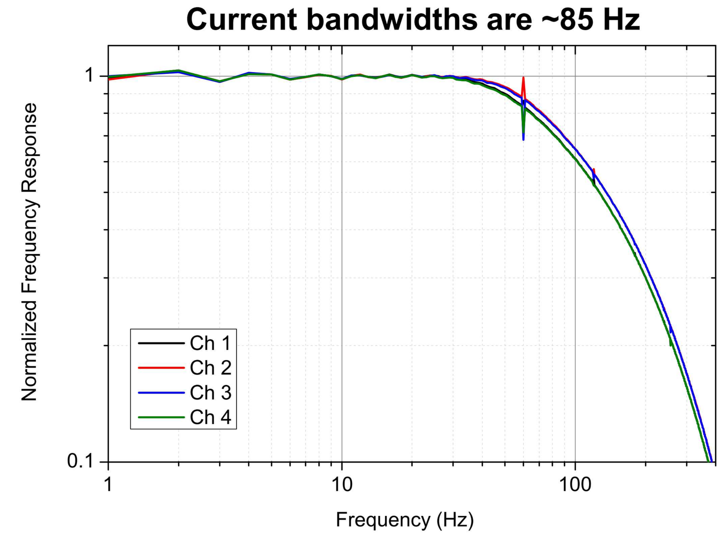
Beam Profiles through Cell



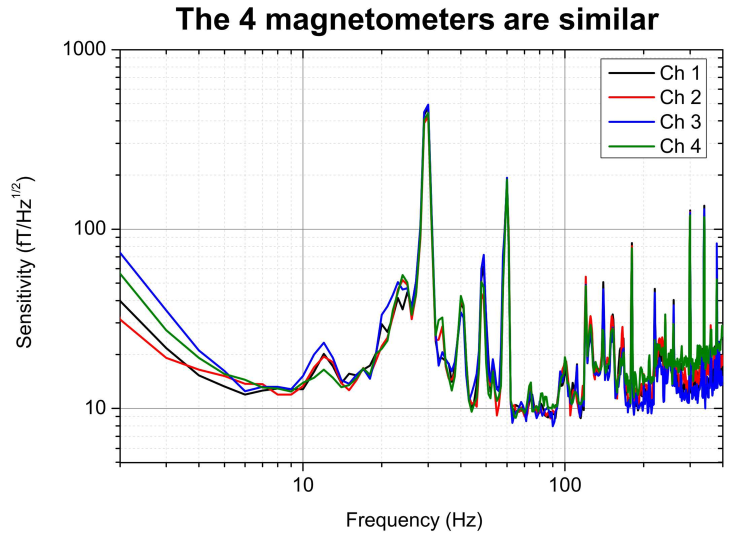


- Cell: 25 x 25 x 4 mm^3, 600 Torr N_2
- ~2.5 mm FWHM beam diameters
- Current sensitivity: < 10 fT/Hz$^{1/2}$ over 5-100 Hz
- Bandwidth: ~85 Hz

