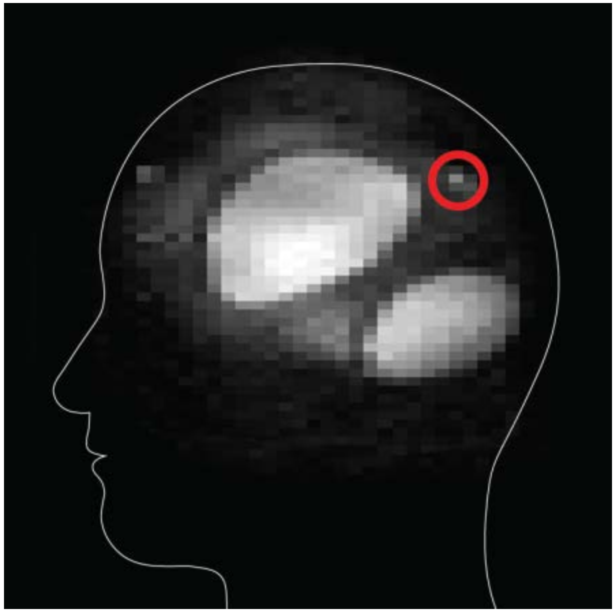
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2015.
Contributed presentation SQ-O08 given at ISEC 2015, Nagoya, Japan, July 6 – 9, 2015.

Multi-channel SQUID-based Ultra-Low Field Magnetic Resonance Imaging in Unshielded Environment



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Motivation

Magnetic Resonance Imaging (MRI):

- best method for non-invasive imaging of soft tissue anatomy
- saves countless lives each year

Conventional (high-field) MRI:

- only in large well-funded medical centers
- is not available in rural settings
- is not deployable to emergency situations or battlefield hospitals

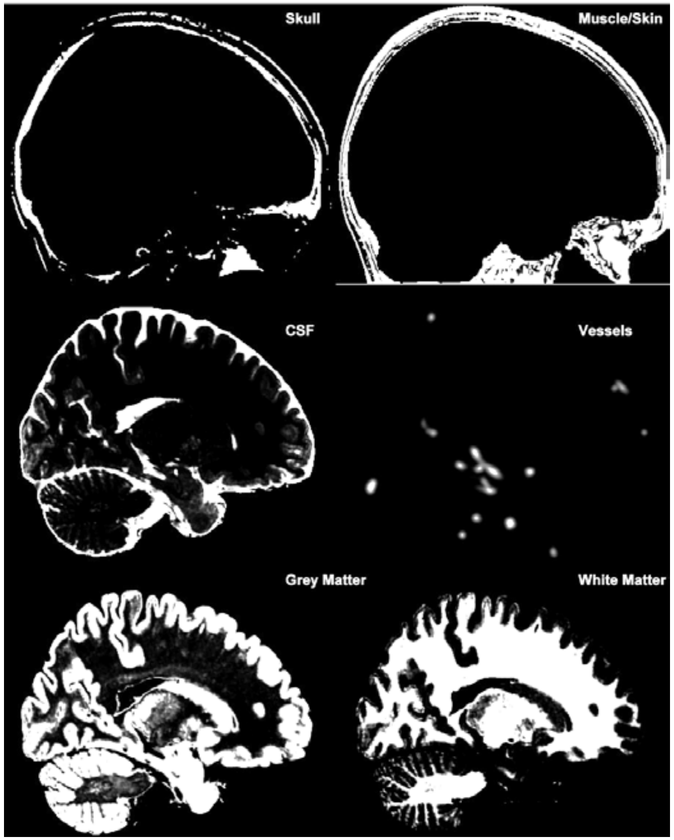
Ultra-low field (ULF) MRI

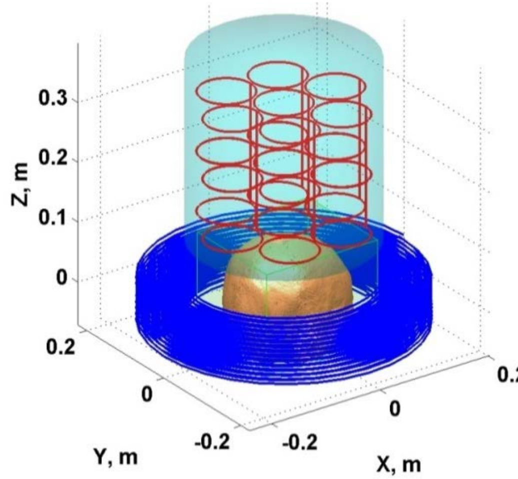
- pulsed pre-polarization at < 0.3 T
- sensitive Superconducting Quantum Interference Device (SQUID) detection
- greatly relaxed measurement field homogeneity
- presence of metal is not an issue
- can be light and made portable

Outline

- **Model: How accurate can we simulate ULF MR Images?**
  - MATLAB model
  - SNR and Resolution
  - How close is our model to reality?
- **Highly Shielded ULF MRI System**
- **Unshielded ULF MRI System**
  - Unshielded ULF MRI of a Gelatin-Agar Phantom
  - Noise Compensation at 8.6 kHz Larmor frequency
- **Summary**

Modeling (McGill University Model)





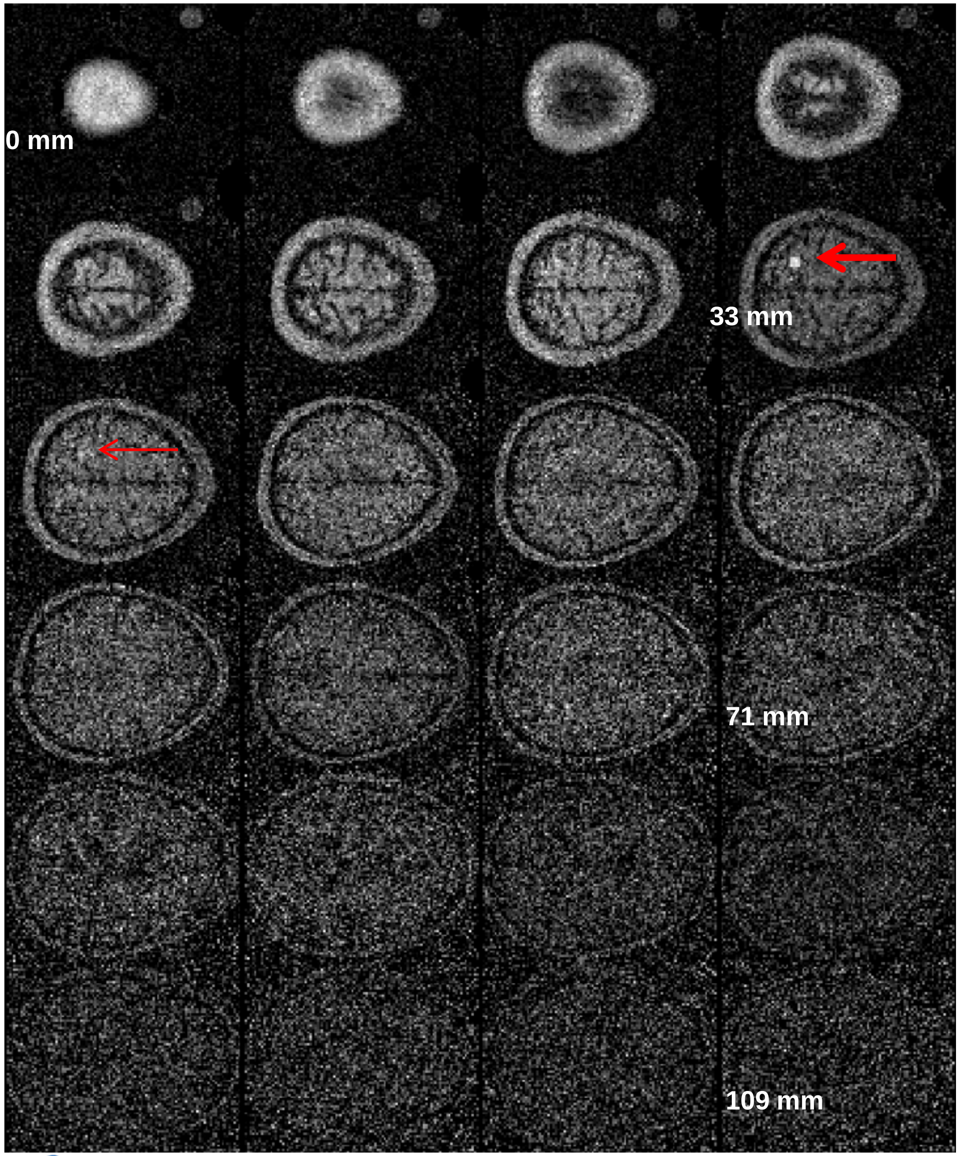
- **A MATLAB model of the geometry**
- **Reciprocity to model NMR signals; Bloch equations;**
- **Realistic digital brain model of anatomy**

