SAND2015-9324C

Towards a Multi-Channel Atomic Magnetometer Array for MEG

Peter D. D. Schwindt
Sandia National Laboratories

Workshop on Optically Pumped Magnetometry

October 9th, 2015

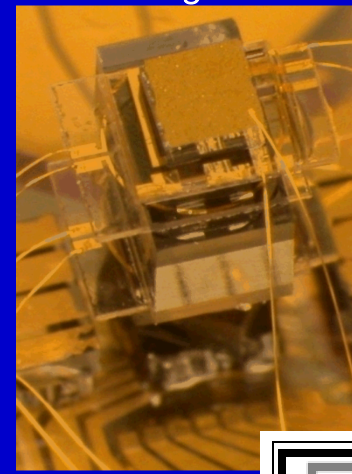
Outline

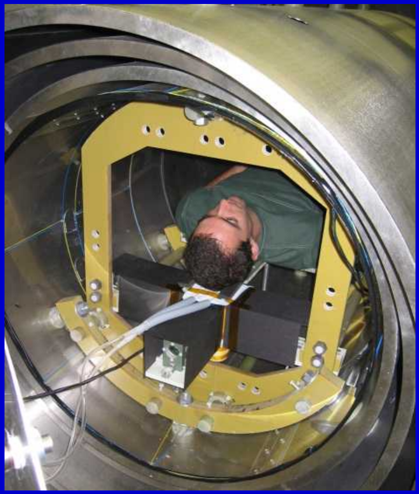
- Introduction
- First generation sensor design
  - Performance
  - MEG measurements
- Scaling up to larger array
  - Second generation sensor design
  - Array interference
  - Magnetic shield design
- Conclusion

Introduction

- Two projects focusing on developing atomic magnetometers (AMs) for MEG
  - Internal funding from Sandia, 2008-2010
  - NIH funding, 2012-present
- Looking to develop a scalable sensor design
  - Toward whole head coverage
  - Took inspiration from the Elekta sensor design
- Goals of our sensor:
  - Adequate sensitivity/bandwidth (<10 fT/Hz$^{1/2}$ / 100 Hz)
  - Small footprint
  - Fiber coupled design
  - Gradiometric 2D output

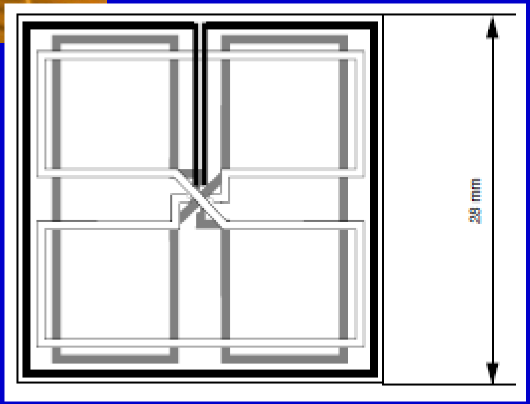
NIST Chip-Scale Atomic Magnetometer





Princeton AM MEG System

Elekta Triple Sensor Chip



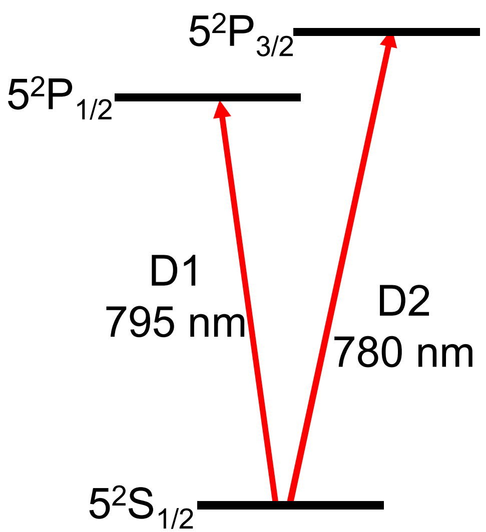
Two-color pump/probe scheme

Single axis, elliptically polarized pump/probe scheme

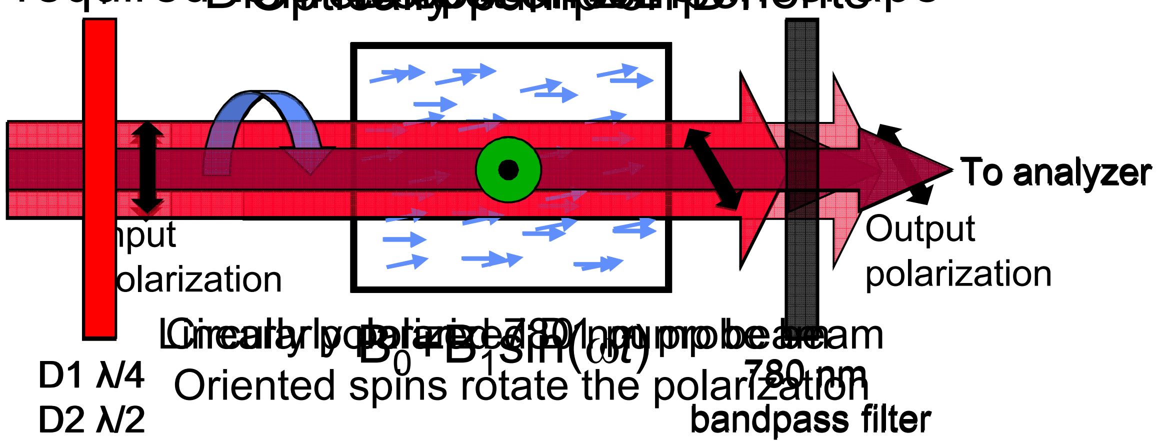
- Circular component pumps, linear component probes
- 7 $fT/Hz^{1/2}$, 150 Hz bandwidth V. Shah and M. V. Romalis, PRA 80, 013416 (2009)
- Pump beam adds noise to detector, pump/probe not independent

Alternate scheme: utilize rubidium fine structure

^{87}Rb Fine Structure

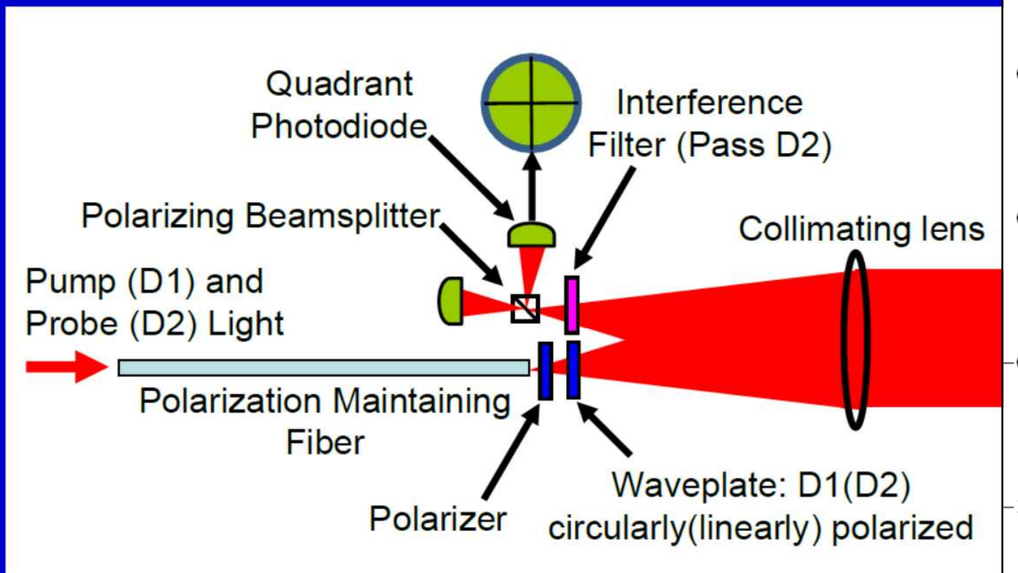


Field modulation/phase sensitive detection required to extract dispersive lineshape

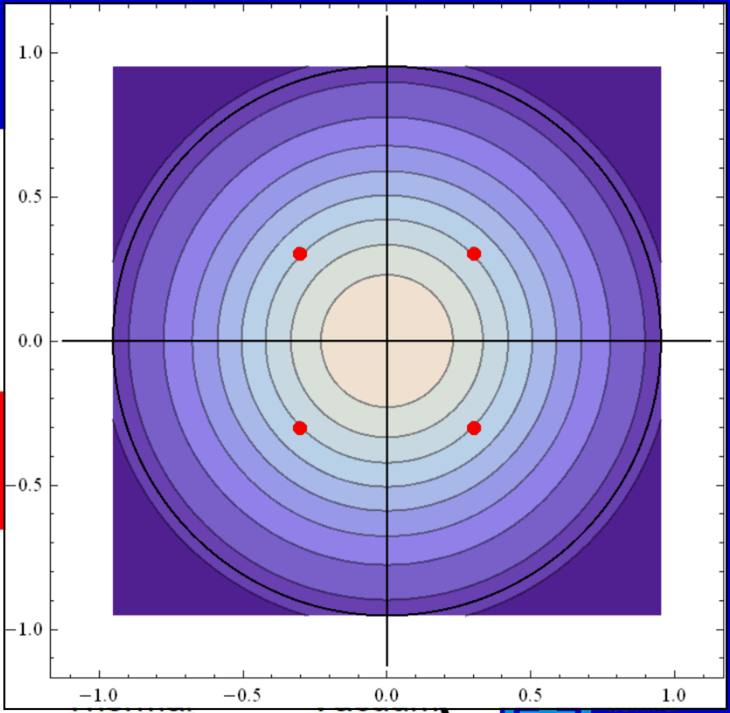


1st Generation Sensor Design

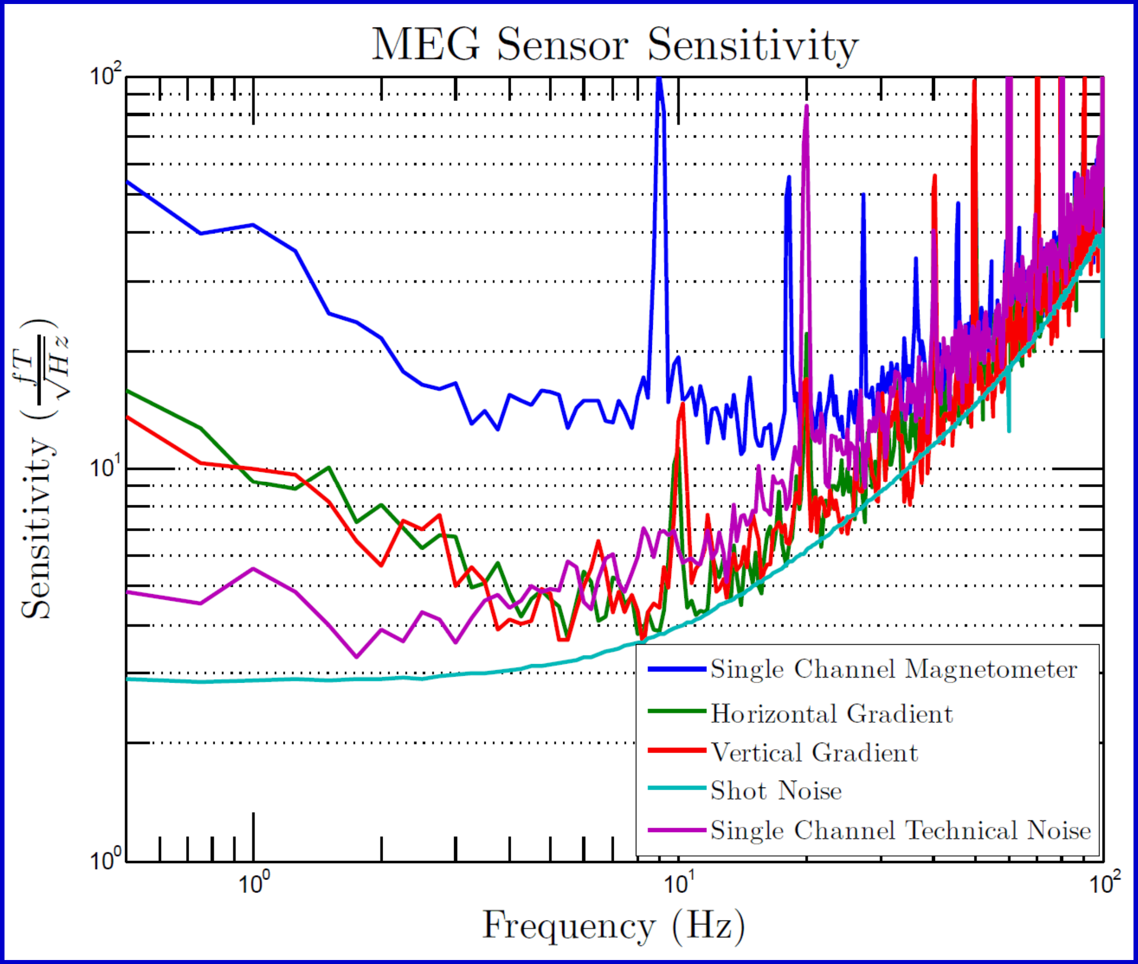
- Single optical axis: compact, single fiber for pump/probe
  - Use ^{87}Rb (D1 795 nm, D2 780 nm)
- Retroreflecting mirror minimizes vapor-cell-to-head distance
- Modulate Bx/By for lock-in detection (choose sensitive axis)
- Gradiometry performed with quadrant photodiode
  - $1/e^2$ diameter of 20 mm: gives a gradiometer baseline of ~4-5 mm



Distance between vapor cell center and head: ~3 cm



Magnetometer Performance



- Gradient measures intrinsic sensitivity
- <5 fT/Hz$^{1/2}$ at 10 Hz
- Noise floor consistent with magnetic shield noise
- Bandwidth = 17 Hz; Could be improved with more pump power or higher temperature