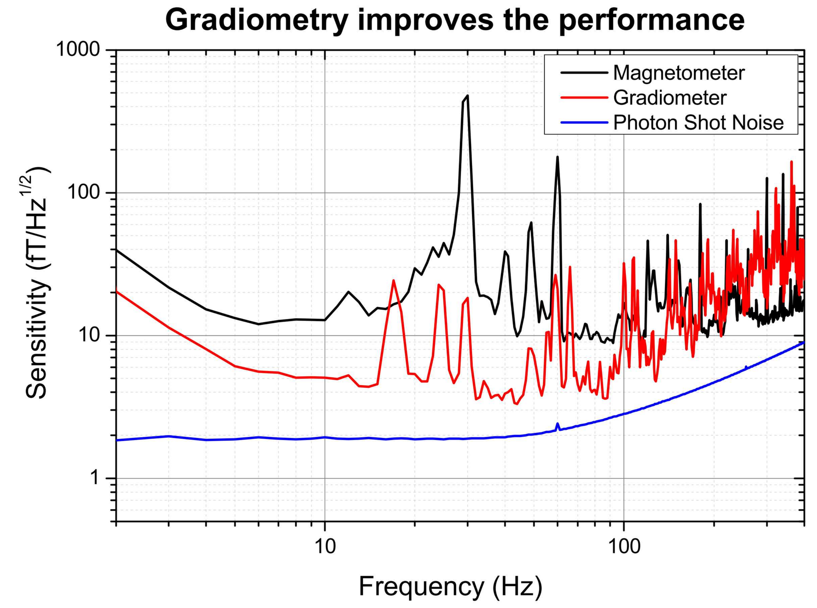
Current bandwidths are ~85 Hz



The 4 magnetometers are similar

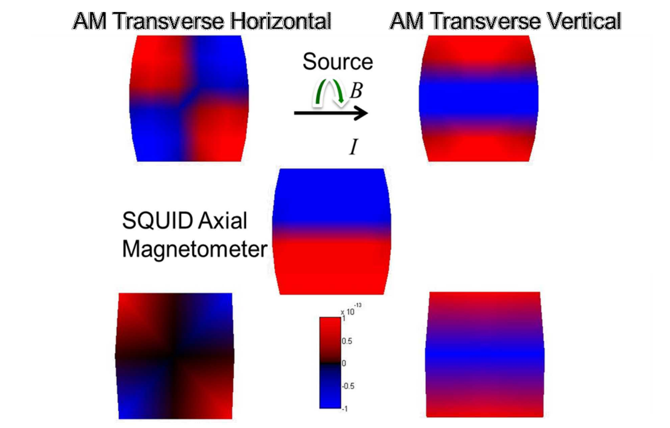


Gradiometry improves the performance



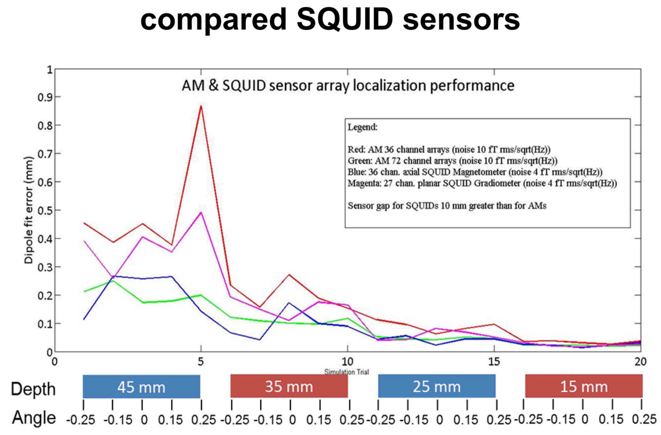
Array Simulations

Sensor Field Maps



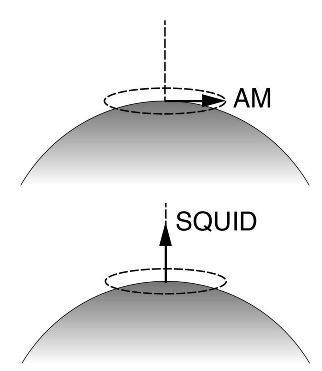
An AM array measuring the field components transverse to the scalp gives similar signals to planar gradiometers measuring the radial component of the field.

AM Localization Performance compared SQUID sensors



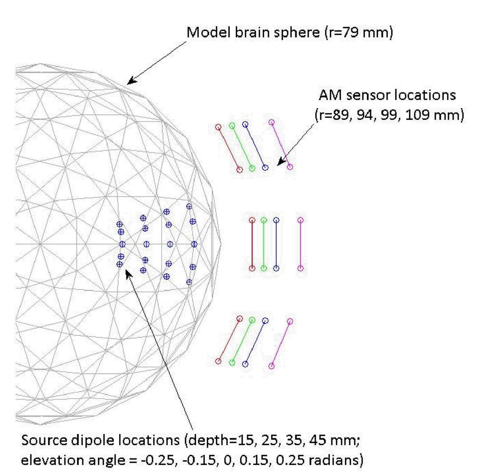
These simulations show that the localization of the AM array is similar to that of SQUID-based systems covering a similar area of the head. Only sensor noise is taken into account.