Eleven high-resolution (0.5x0.5x0.5 mm) volumes describing content of a voxel

	Tissue name	PD	T_1 (ms)	T_2 (ms)
1	CSF	1	4360	329
2	GREY MATTER	0.86	635	83
3	WHITE MATTER	0.77	360	70
4	FAT	1	350	70
5	MUSCLE	1	120	47
6	MUSCLE/SKIN	1	120	47
7	SKULL	0	0	0
8	VESSELS	0	0	0
9	CONNECTIVE	0.77	500	61
10	DURA MATTER	1	2569	329
11	BONE MARROW	0.77	500	70

McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University
B Aubert-Broche, AC Evans, and DL Collins, "A new improved version of the realistic digital brain phantom," NeuroImage, vol. 32, no. 1, pp. 138–45, 2006.

Modeling: SNR and Resolution



Imaging parameters:

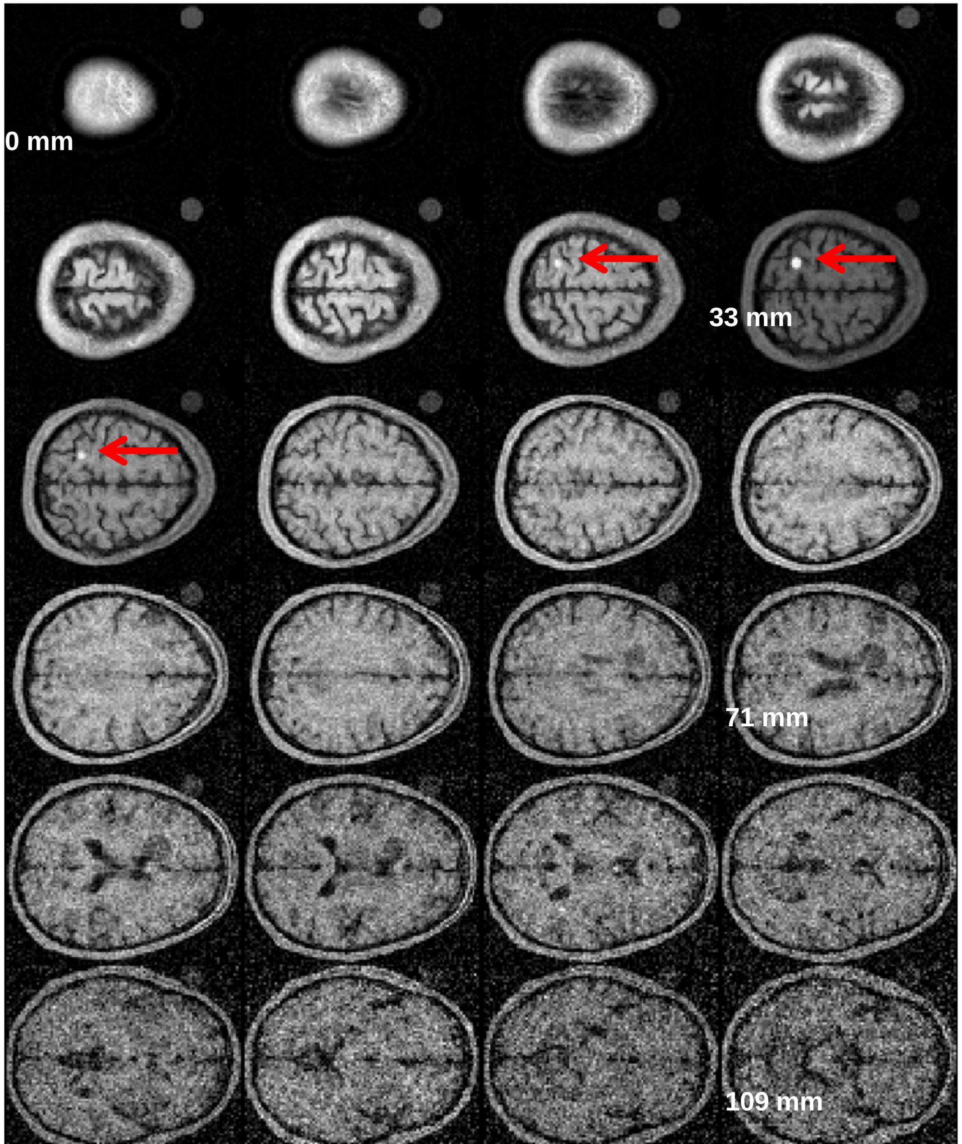
Polarization Field: 100 mT

Polarization inversion time:	750 ms
Polarization time:	750 ms
Delay time:	10 ms
Encoding time:	35 ms
Acquisition time:	70 ms
N_y (phase):	103
N_z (phase):	41
Readout gradient, G_x:	7.00 Hz/mm
Phase gradient, G_y:	7.00 Hz/mm
Phase gradient, G_z:	3.00 Hz/mm
Voxel size:	2.04 × 2.04 × 4.76 mm^3
Total imaging time:	106.5 minutes

Noise, 1.80 $fT/Hz^{1/2}$

O ← 1 cm^3 blood inclusion

Modeling: SNR and Resolution



Imaging parameters:

Polarization Field: 250 mT

Polarization inversion time:	**750 ms**
Polarization time:	**750 ms**
Delay time:	**10 ms**
Encoding time:	**35 ms**
Acquisition time:	**70 ms**
N_y (phase):	**103**
N_z (phase):	**41**
Readout gradient, G_x:	**7.00 Hz/mm**
Phase gradient, G_y:	**7.00 Hz/mm**
Phase gradient, G_z:	**3.00 Hz/mm**
Voxel size:	**2.04 × 2.04 × 4.76 mm^3**
Total imaging time:	**106.5 minutes**