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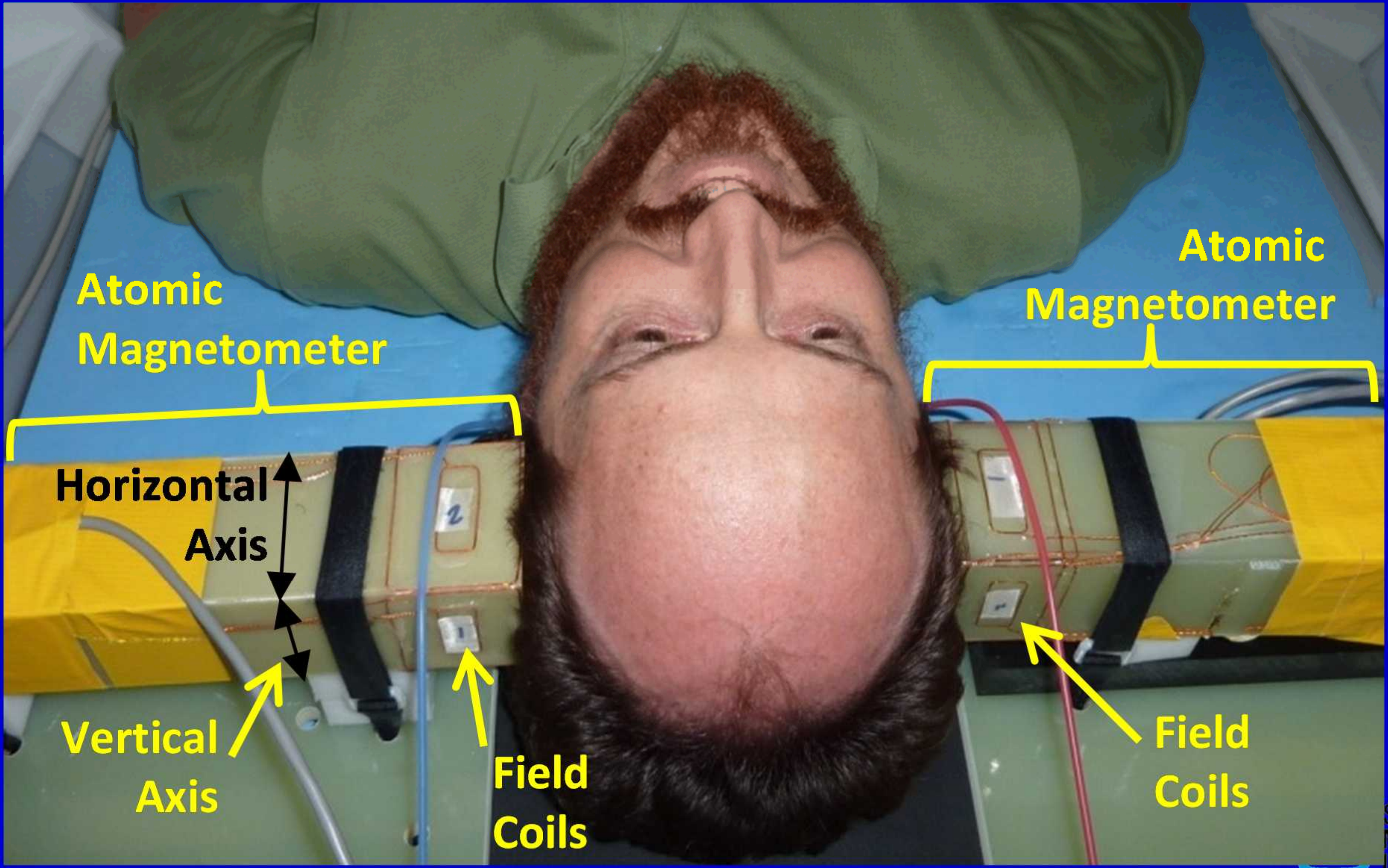
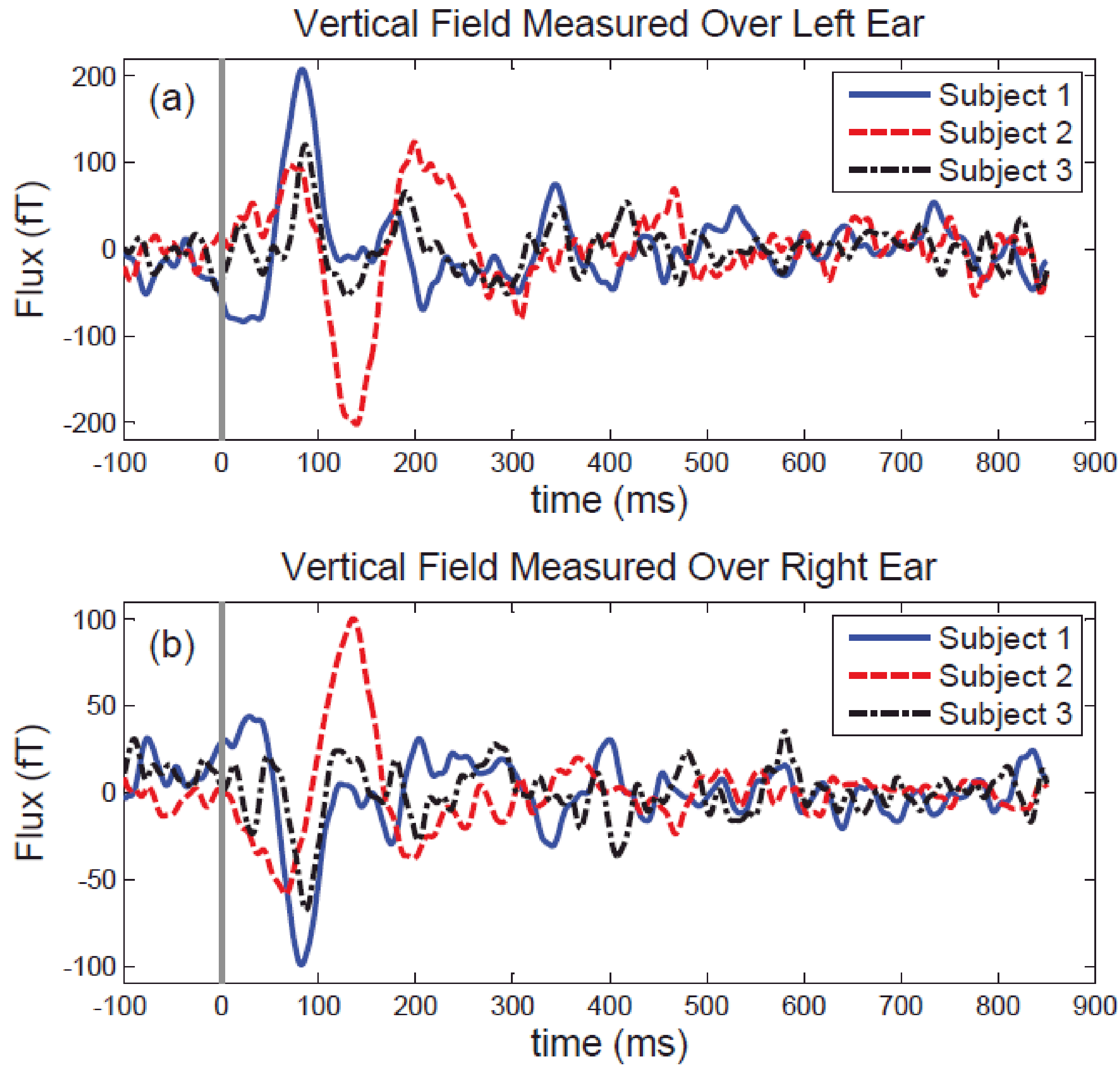
Two Sensor MEG Measurements

- Three subjects measured with auditory stimuli
- Two subjects measured with somatosensory stimuli



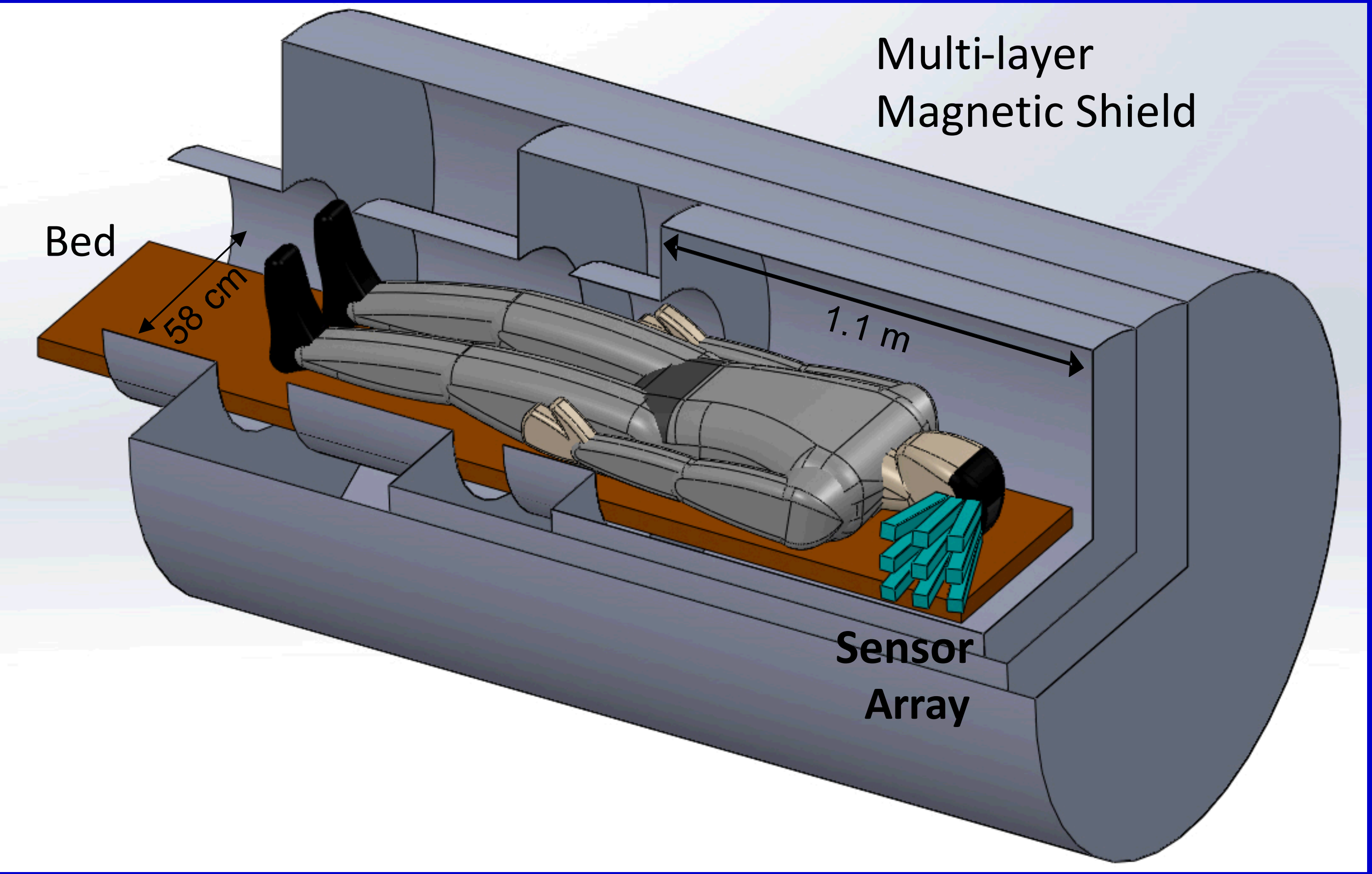
Auditory Stimuli Multiple Subjects



C.N. Johnson, P.D.D. Schwindt, and M. Weisend, *Phys. Med. Biol.* **58** 6065 (2013).

NIH Project: Build a System

- 36 channel AM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation
- Compare AM and SQUID magnetic source localization in human subjects: auditory and somatosensory



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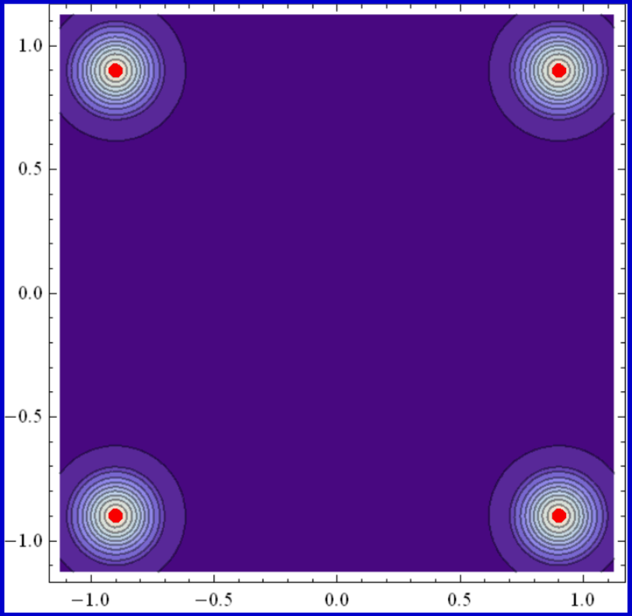
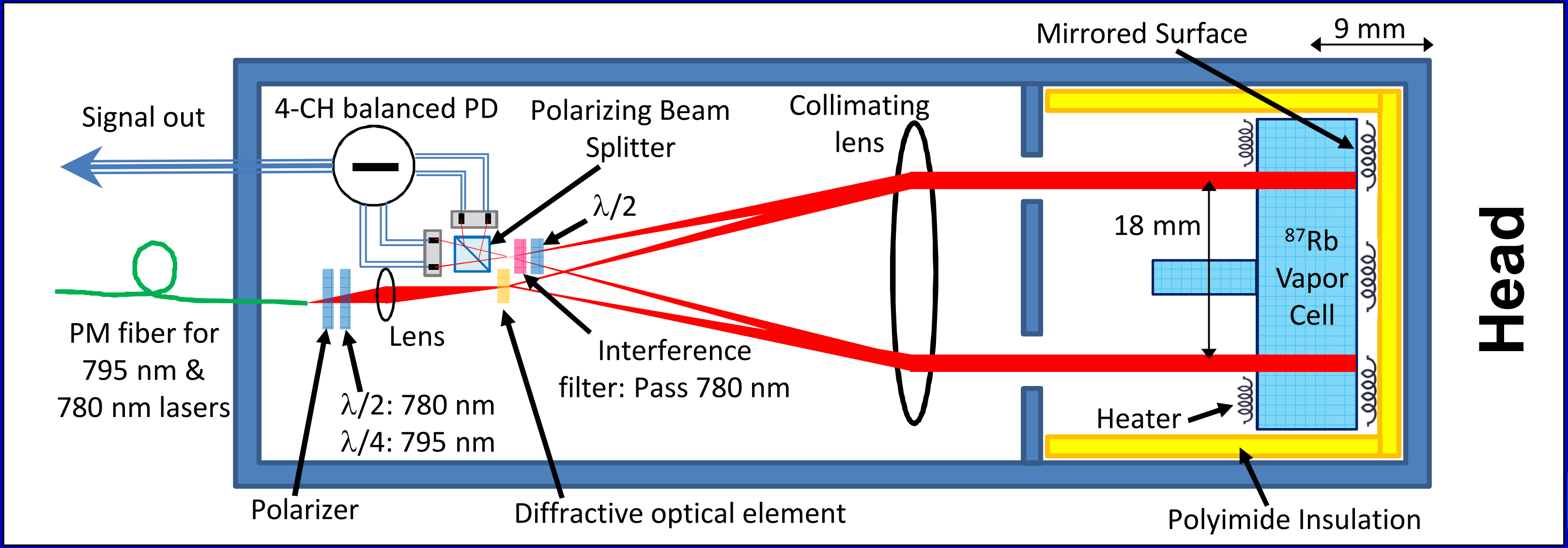
2^{nd} Generation Sensor Design

- Previous single-beam design was very difficult to align and had a short gradiometer baseline, ~5 mm
- Switch to four beams, 18 mm baseline, 2.5 mm FWHM beam diameter
- Vapor cell:
  - Previous: 19 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