Magnetic Field Component



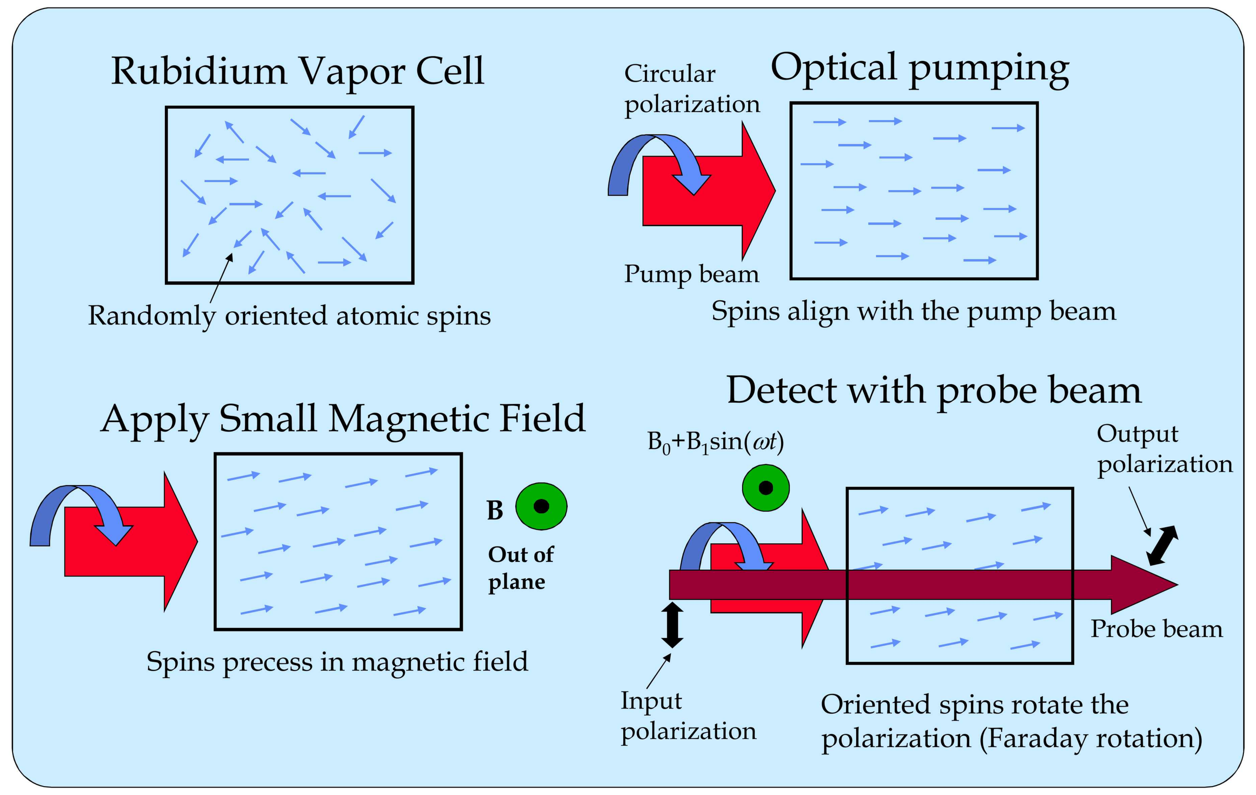
While SQUIDs measure the radial magnetic field component (perpendicular to the scalp), AMs measure the field components tangential to the scalp.