Noise, 0.90 fT/Hz$^{1/2}$

O ← 1 cm^3 blood inclusion

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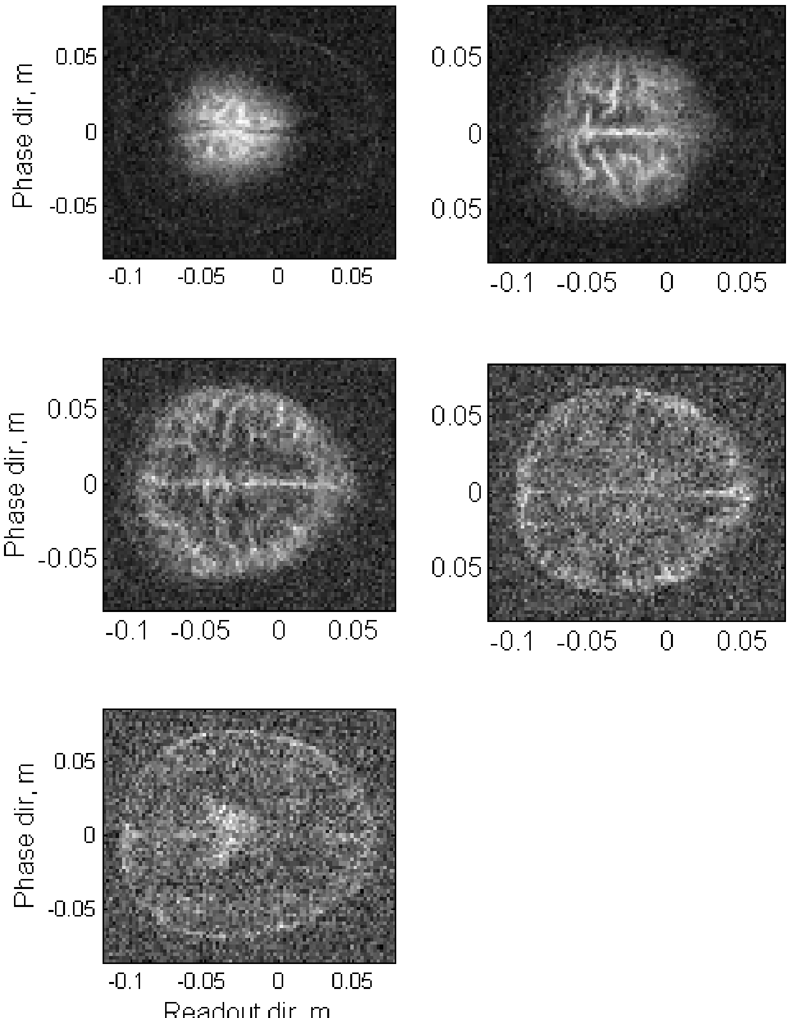
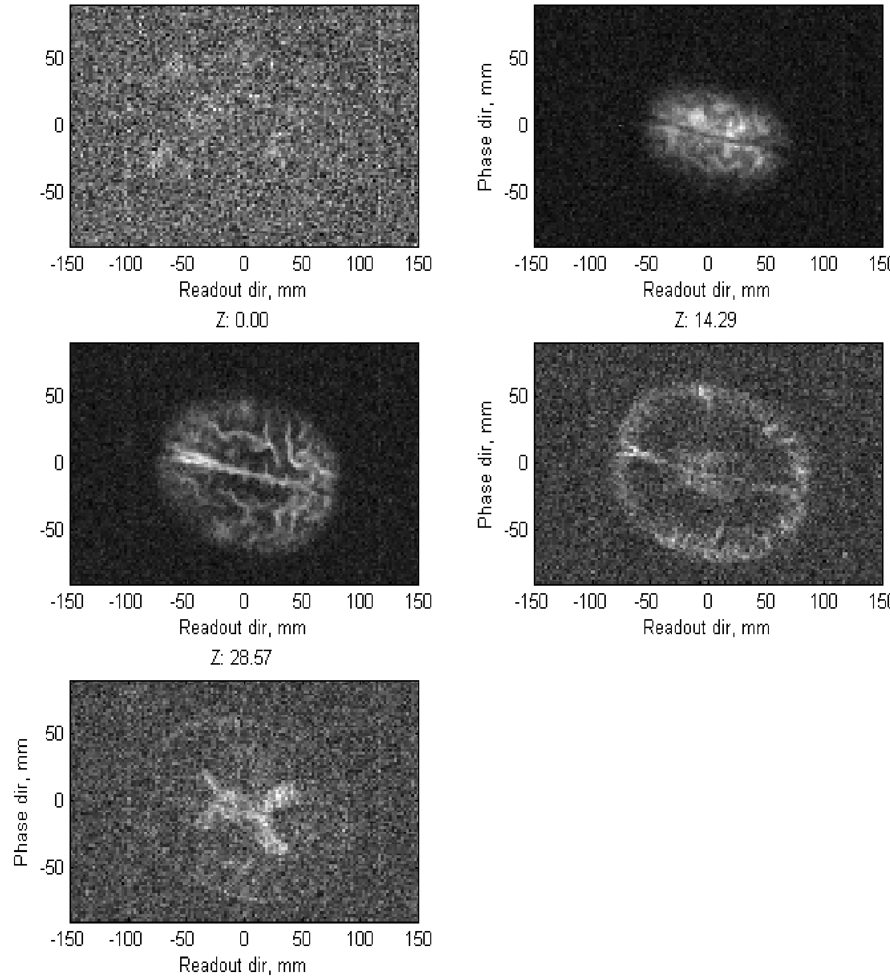
How Good is Our Modeling