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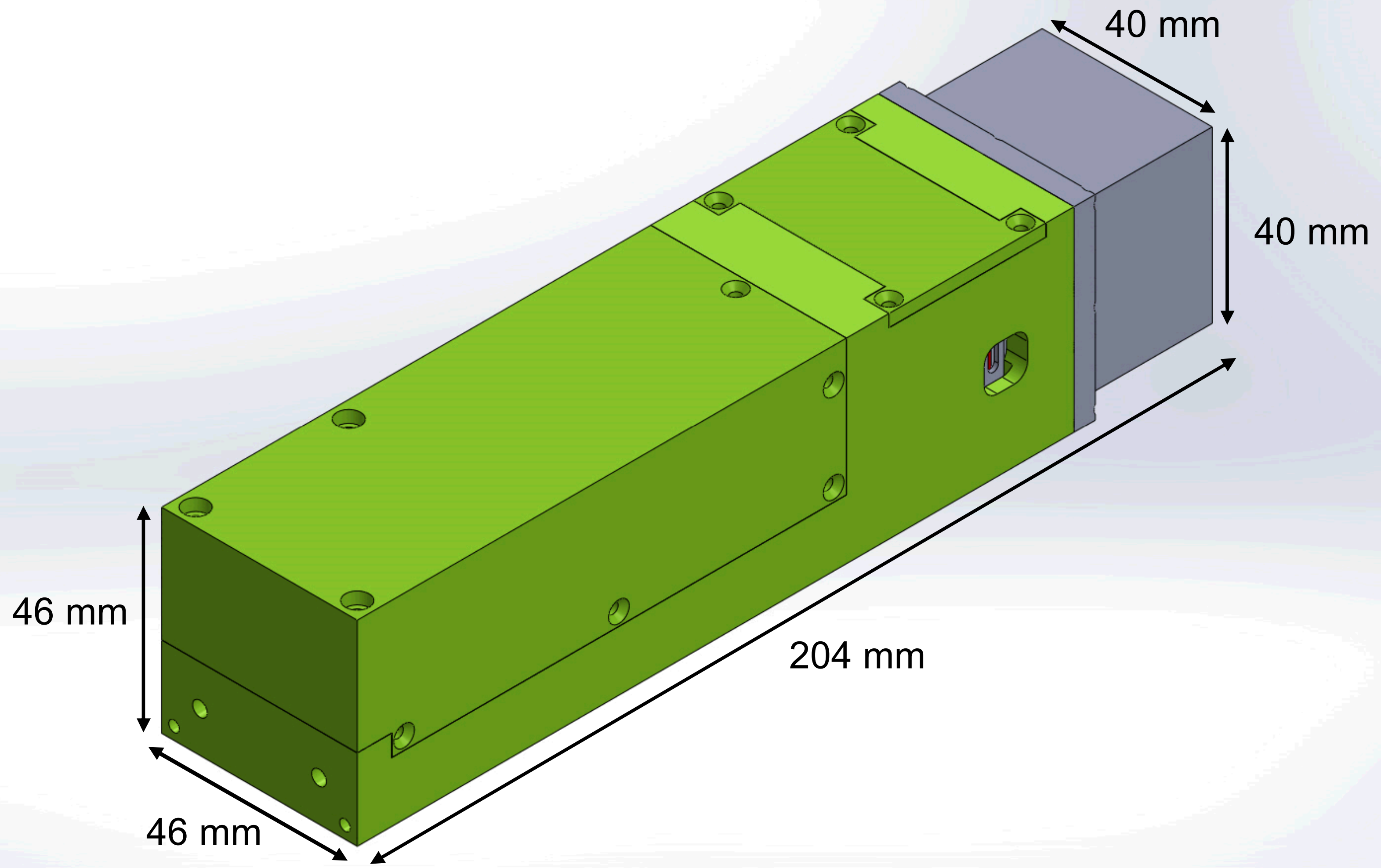
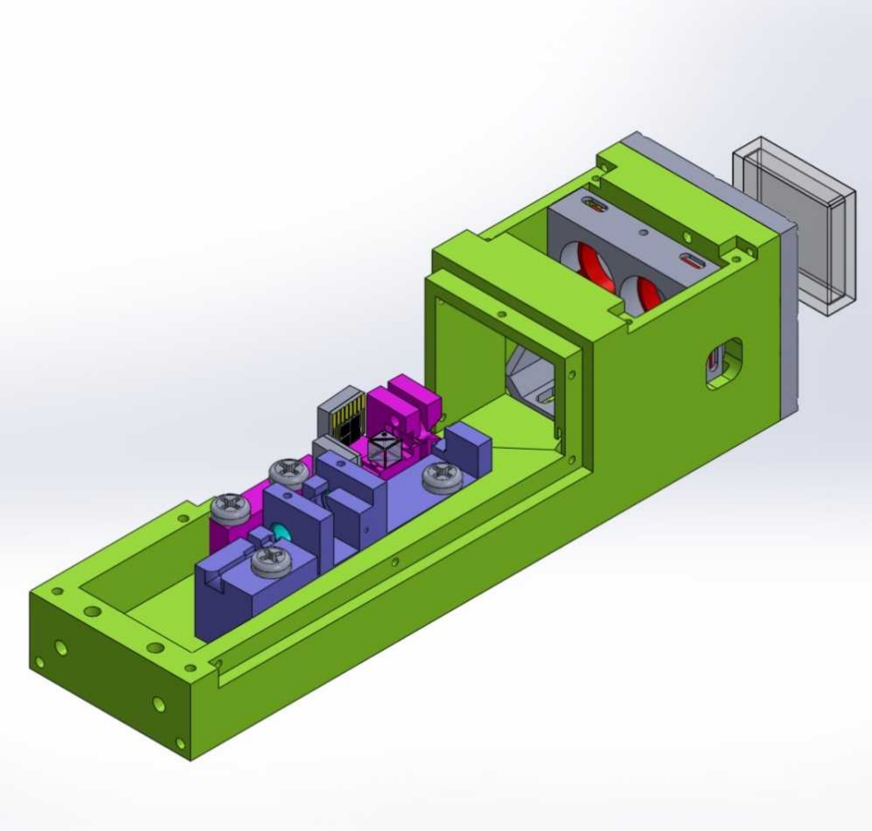
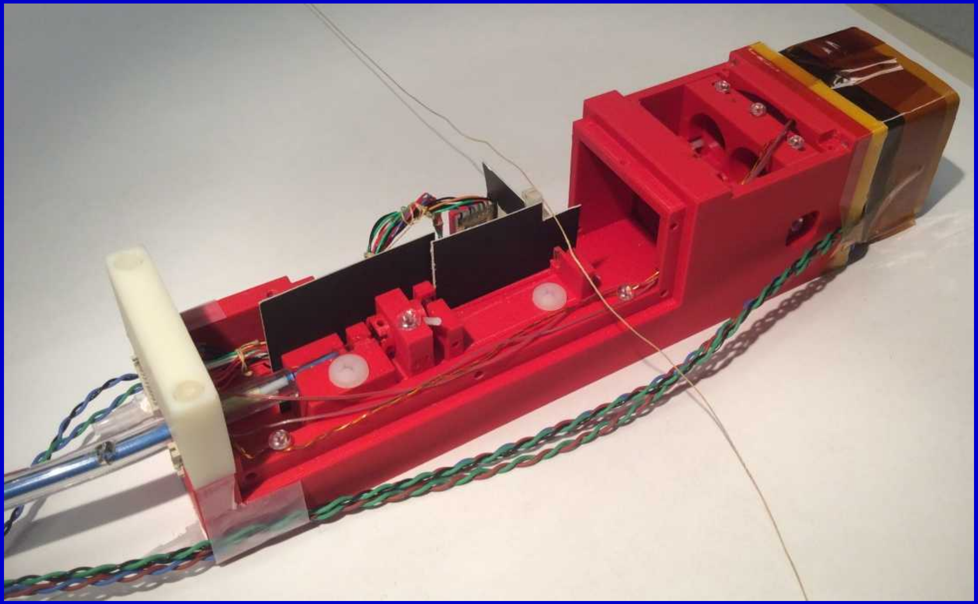
2nd Generation Sensor Design



2nd Generation Sensor Design





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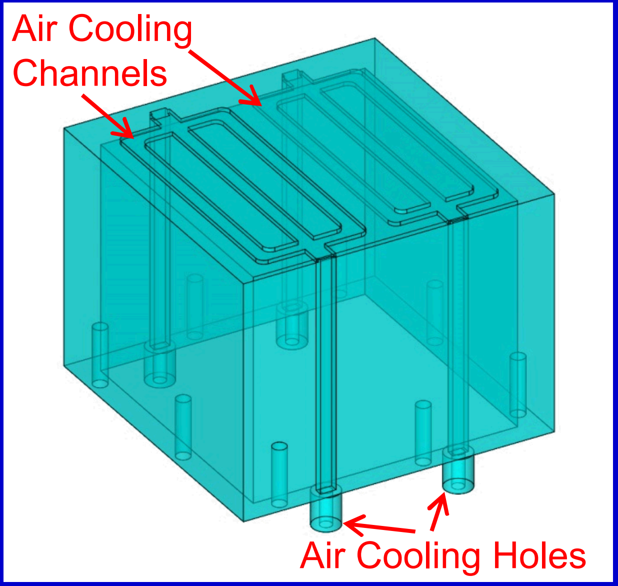
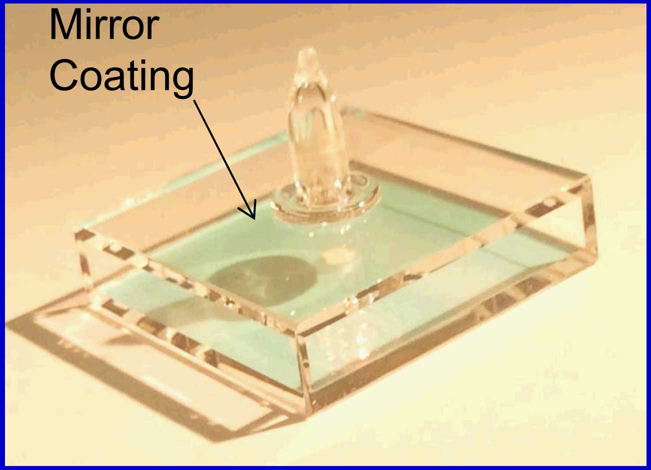
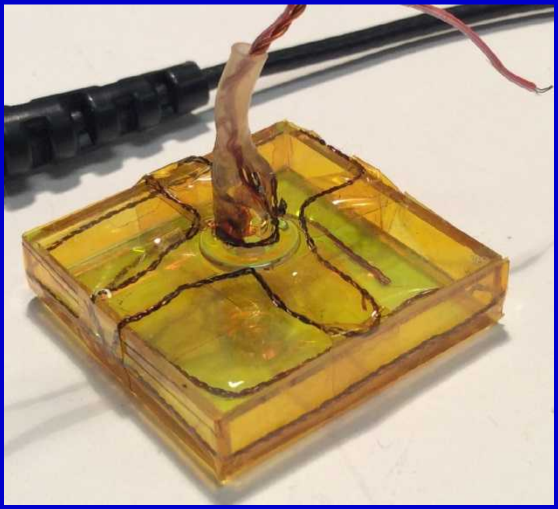
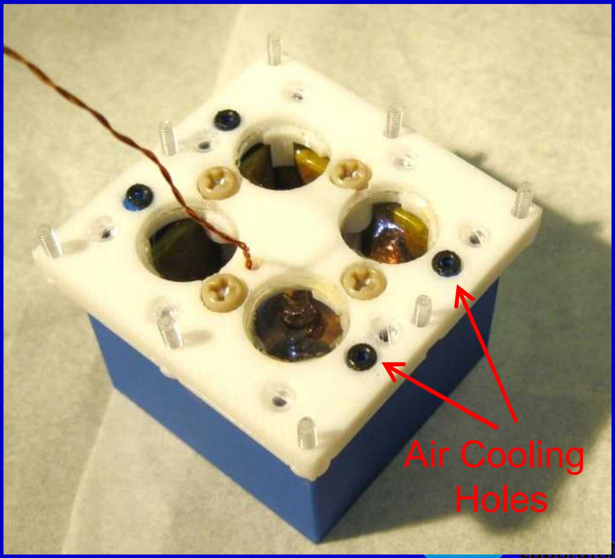
Vapor Cell and Oven

- Vapor cell inner dimensions: 4 mm x 25 mm x 25 mm
- Vapor cell material: Fused silica fails in a month. Switch to Pyrex (sourced from QuSpin).
- Heater: twisted pair of phosphor-bronze wire. Electrical insulation: Formvar fails and Polyimide so far so good.
  - Considering flex circuit material (slightly magnetic, 2-4 pT)
- Oven: 3D-printed ABS and polycarbonate plastic
- Insulation: Aerogel blanket: Pyrogel 2250 (slightly magnetic, ~50 pT); Polyimide blanket: Pyropel MD (less insulating)