Source and Sensor Locations



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

Low-field Atomic Magnetometers



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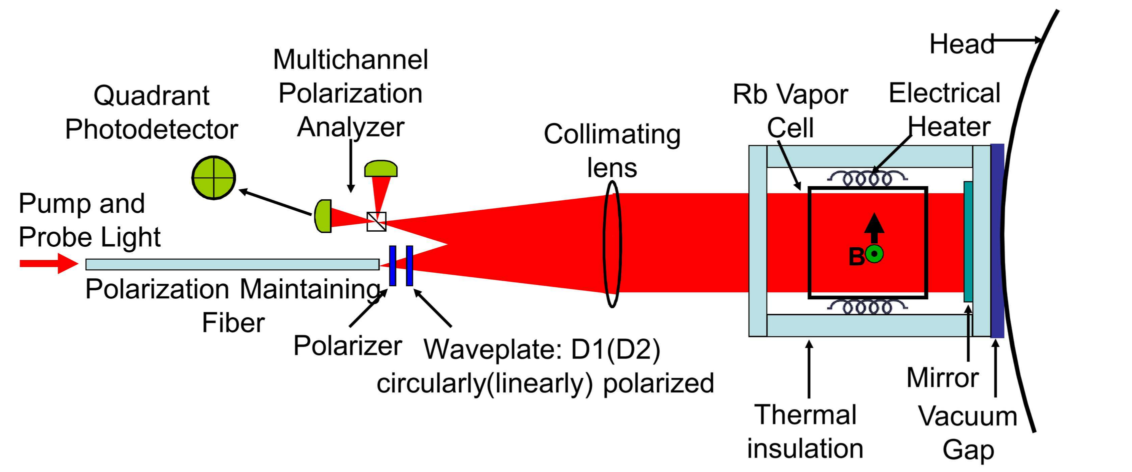
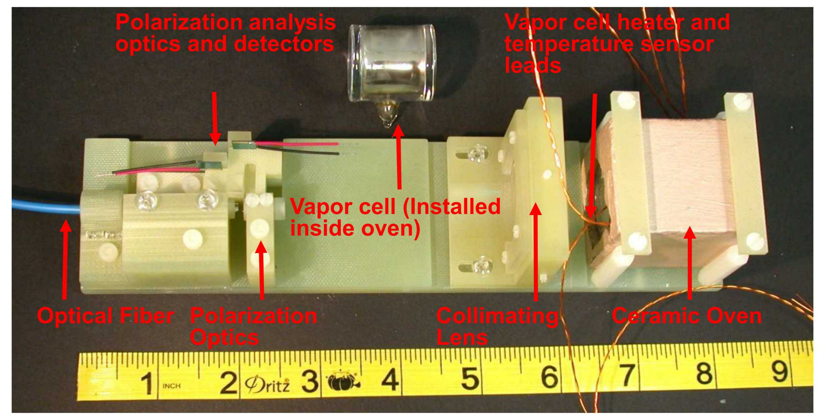
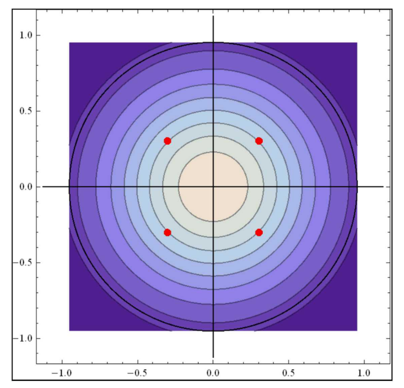
1st Generation Magnetometer





Beam Profile through Cell



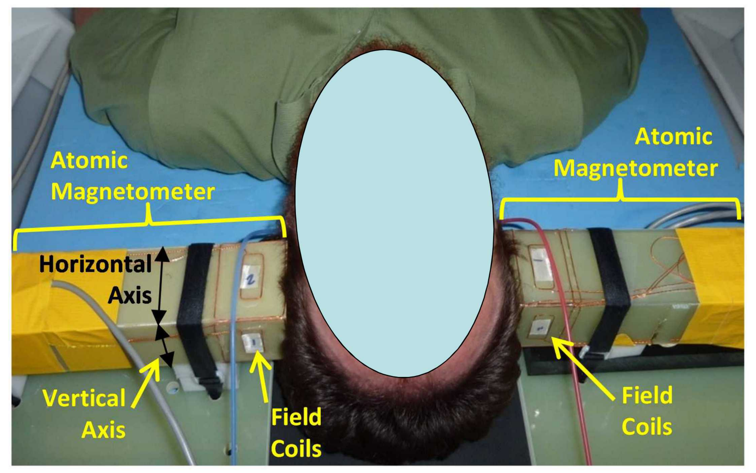
Fiber-optic coupling:
- One laser may drive multiple sensors.