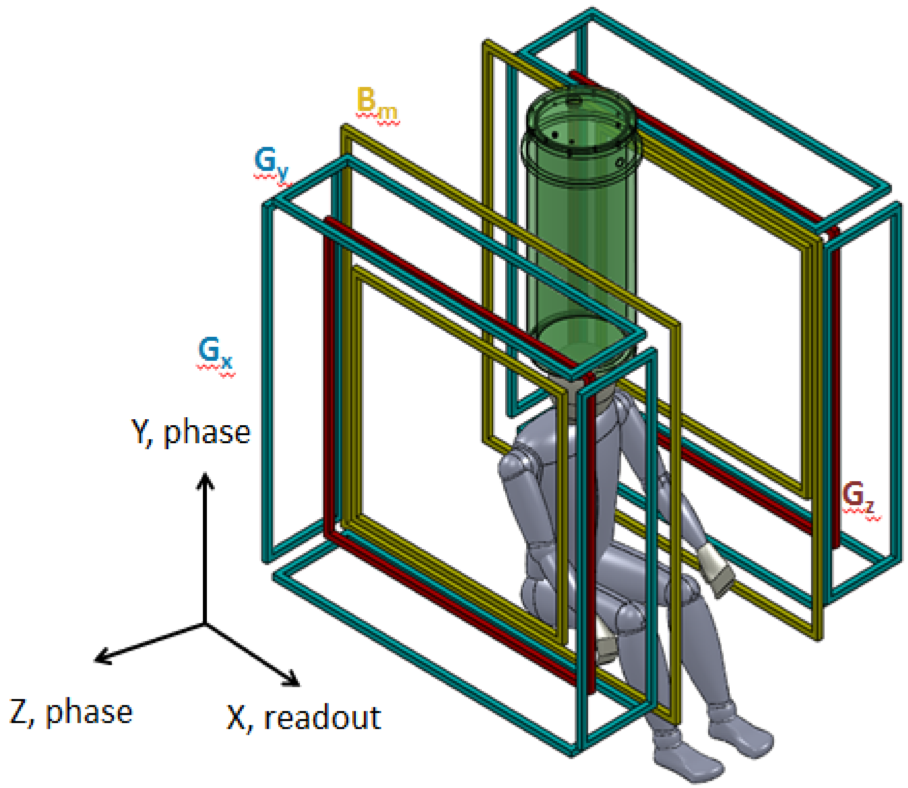


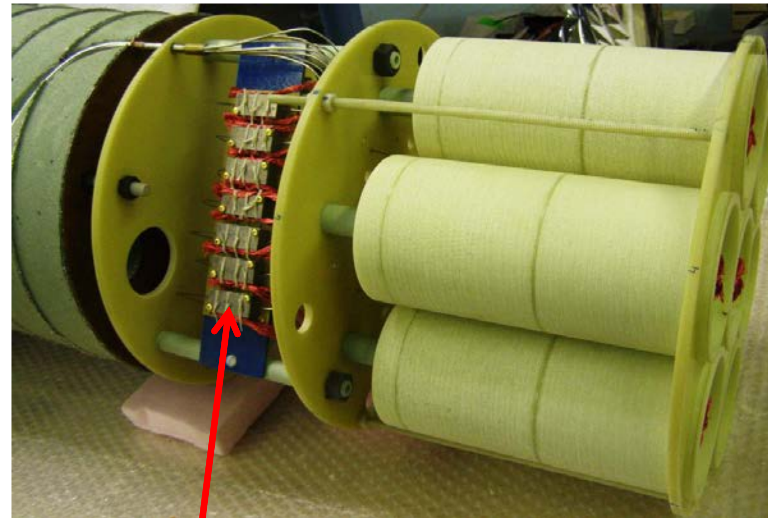
Model



Reality: MRI inside MSR

Shielded ULF MRI System & LANL





Lead-Bismuth alloy SQUID shields

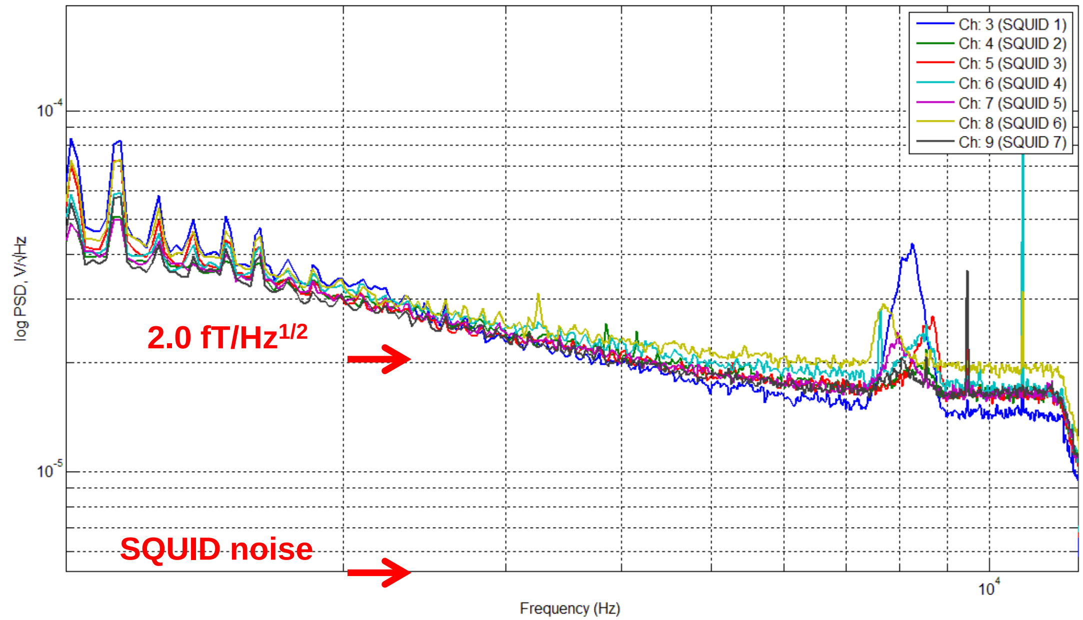
2-layer Magnetically shielded Room, *S* = 1000 at 1 Hz

Ø 90 mm second-order gradiometers, $N = 0.4 \times 10^{-15}$ T/Hz$^{1/2}$
Pre-polarizing Field: 100 mT
Larmor Frequency: 8.3 kHz

Gradients	
Phase encoding, G_y	47.6 µT/m (2 Hz/mm) @ 5.3 A
Phase encoding, G_z	221.7 µT/m (9 Hz/mm) @ 10.8A
Readout, G_x	248 µT/m (11 Hz/mm) @ 25.5 A

Michelle A. Espy *at al.* "Progress toward a deployable SQUID-based ultra-low field MRI system for anatomical imaging." ." *IEEE Transactions on Applied Superconductivity*, VOL. 25, NO. 3, (JUNE 2015) 1601705

Shielded ULF MRI System & LANL



Copper coil (Litz wire)

Liquid Nitrogen cooling

0.5 Ohm at 75K, 3 Ohm at RT
***L*= 0.19 H**

B_P = 100 mT at 100 A

J. R. Sims *at al.* "Low-Noise Pulsed Pre-Polarization Magnet Systems for Ultra-Low Field NMR." *IEEE Trans. on Appl. Supercond,*, Vol. 20, No. 3, p.752 (2010)

Michelle A. Espy *at al.* "Progress toward a deployable SQUID-based ultra-low field MRI system for anatomical imaging." ." *IEEE Transactions on Applied Superconductivity*, VOL. 25, NO. 3, (JUNE 2015) 1601705