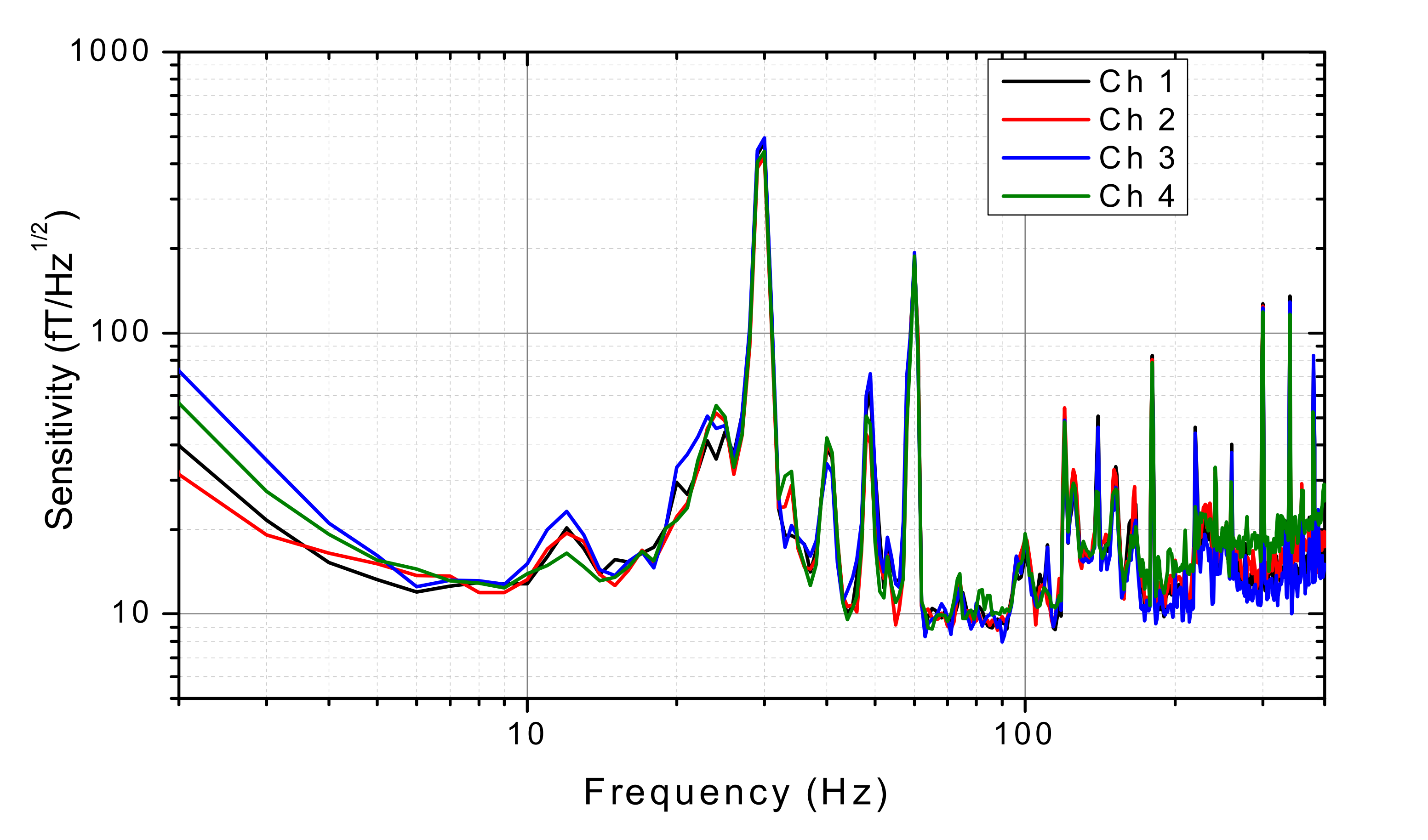








Prototype Performance: 4 Channels



- Current sensitivity: 10–20 fT/Hz$^{1/2}$ over 5–200 Hz

	Ch 1	Ch 2	Ch 3	Ch 4
DC Slope	19.5 V/nT	18.0 V/nT	18.7 V/nT	19.7 V/nT

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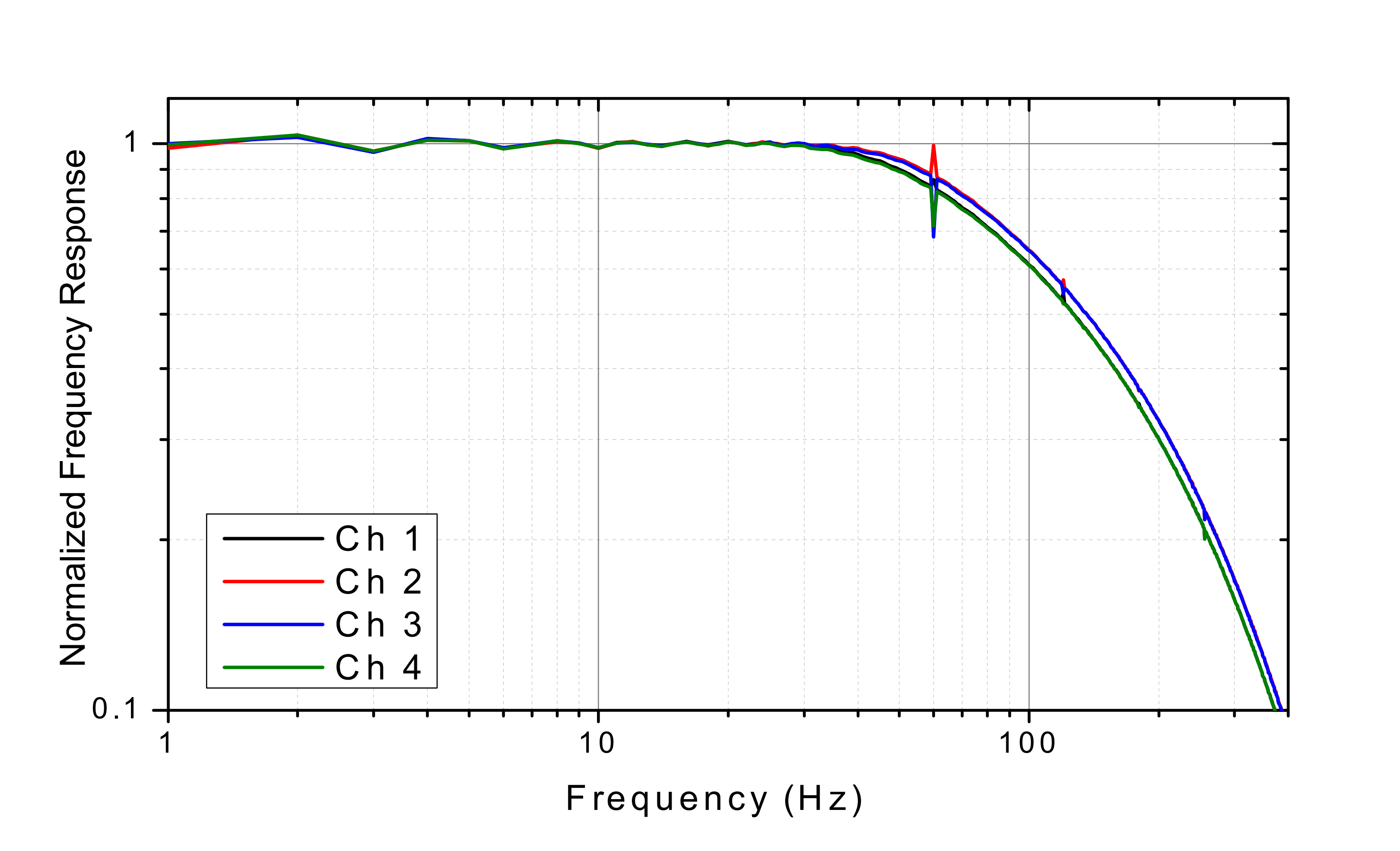
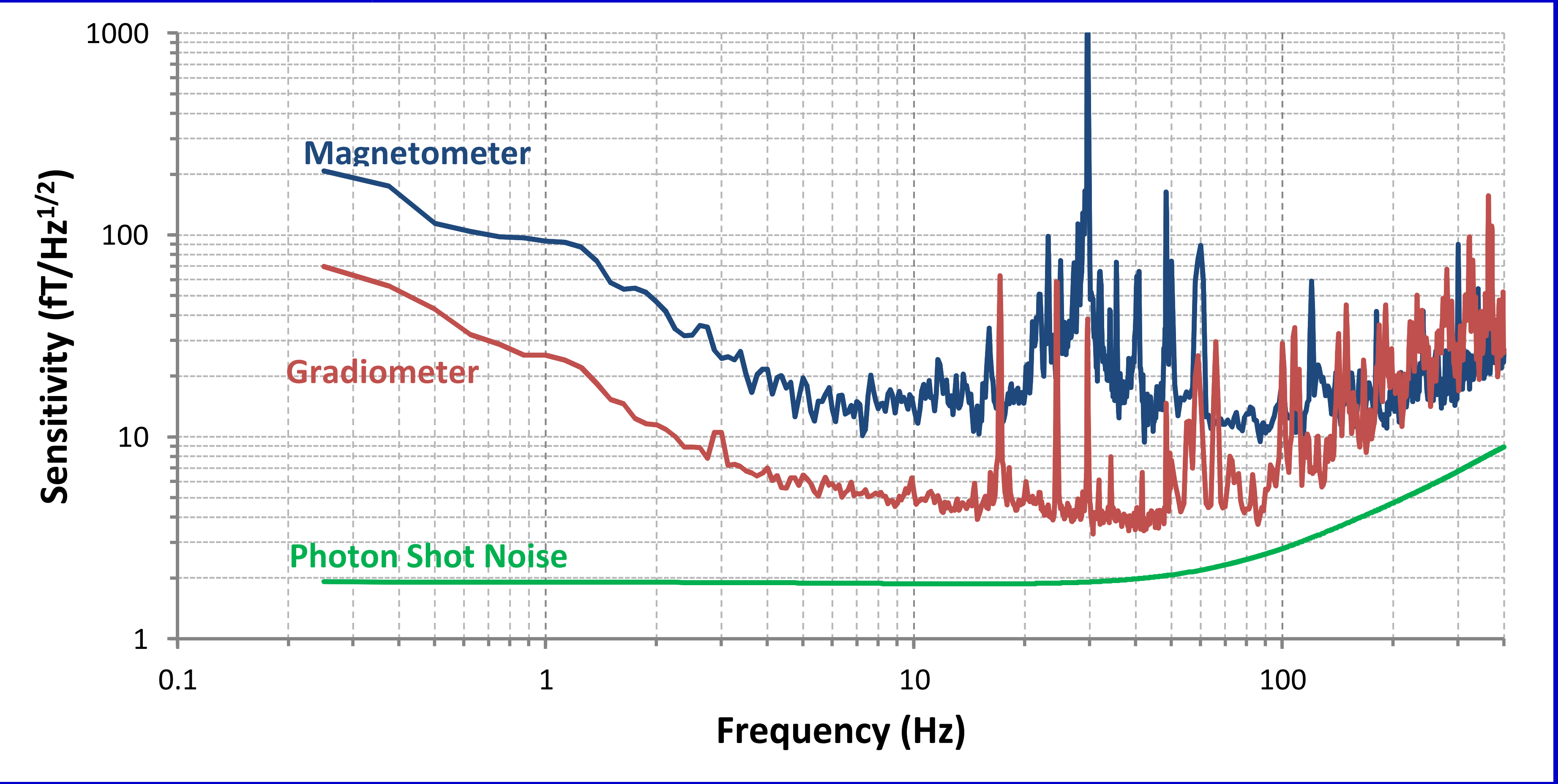
Bandwidth of All Channels



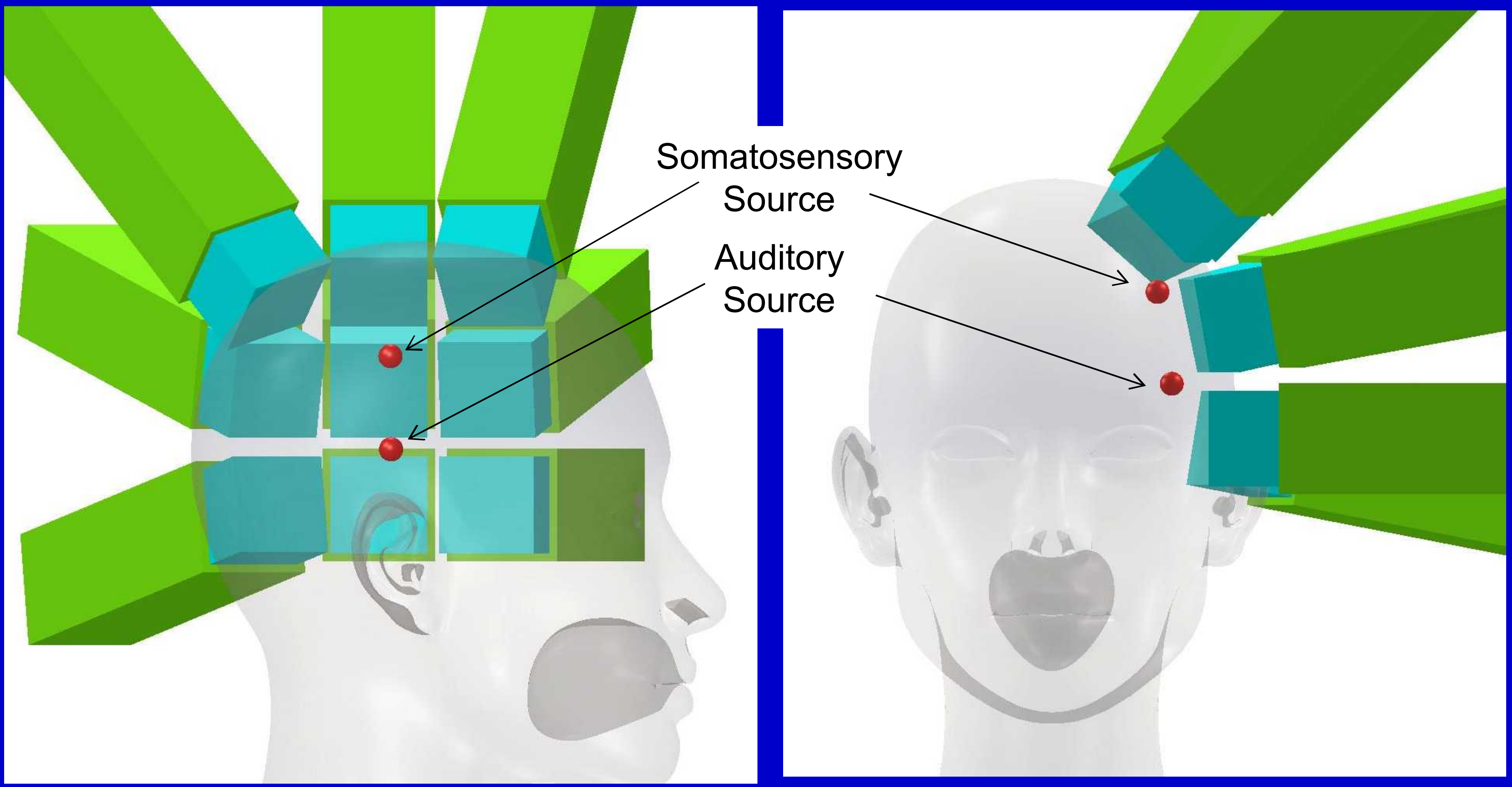
	Ch 1	Ch 2	Ch 3	Ch 4
3 dB Bandwidth	81 Hz	88 Hz	88 Hz	80 Hz