Co-linear pump/probe beams:
- Compact construction.
- Independent control of each beam.

Head to vapor cell center distance: 3 cm.

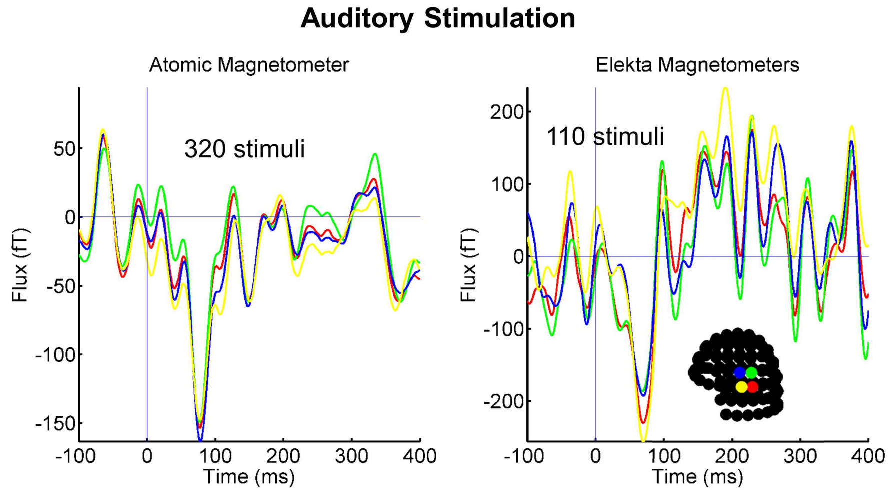
Gradiometry performed with quadrant photodiode.
- 1/e^2 diameter of 20 mm gives a gradiometer baseline of ~4-5 mm.

MEG Measurements with 1st Generation, 4-Channel Magnetometers



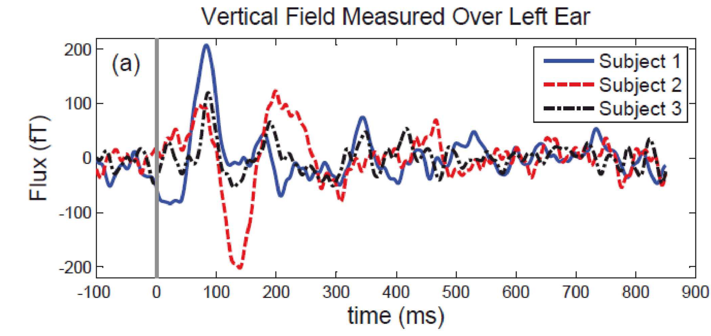
Atomic magnetometer installed in the magnetically shielded room at the Mind Research Network
- Conventional magnetically shielded room has large DC and AC fields.
- Ambient DC field of ~100 nT is canceled with large cancellation coils surround the subject.
- Coils installed on the magnetometer provide the required field modulation and define the sensitive axis.

Auditory Stimulation

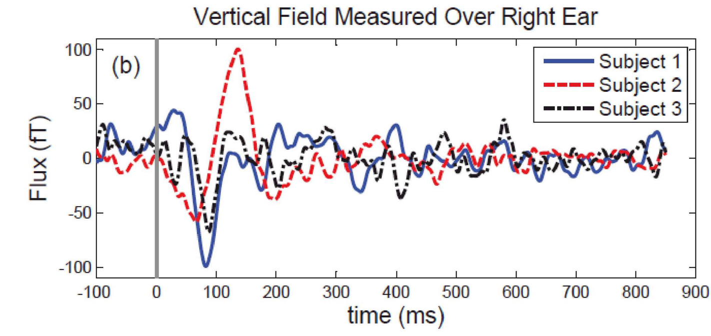


- Comparisons of brain activity recorded with the AM and the Elekta-Neuromag MEG instrument are quite favorable.
- 1000 Hz tones presented for 250 ms presented at intervals of either 0.9 s, 1.0 s, or 1.1 s. Data averaged and filtered 1-40 Hz.
- Differences in the waveforms are likely due to the differences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