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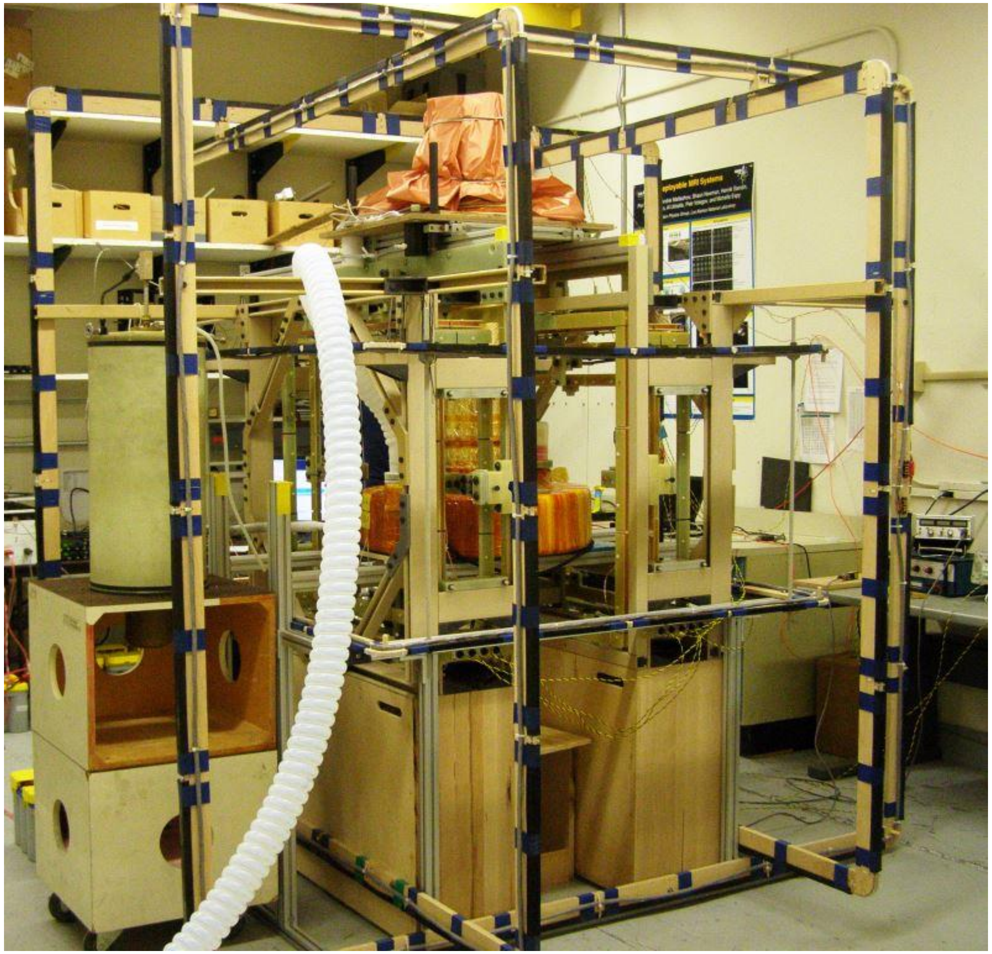
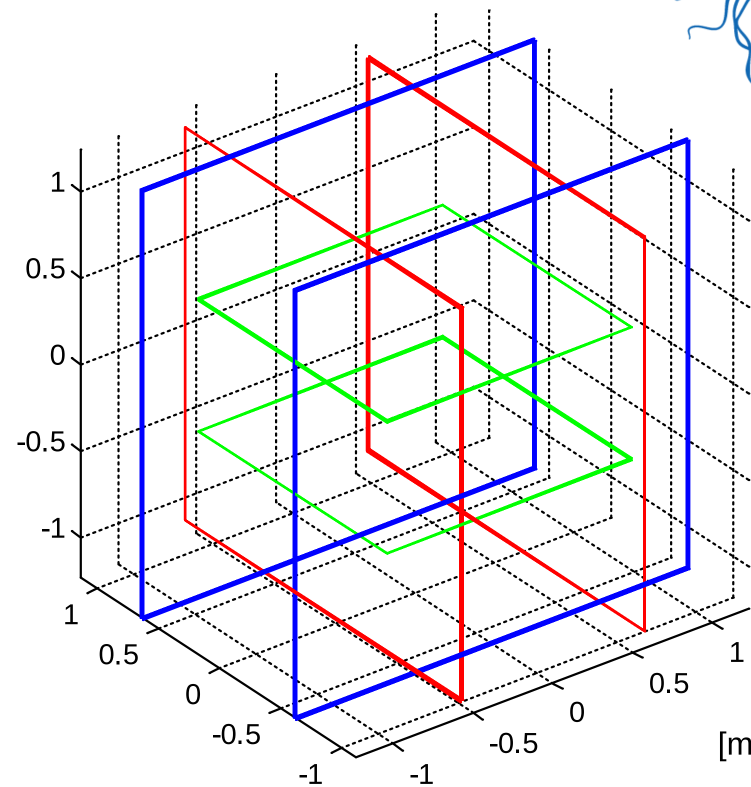
Unshielded ULF MRI System & LANL



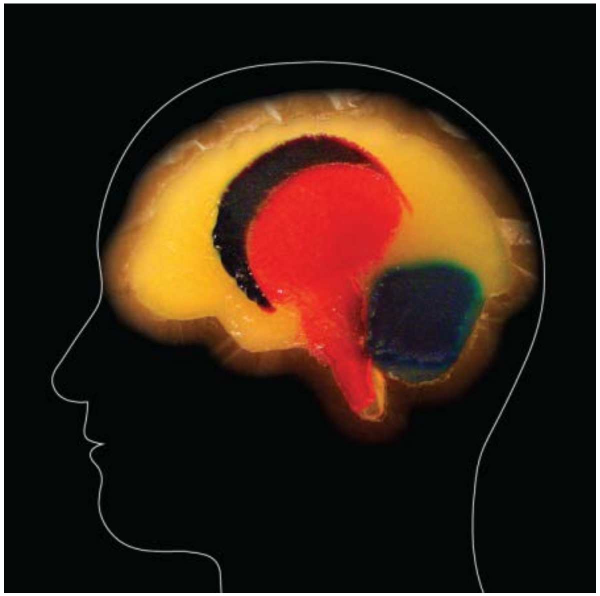


3 pairs of square Helmholtz coils cancel the Earth's magnetic field below 1 mG (10^{-7} T).

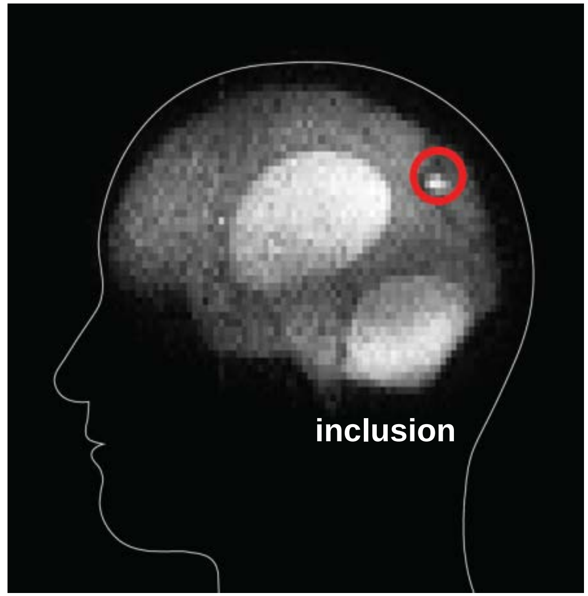
B_m continuously ON - power supply with a large capacitor across its terminals to reduce the noise. Gradients and spin-flip field were generated by battery-powered current generators receiving input voltages from an NI-6733 card. B_p was generated by 2–3 sealed 12 V lead-acid car batteries in series and ramped down through banks of solid-state switches (40 mT at 40 A). Spin-flip coil placed on top of the pre-polarization coil.

ULF MRI of a “Blood Inclusion”