Gradiometer Performance

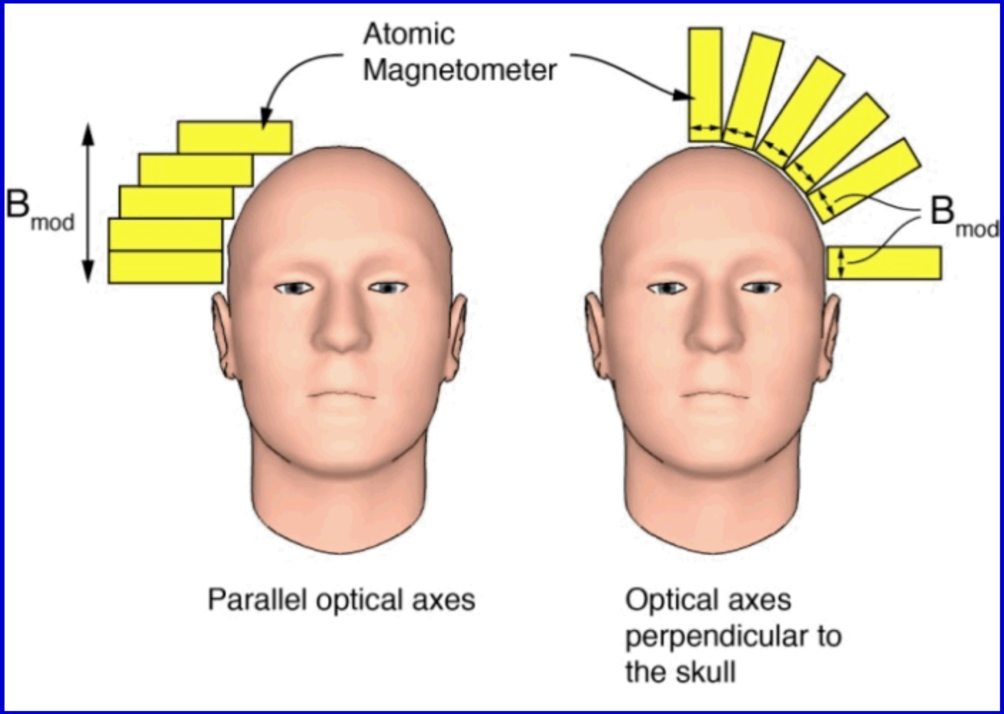


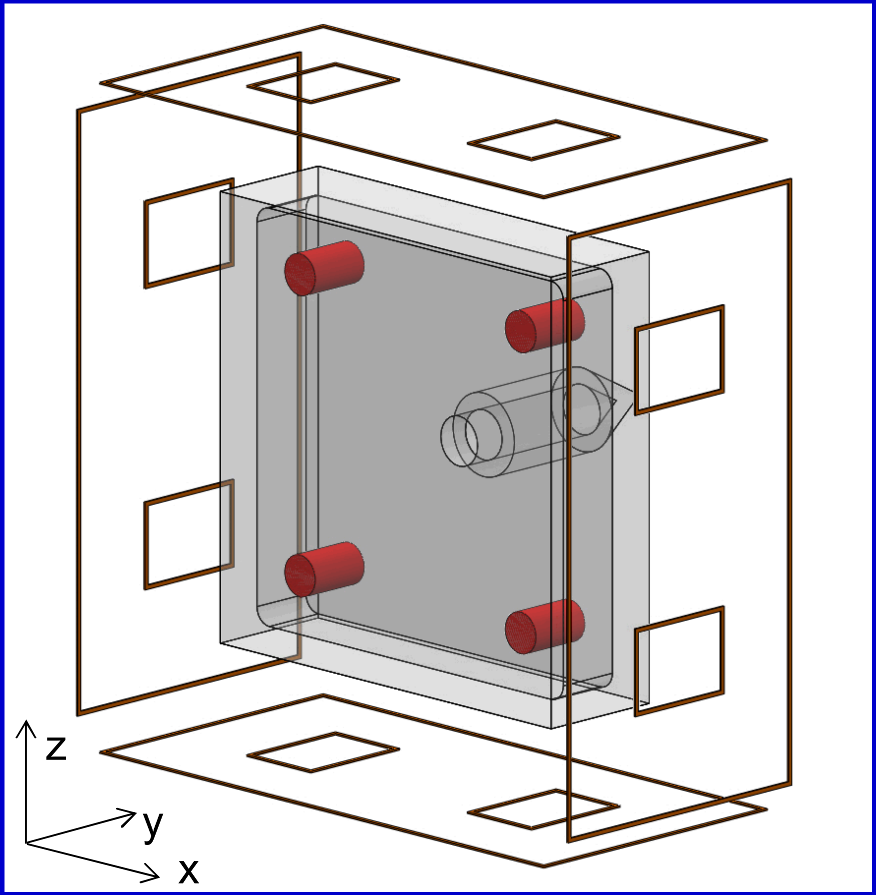
- Gradiometer: Channel 1 – Channel 3
- Noise floor below 10 fT/Hz$^{1/2}$ from 5-100 Hz
- Need to work on the technical noise sources

36-Channel Array on the Head



Field Modulation and Coils

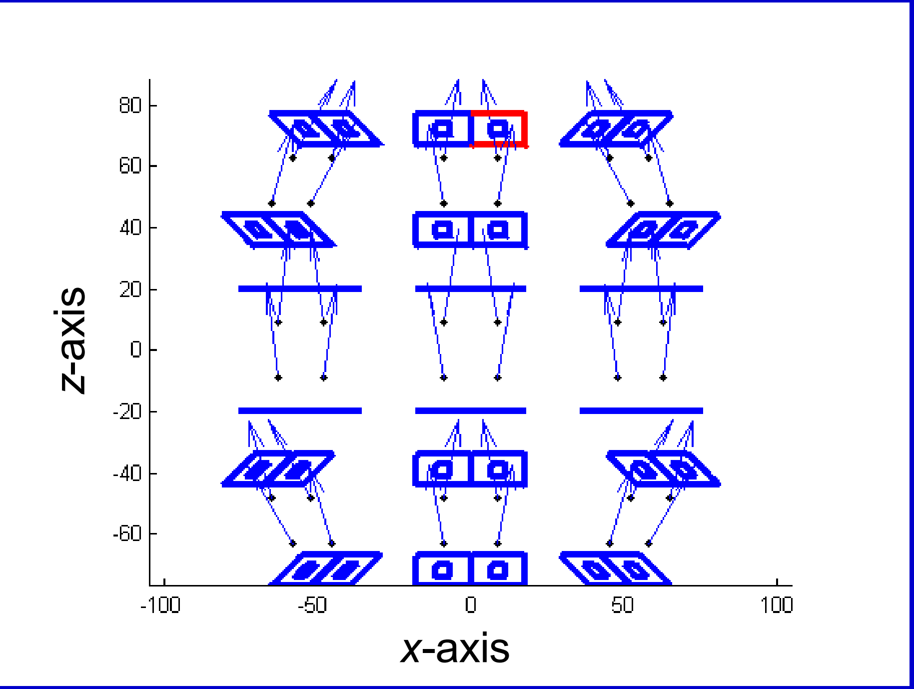


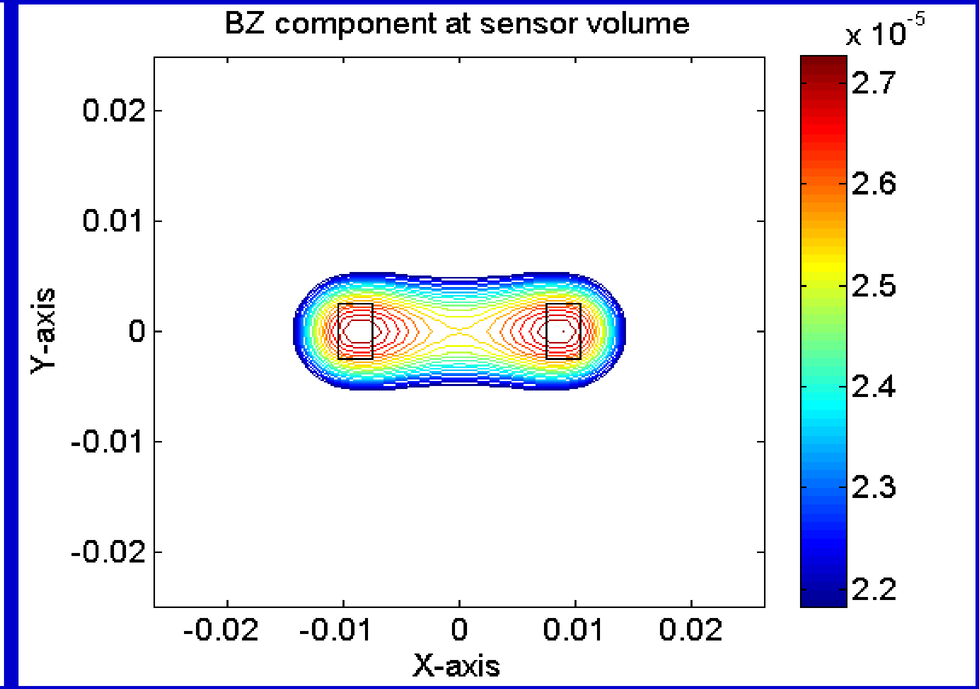


Outer coil 18 mm x 36 mm, Current = +1

Inner coils 5 mm x 7 mm, Current = +1,
offset from center is 9 mm

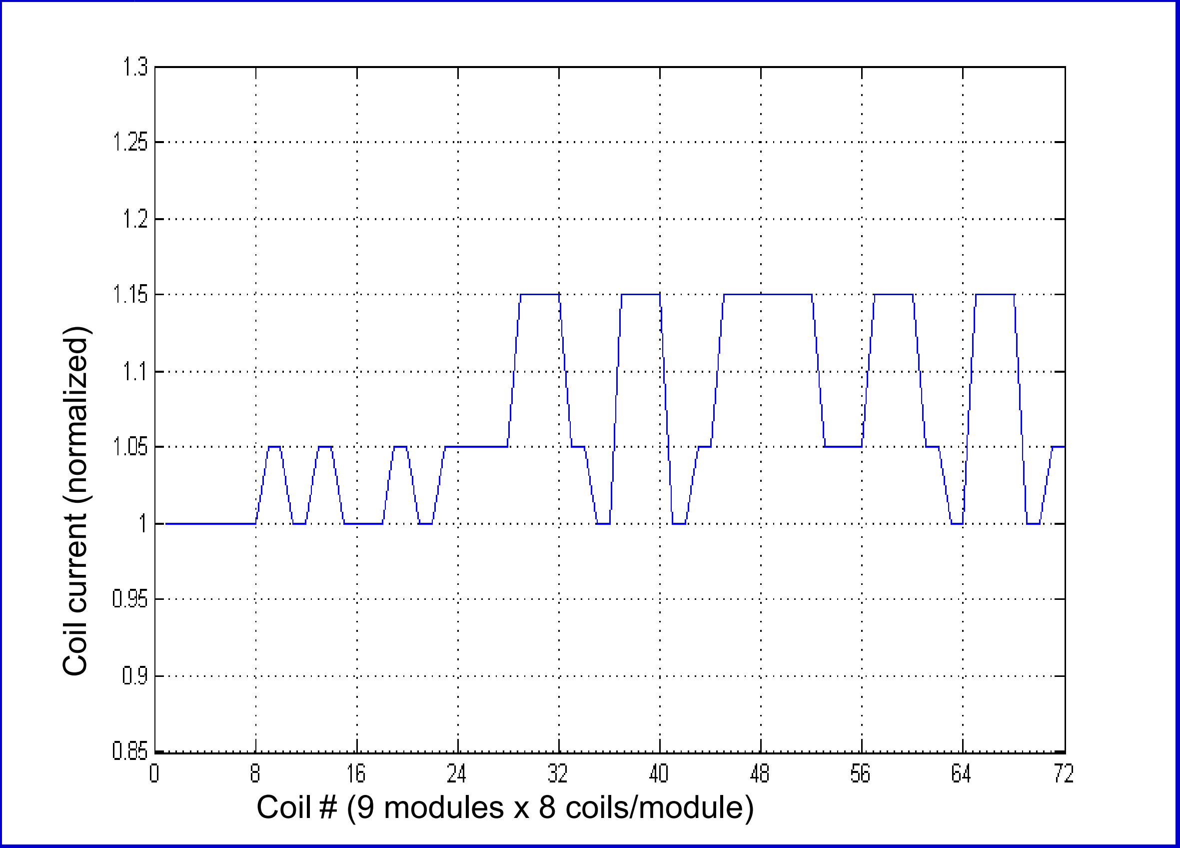
36-Sensor Array





- Field direction difficult to know exactly
- Will need to calibrate each sensor to know its measurement direction

Field Uniformity



- Calculate field at each magnetometer channel position in the array
  - Sensor module spacing = 68 mm
  - Perform optimization routine
- Optimization of current in 18 coils gives < 2 % variation

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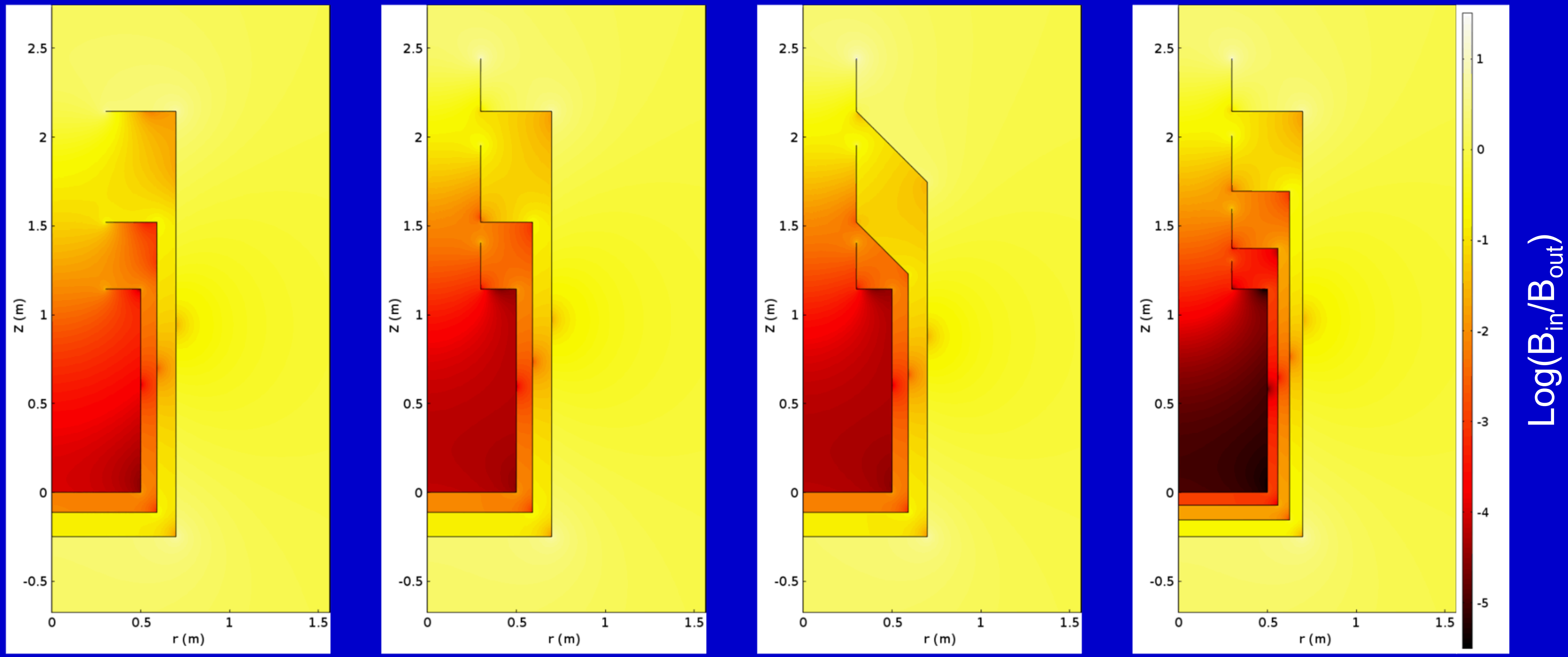
Magnetic Shield Modeling

3-Layer Cylinder | 3-Layer Cylinder with tubes | 3-Layer Cylinder with Chamfer | 4-Layer Cylinder with tubes



- Focused mainly on longitudinal shielding (transverse shielding much better)
- Asymmetric shield design with tubes leads to larger area of uniform field