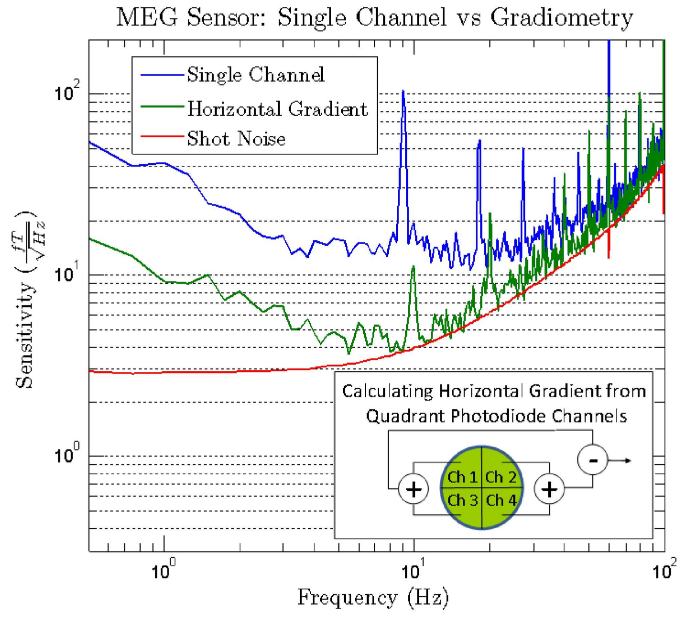
Vertical Field Measured Over Left Ear



Vertical Field Measured Over Right Ear



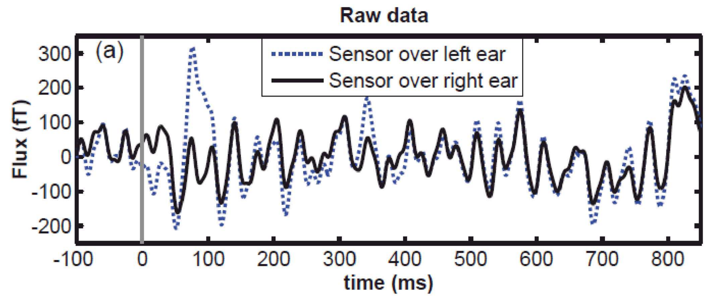
Intrinsic Sensitivity



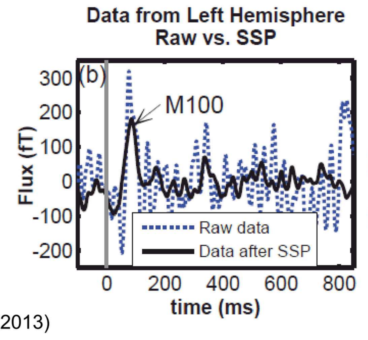
- 1000 Hz auditory stimulus applied to both ears
- Recordings from left/right sensors measured simultaneously
- Recordings of vertical component
- Bandpass filter: 2-55 Hz, Trials averaged: 330
- Use a signal space projection technique to cancel noise.
- With noise projected out, a clear M100 response is observed.

Auditory evoked responses

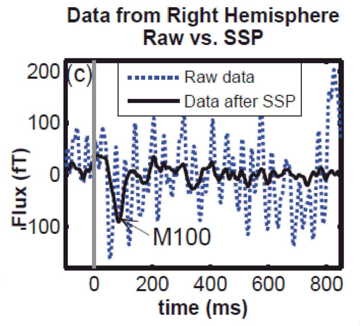
Raw data



Data from Left Hemisphere Raw vs. SSP



Data from Right Hemisphere Raw vs. SSP



C. Johnson, P.D.D. Schwindt, and M. Weisend, *Appl. Phys. Lett.* **101**, 253518 (2012); Cort N Johnson, P D D Schwindt and M Weisend, *Phys. Med. Biol.* **58** 6065 (2013)