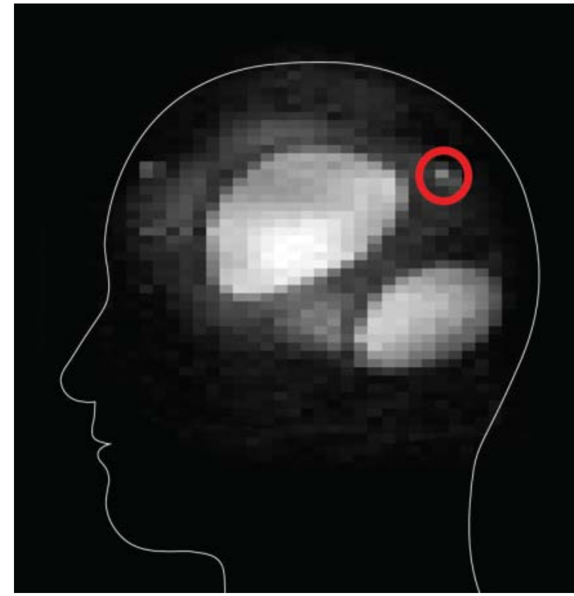
Gelatin-Agar Phantom



Shielded MRI



Unshielded MRI



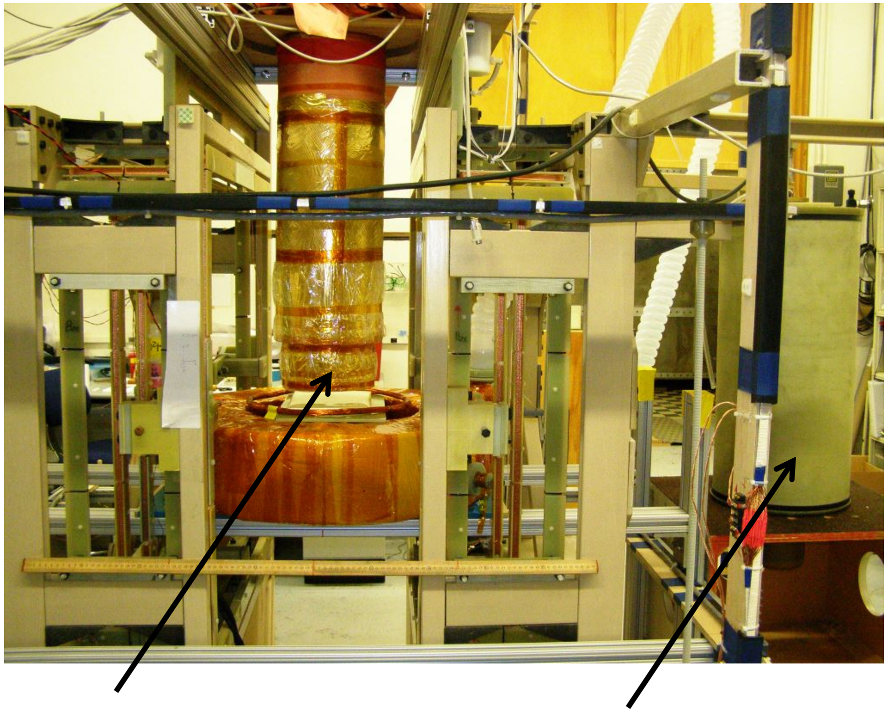
ULF MR Images of 1 cm^3 “blood inclusion” using a phantom made of gelatin-agar mixtures:

Gelatin-agar “white matter” with T_2 ~ 120 ms (the surrounding tissue) and “blood” with T_2 ~ 300 ms (white dot)

Unshielded MRI was recorded at B_P= 65 mT and pre-polarization time t_p = 2.5 s, during “low-noise time period”
2D resolution is about 3 × 3 mm^2
Four averages (6.5 minutes per one image)

Michelle A. Espy *at al.* “Progress toward a deployable SQUID-based ultra-low field MRI system for anatomical imaging.” .” *IEEE Transactions on Applied Superconductivity*, VOL. 25, NO. 3, (JUNE 2015) 1601705

Reference channels



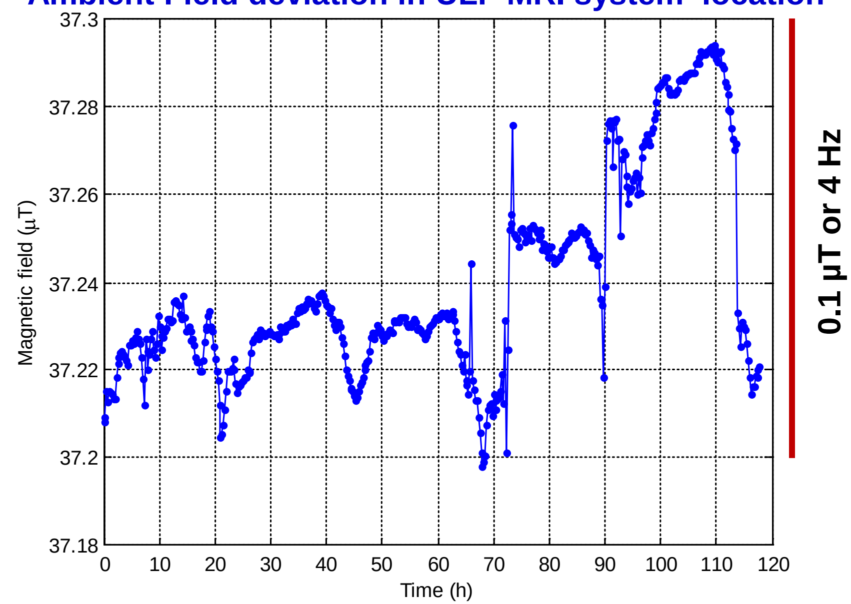
7 Gradiometers

Ref. Magnetometer

- **Manual Ambient DC field compensation**
- **A low-frequency dynamic cancellation system is being tested to enable automatic adjustments.**

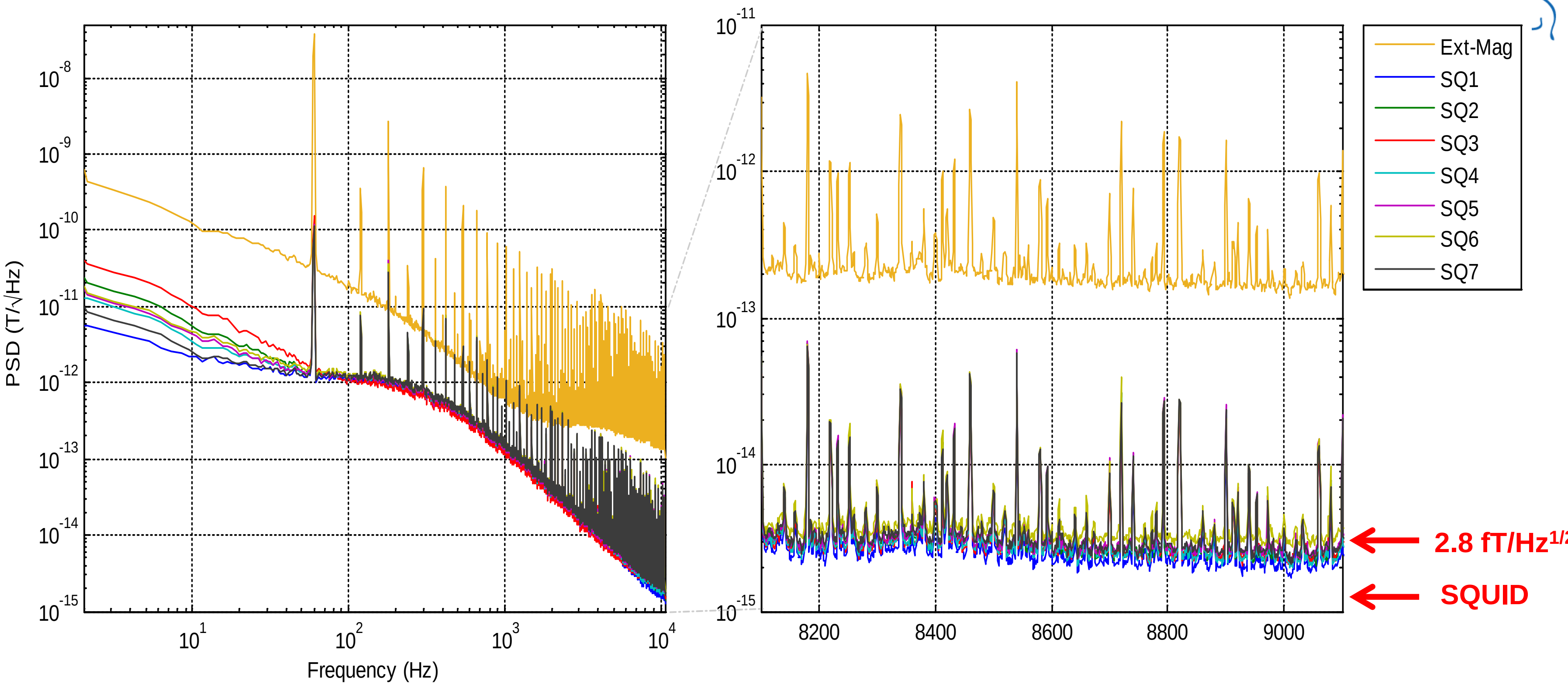
- **Reference two vector magnetometers and one gradiometer configuration was initially implemented and tested.**
- **<u>Current configuration includes only one vertically oriented reference magnetometer.</u>**
- **Electronic compensation and software compensation have been tested and compared .**
- **In both cases it was possible to completely eliminate noise lines from all range of our NMR signals with central Larmor frequency 8630 Hz.**