- Permeability = 40,000
- Thickness = 1/16”

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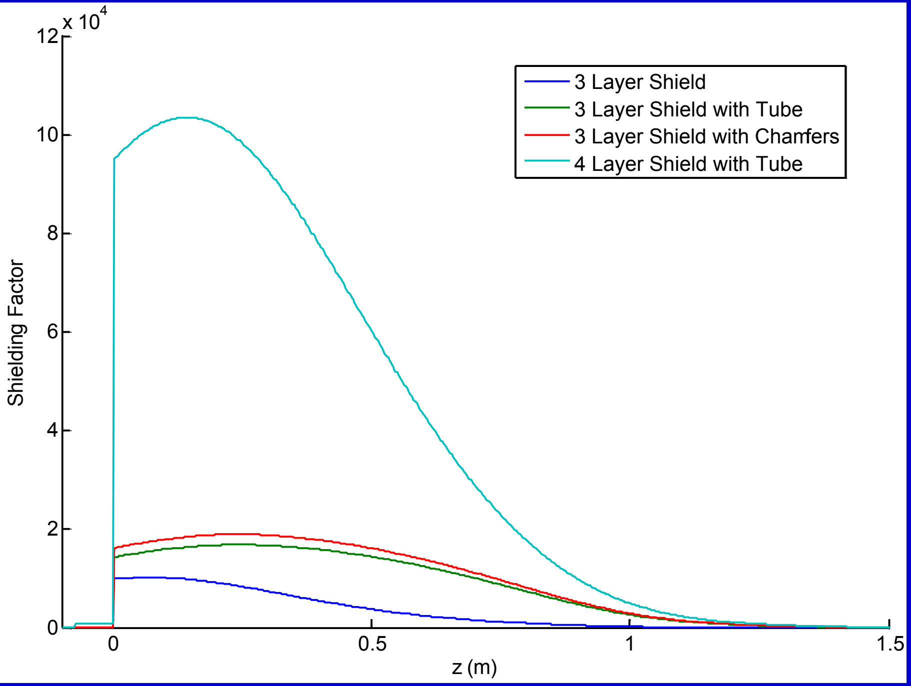
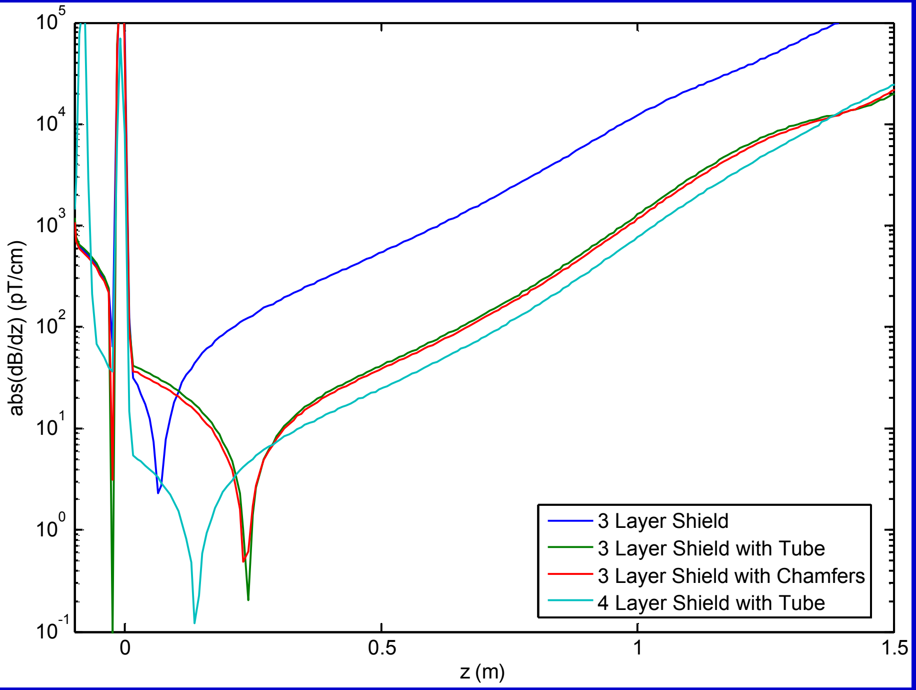
Longitudinal Field

Longitudinal Field



Longitudinal Field Gradient



- 4-layer performs better
- Gradient minimum closer to the center of the shield with 3-layer
- 3-layer is about $20k cheaper

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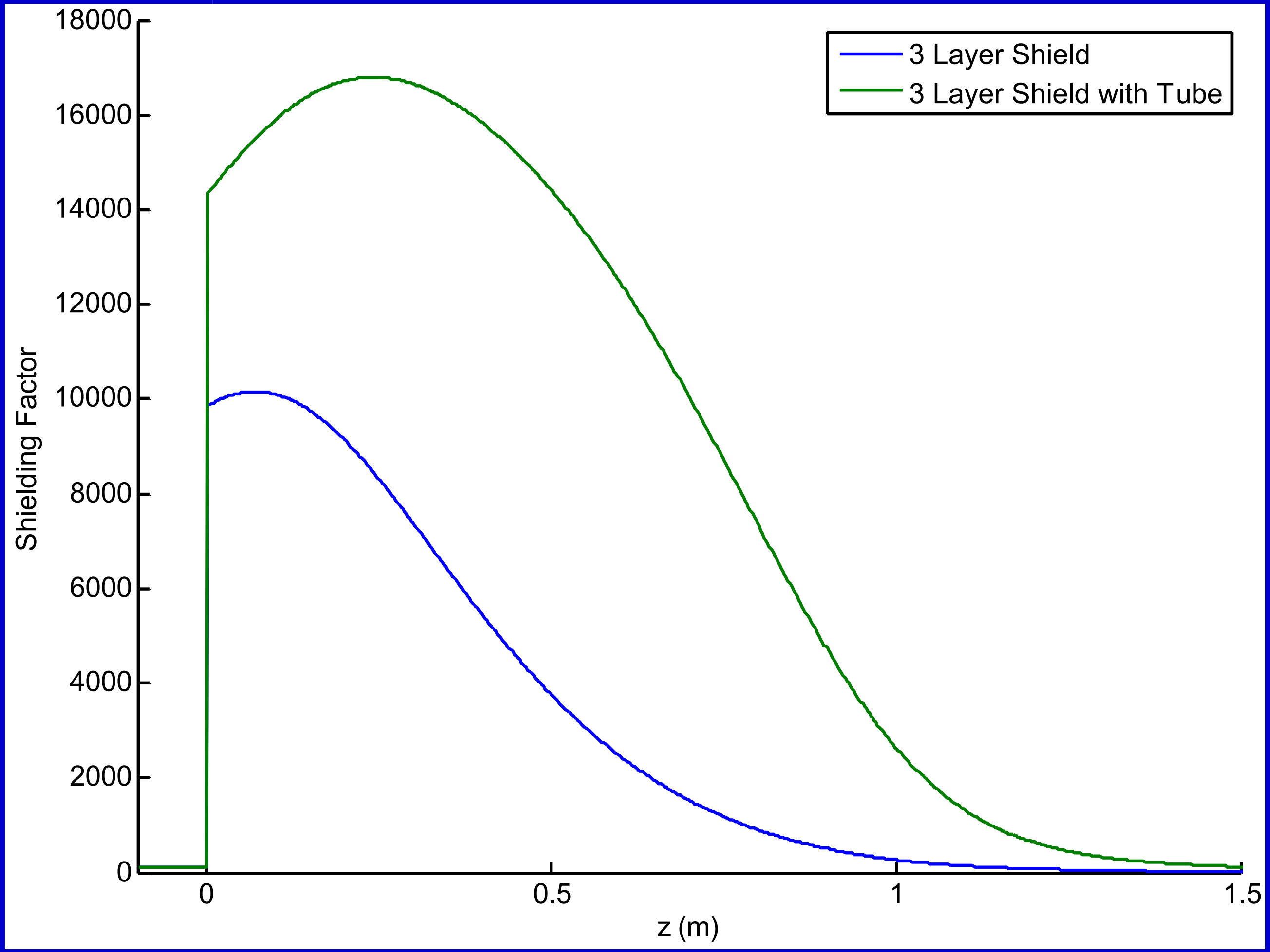
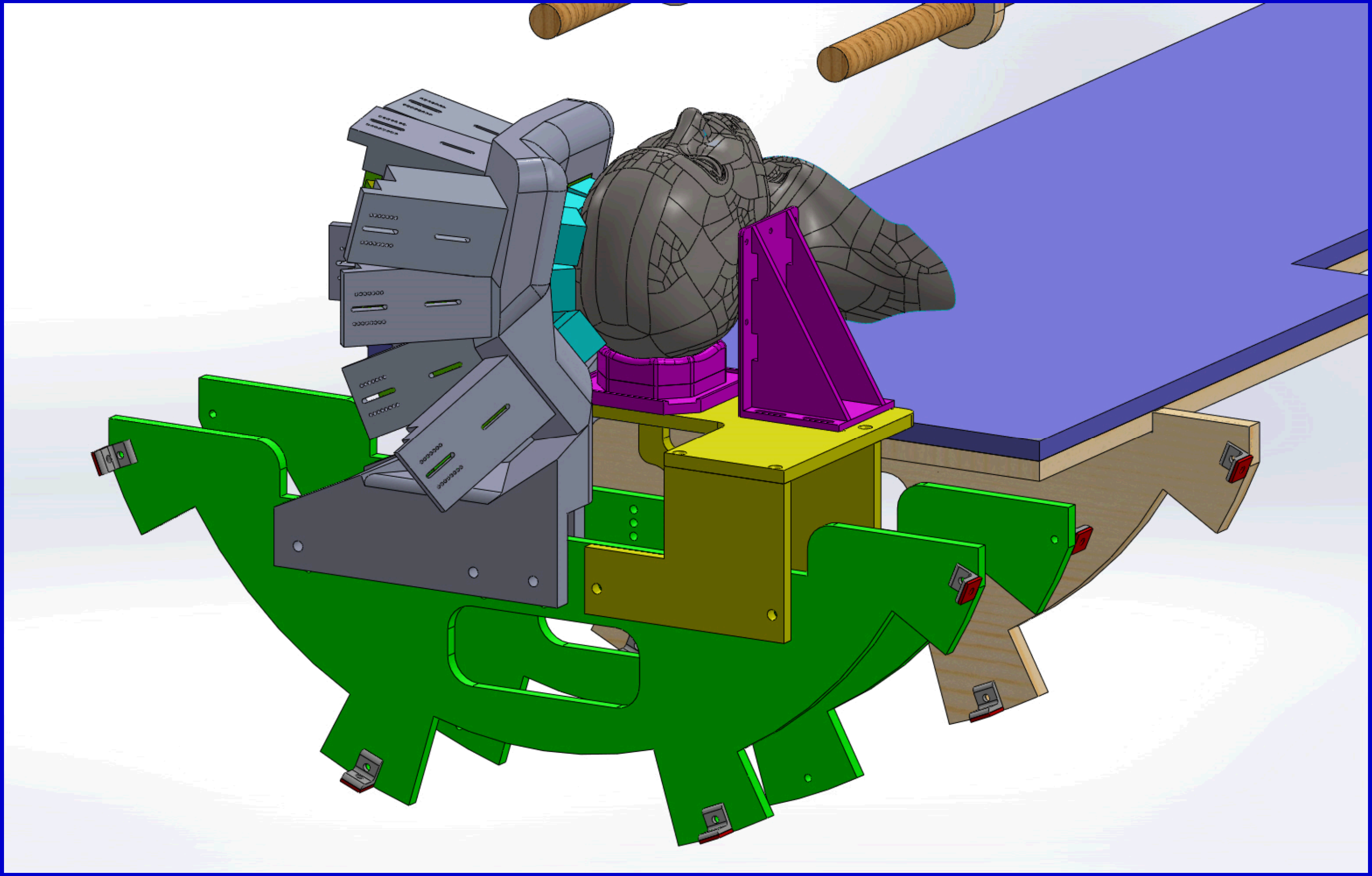
3-Layer Shields



- 3-layer shield with tube shielding factor = 17,000

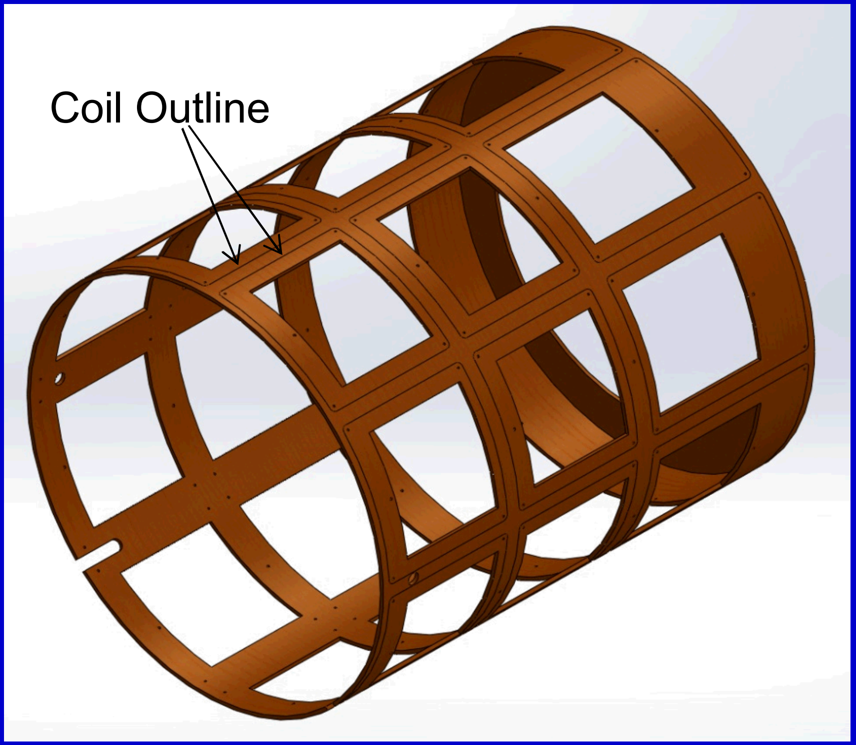


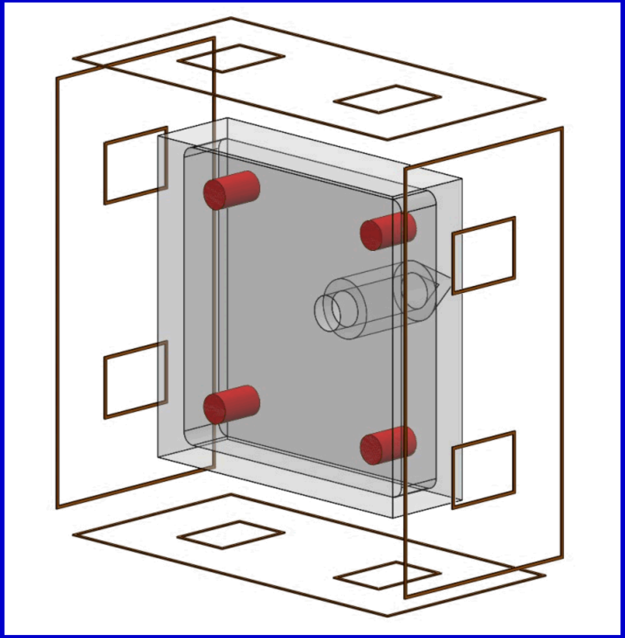

Solid Model of the MEG Array and Subject Support



Magnetic Field Control and Data Acquisition

Magnetic Field Control
- 63 coils to control
- 18 large coils *a la* Romalis
  - Homogenize the field across the array
  - Optimization using the sensor array
- 5 x 9 = 45 on-sensor coils
  - Mainly to provide modulation
- 96-channel analog output from National Instruments
  - Filtering with a custom buffer board