Ambient Field deviation in ULF MRI system location



- **<u>Compensation works only if the gradiometers are placed under the pre-polarization coil and the coil is shunted with a resistor, *R* < 500 Ohm</u>.**
- **If B_P coil is not shunted or if the gradiometers are moved away, this technique does not work.**
- **Hypothetically the pre-polarization coil makes the high frequency noise recorded by gradiometers highly correlated with the signal picked up by the nearby reference magnetometer.**

Noise in Unshielded Conditions

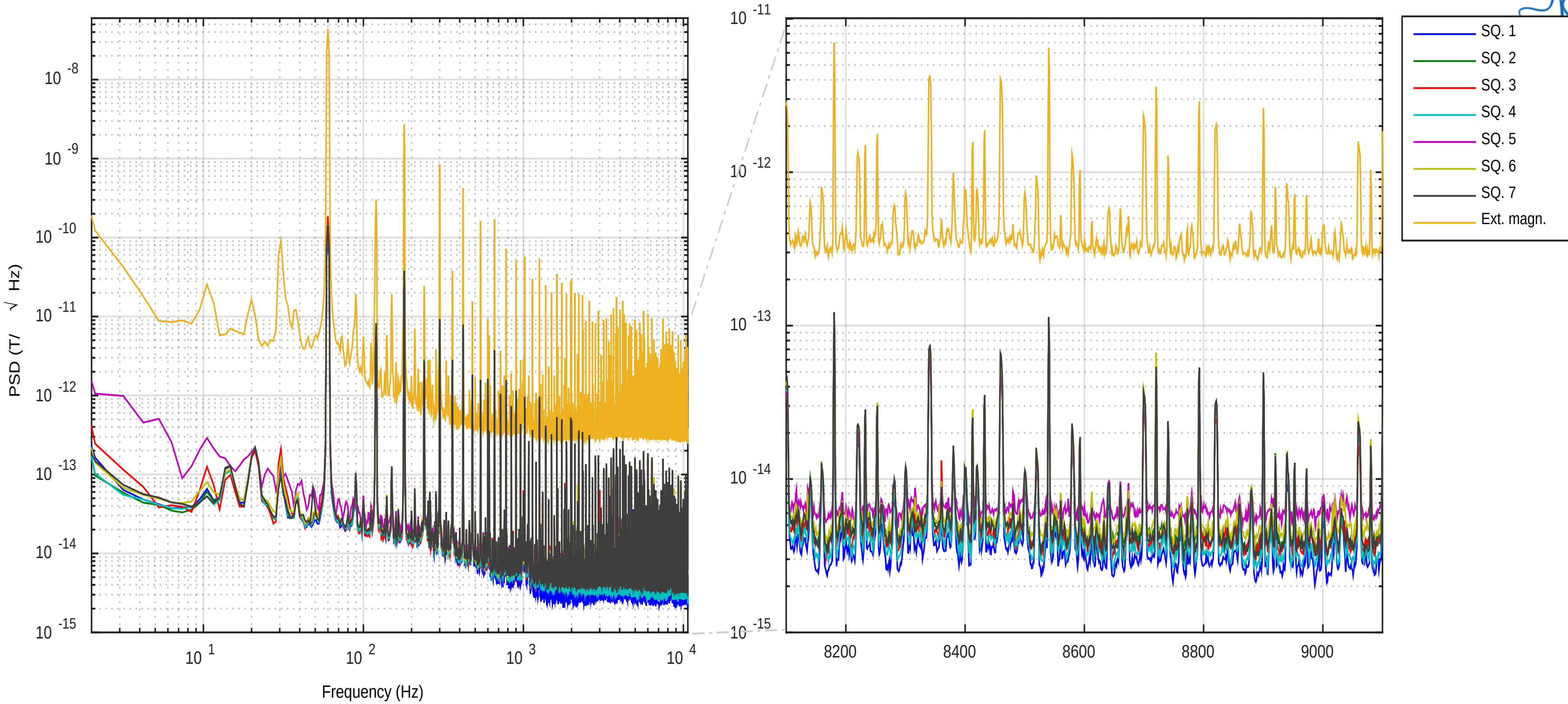


Power spectral densities of seven SQUID gradiometers inside the MRI dewar, and one external magnetometer in a separate dewar:

Gradiometers pick-up Johnson noise from shunted B_P coil at T=75K
R_{shunt} = 0 Ohm

SQ 1 has intrinsic noise about 1.2 fT/Hz$^{1/2}$
SQ 2–7 pick up 2.4 fT/Hz$^{1/2}$ Johnson noise from thermal shields inside the dewar