Data Acquisition
- Two 20-channel custom-built transimpedance amplifier (QuSpin)
- NI 48-channel 24-bit analog input card
  - Other channels for stimulation triggers, eye blink, and heartbeat monitor
- LabView software lock-in

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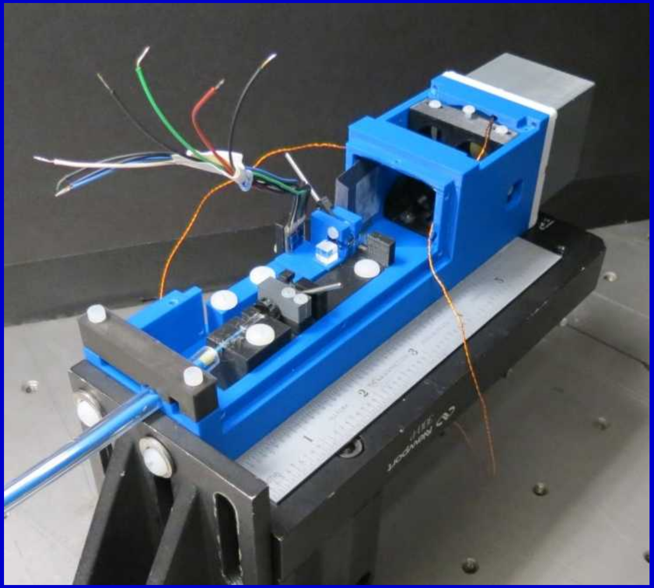
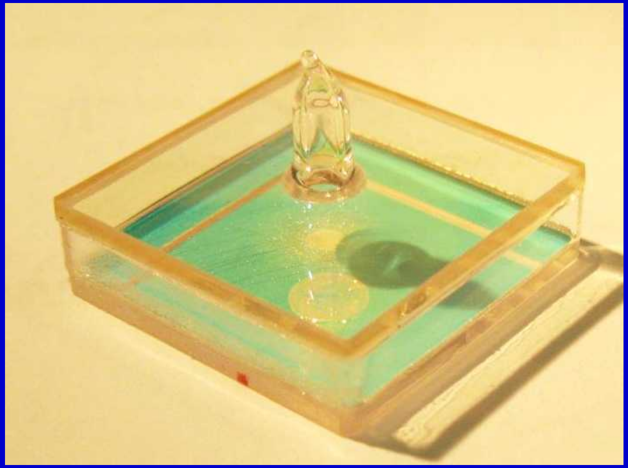
Conclusion

- Current status
  - Two functioning sensors
  - Magnetic shield installed
  - Big setbacks due to failing heaters and fused-silica cells.
- 2^{nd} generation sensor
  - Compact, 4-channel sensor design
  - 18 mm channel separation
  - 5 $fT/Hz^{1/2}$ sensitivity
- Future
  - Build more sensors and install in the shield
  - Implement electronic control of magnetic field
  - Measure humans





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Acknowledgements

- Sandia MEG Team: Peter Schwindt, Anthony Colombo, Yuan-Yu Jau, Tony Carter, Amber Dagel, Christopher Berry
  - Former Team Members: Cort Johnson, George Burns, Jon Bryan, Grant Biedermann, Michael Pack, Aaron Hankin
- Collaborators: Mike Weisend (Wright State Research Institute), Jim McKay (Candoo Systems), John Mosher (Cleveland Clinic), Bruce Fisch (UNM School of Medicine), Mind Research Network
- Funding:
  - LDRD – Laboratory Directed Research & Development
  - National Institutes of Health
  - NIBIB – National Institute of Biomedical Imaging and Bioengineering

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Backup

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What's ***truly*** non-magnetic?

Adhesive	Magnetism
Epo-Tek H74	0.5 – 1 nT (3 batches tested)
Epo-Tek H70E	Similar to H74
Epo-Tek 930-4 (0.6 g)	12 pT (3 pT after demagnetization)
Epo-Tek 353ND	None detected
Hysol EccoBond 104	> 10 pT
Ceramabond 865	> 150 pT
Resbond 940HT	> 500 pT
Super glue from the store	None detected
Kapton tape	None detected

Tested 0.5 – 1 g of most adhesives
Samples placed approximately 1 – 2 cm from the magnetically sensitive volume

What's ***truly*** non-magnetic?

Insulation	Magnetism
Aerogel blanket (Pyrogel 2250), 25 mm x 10 mm x 3 mm section	> 50 pT (2 batches tested)
Zircar Microsil …and the paint coating that goes with it	None detected > 80 pT
Polyimide blanket (Pyropel MD)	None detected

Other components	Magnetism
Type E thermocouple	None detected, Magnetizable to > 70 pT
Hirose DF13 electrical connectors, tin pins	None detected
Nail polish from Costco	None detected
Flex circuit material (unpatterned, ~2 cm^2), Pyralux AP 8515R	2-4 pT, (Material from other companies much more magnetic)

Samples placed approximately 1 – 2 cm from the magnetically sensitive volume

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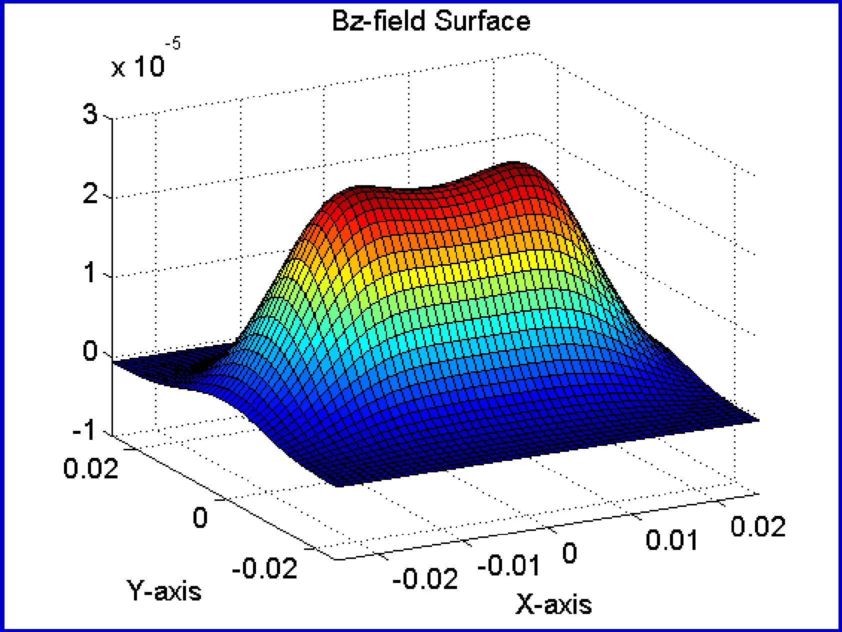
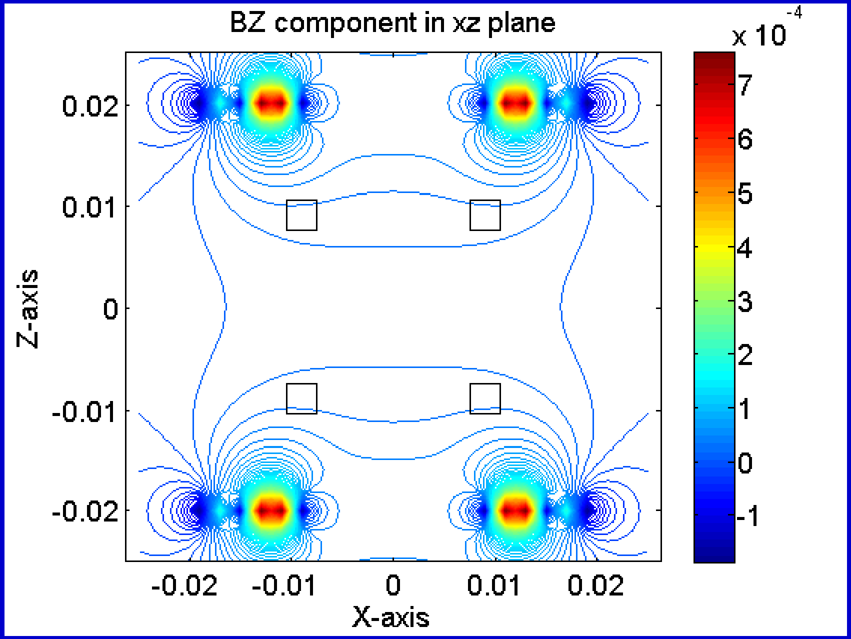
Field of the Modulation Coils

x-y plane through two sensor volumes



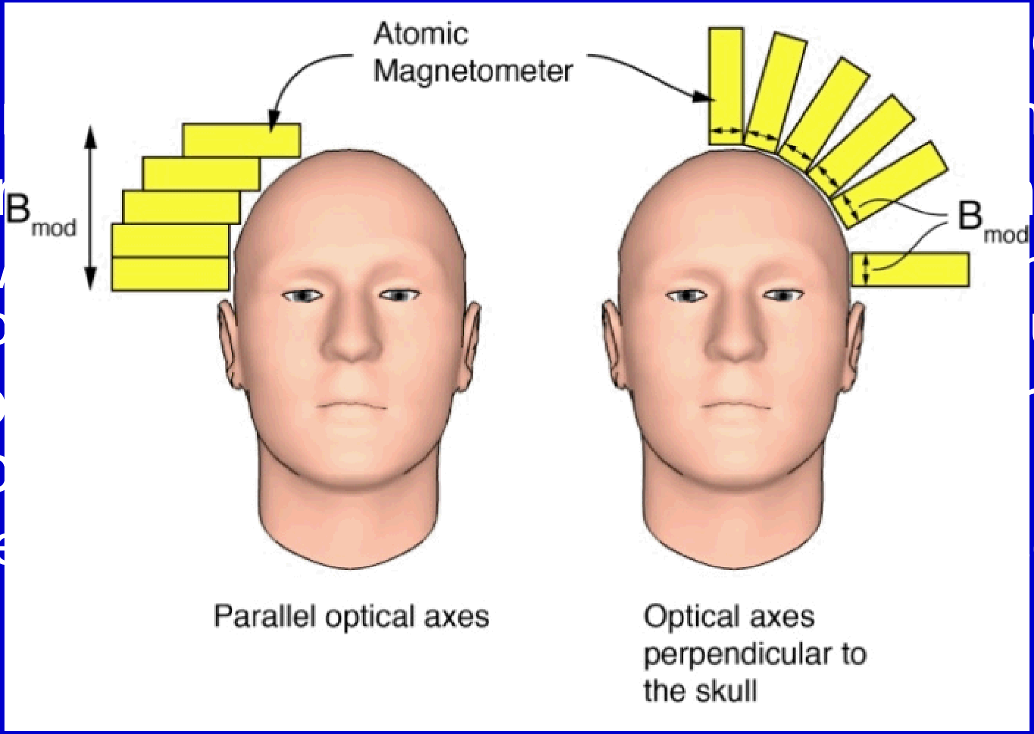
x-z plane



Gradient through the sensor area in the x-z plane
Delta Bx is 14%
Delta Bz is 24%

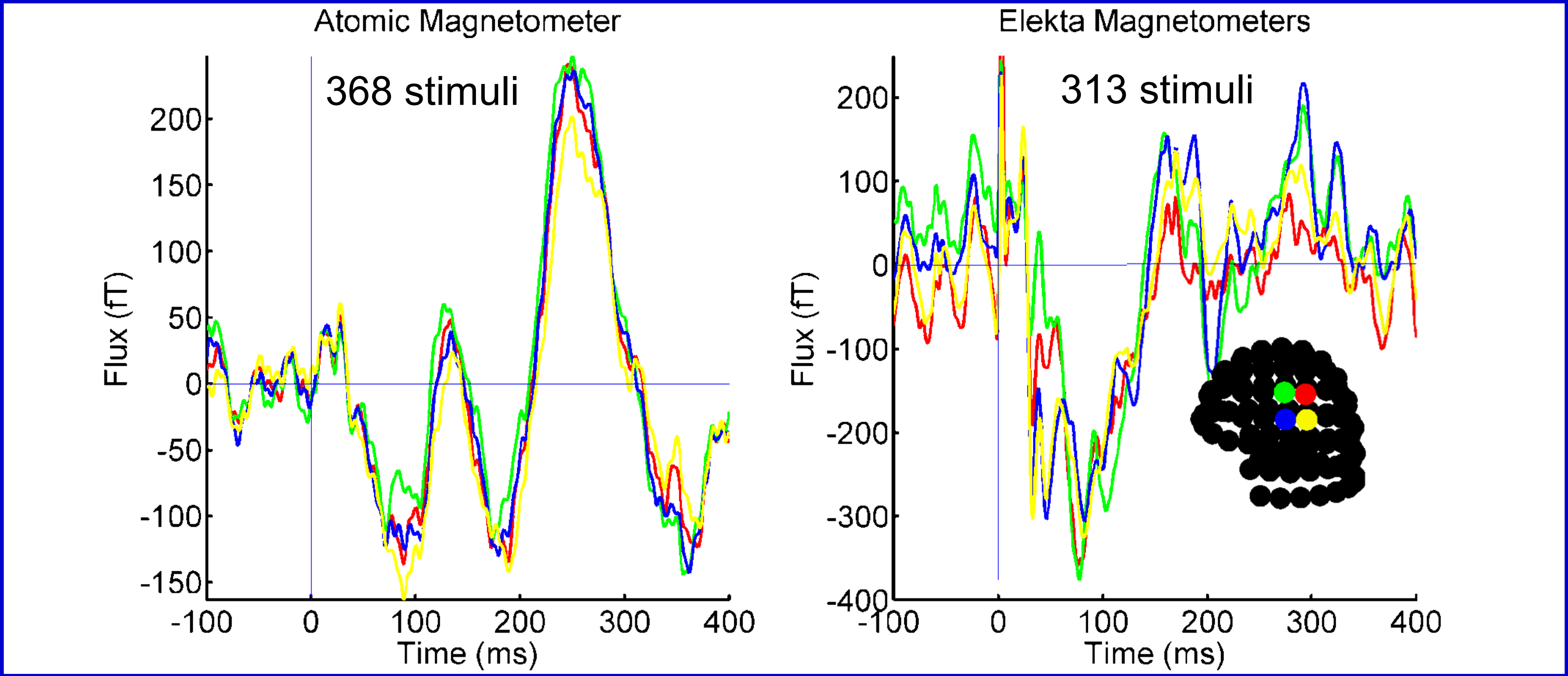
NIH Project: Major Tasks

1. Redesign, miniaturize sensor (4 cm X 4 cm)
   - <10 fT/Hz$^{1/2}$, >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 … geometry
   - Brai… modeling
5. Constr… phantom
   - How… nd know pred… ured?
6. Audito… human subjec…
   - Core… on



Comparison of the Atomic Magnetometer to the SQUIDs

Median Nerve Stimulation

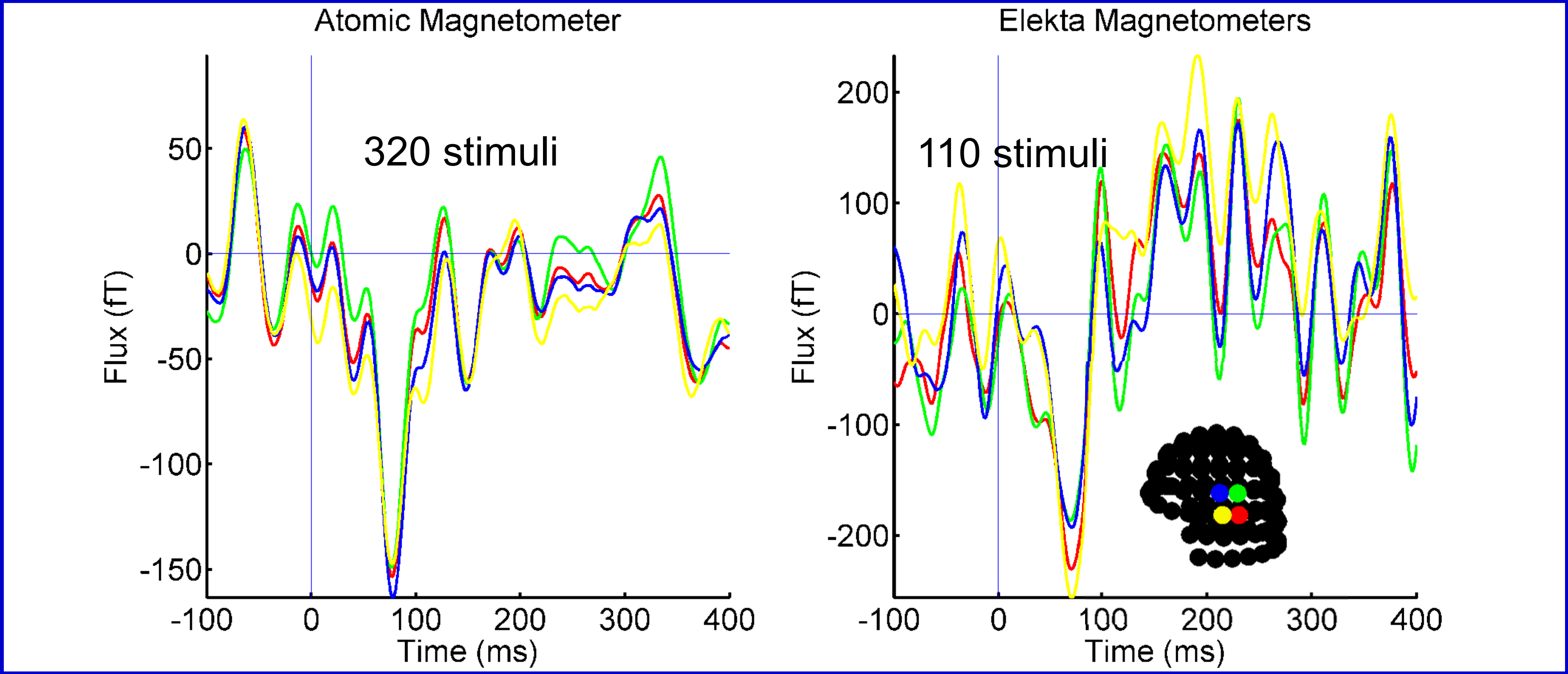


Stimulate Median Nerve, measure evoked response in somatosensory cortex

Cort Johnson, Peter D. D. Schwindt, and Michael Weisend,
Appl. Phys. Lett. 97, 243703 (2010)

Comparison of the Atomic Magnetometer to the SQUIDs

Auditory Stimulation



- Present 1000 Hz tones in both ears, measure evoked response in auditory cortex
- Expected signal at ~100 ms is present in AM and SQUID data

Cort Johnson, Peter D. D. Schwindt, and Michael Weisend, Appl. Phys. Lett. 97, 243703 (2010)

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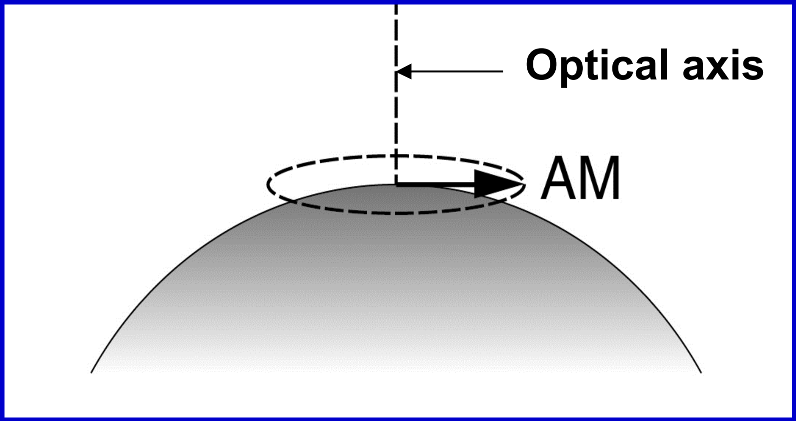
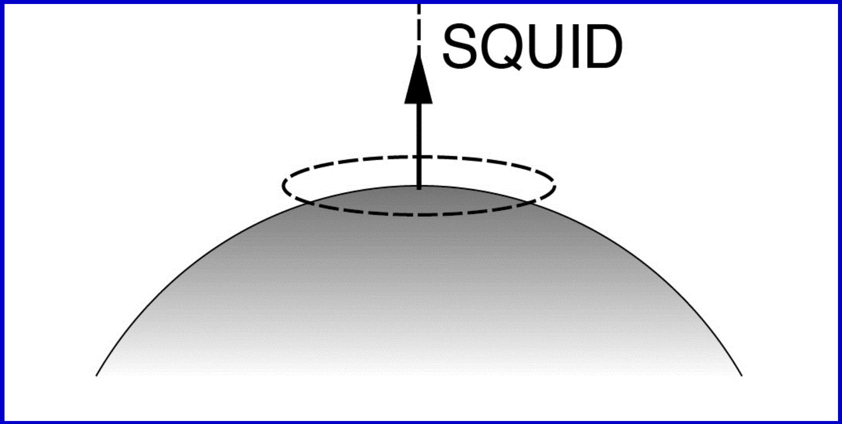
AM vs SQUID

SQUID and AM signals are not identical. Why?

AMs measure fields parallel to scalp (optical axis perpendicular to scalp)



SQUIDs measure fields perpendicular to scalp (coils are parallel to scalp)



- Magnetometer channel separation: ~5mm
- SQUID channel separation: ~30 mm
- Different bandwidth (AM: ~20 Hz, SQUID: ~ kHz)

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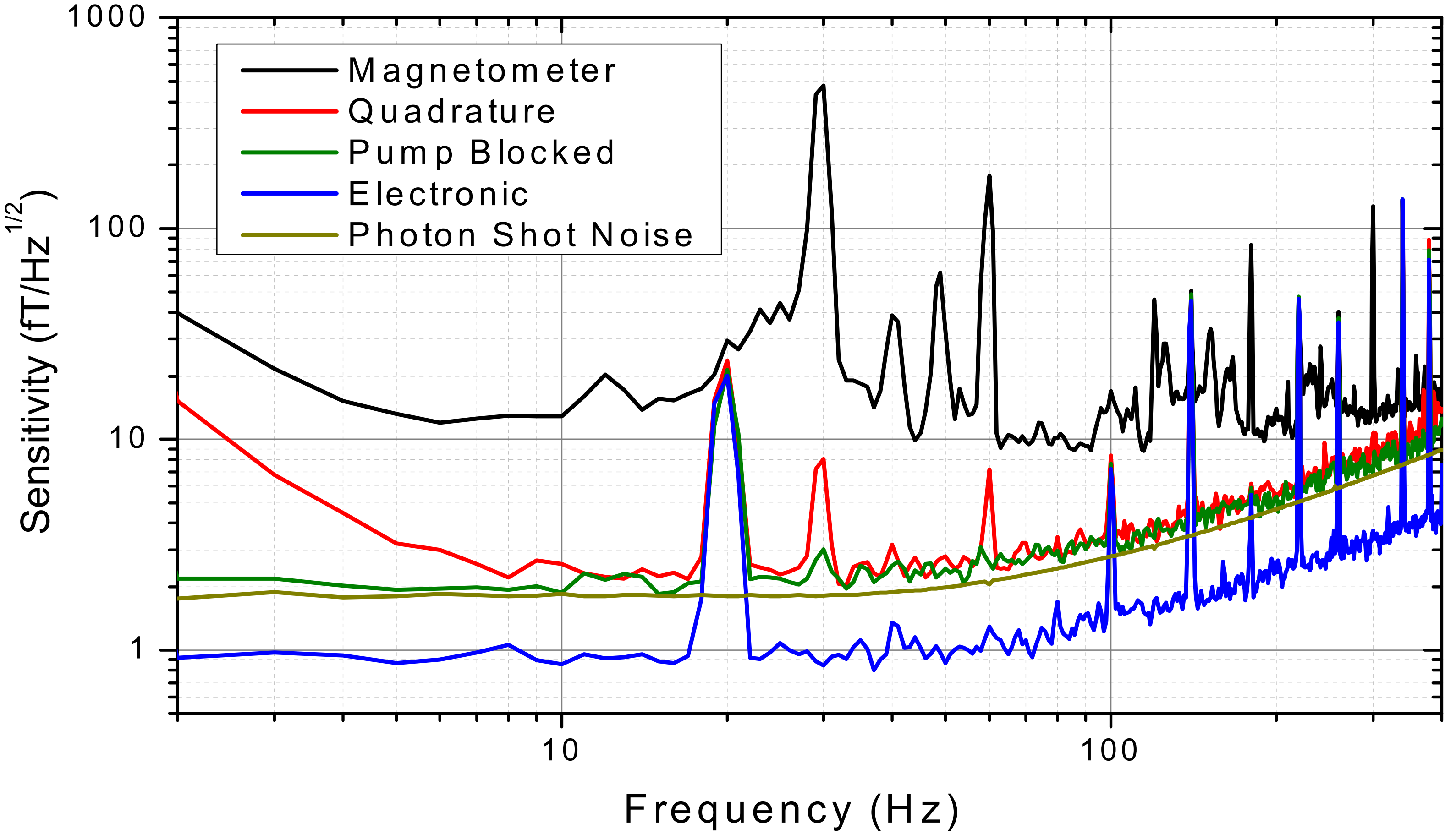
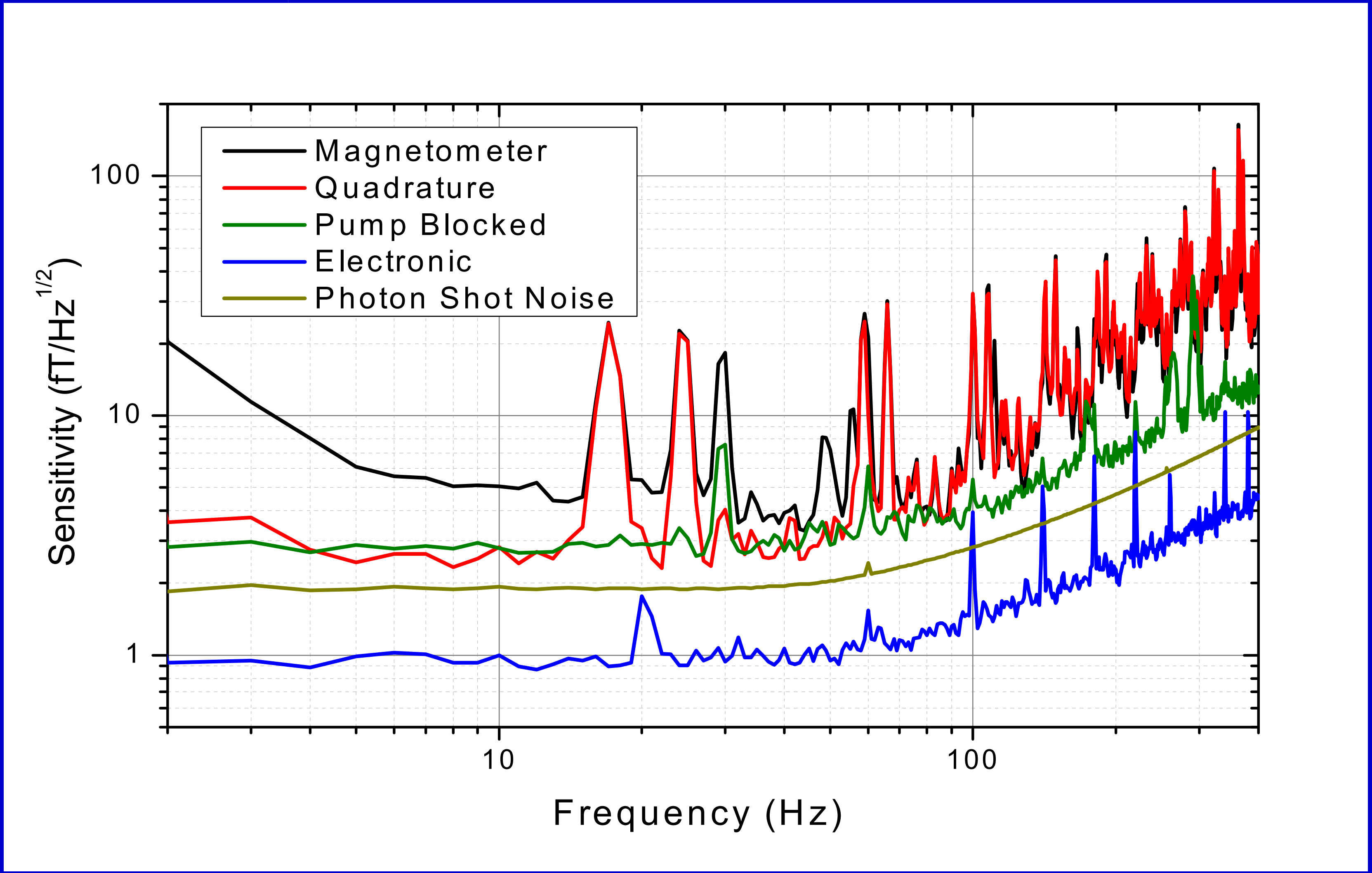
Channel 1 Performance



Gradiometer: Channel 1 – Channel 3



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