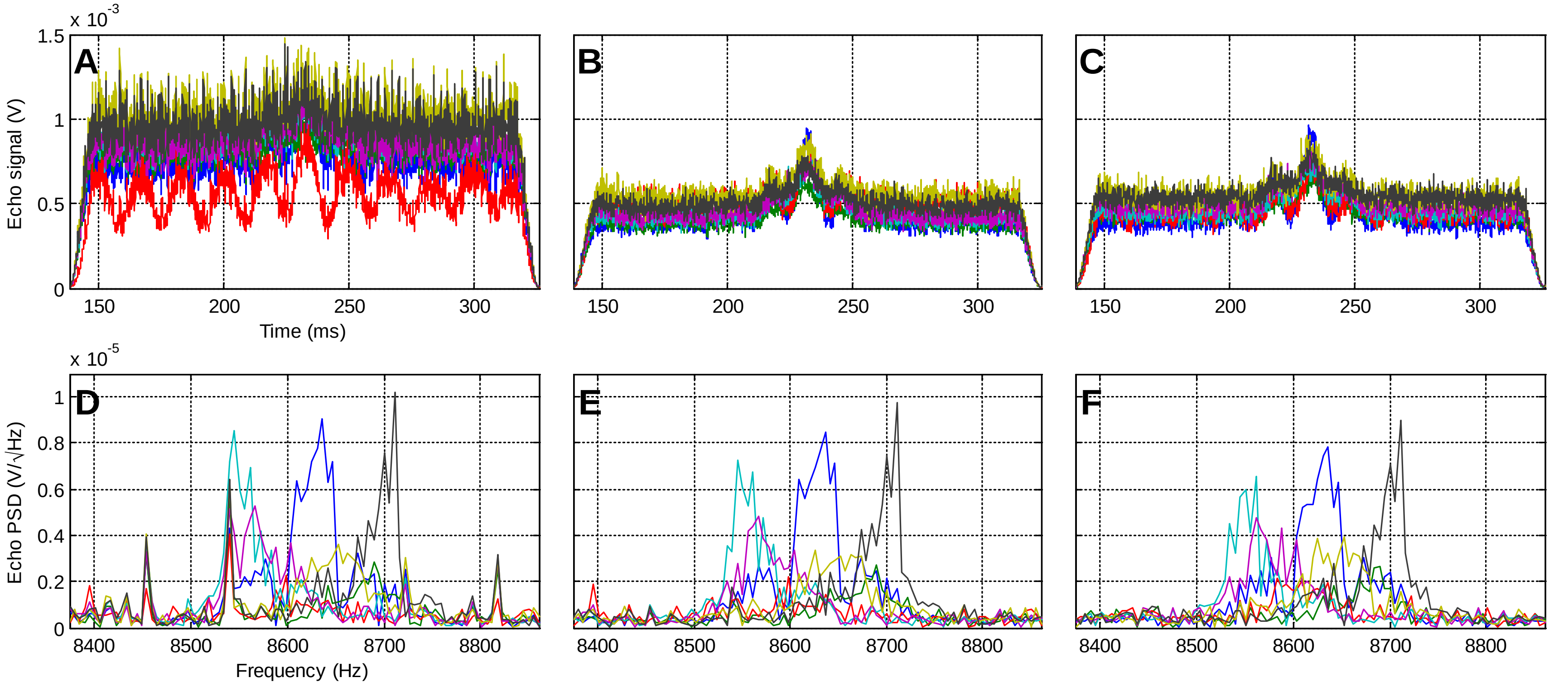
Noise in Unshielded Conditions



Power spectral densities of seven SQUID gradiometers inside the MRI dewar, and one external magnetometer in a separate dewar:

***R*$_{SH}$= 500 Ohm : Johnson noise becomes much smaller at a higher shunt resistor**

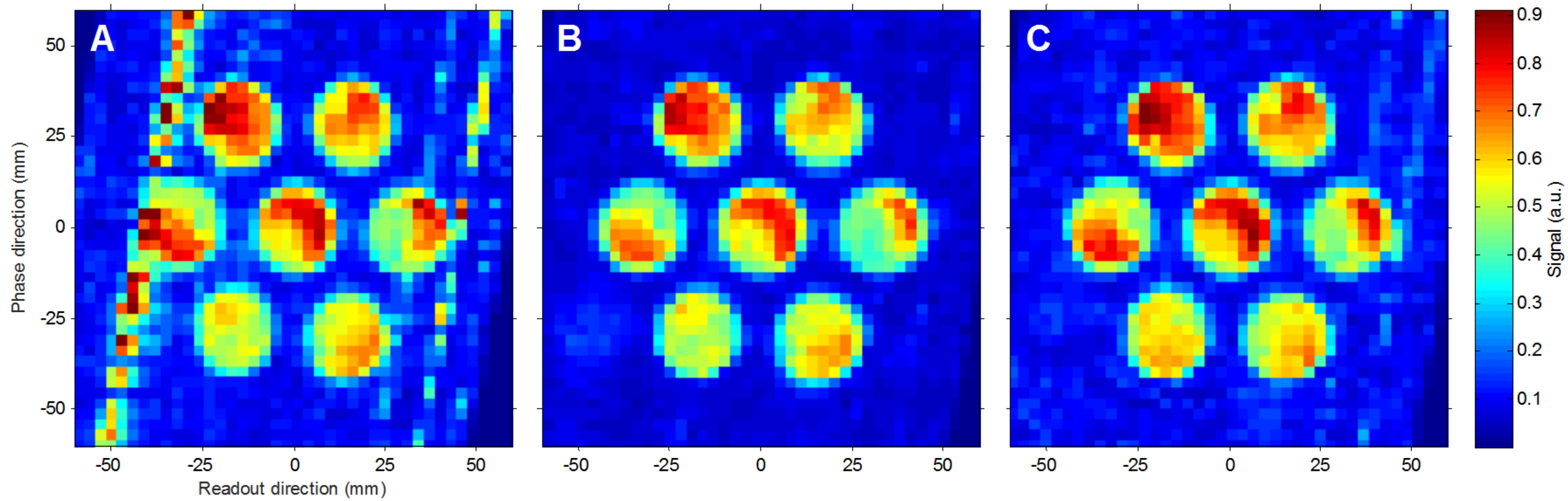
Signals with and without Compensation



Top panels (A–C) show time-domain echo signals from 2D imaging, and the bottom panels (D–F) show the power spectral densities (PSDs) of the echo signals:

(A,D) no noise-cancellation,
(B,E) post-processing software noise-cancellation using the external reference magnetometer signal,
(C,F) real-time electronic noise-cancellation using the external magnetometer.

ULF MRI of a Water Phantom

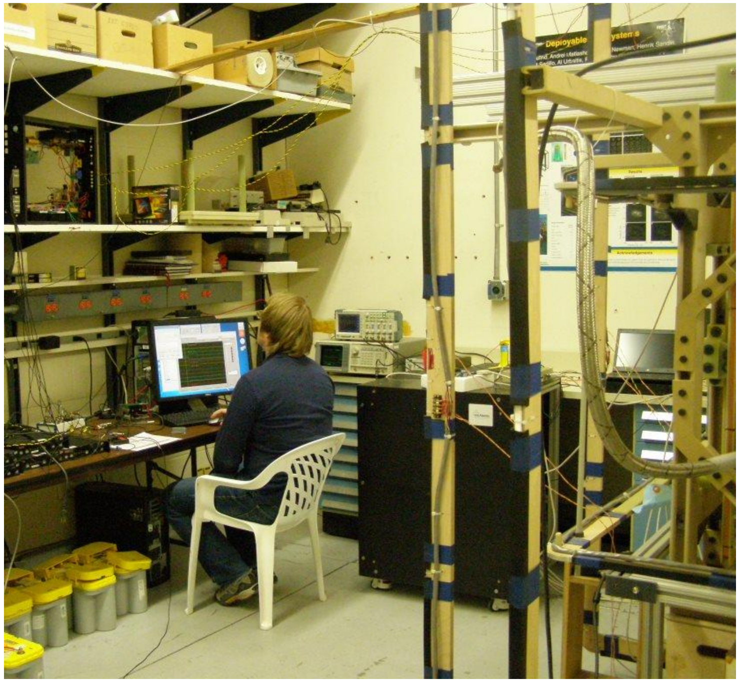


2D single-shot MRIs of seven vials of water:

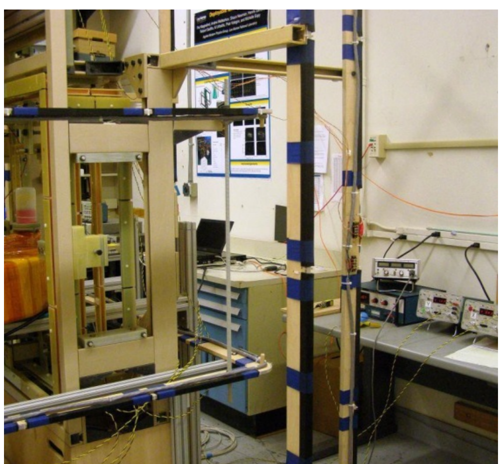
A) Data acquired without any noise cancellation.
B) Noise cancellation in post-processing cancellation using the external magnetometer signal.
C) Real-time electronic noise cancellation using the external magnetometer.

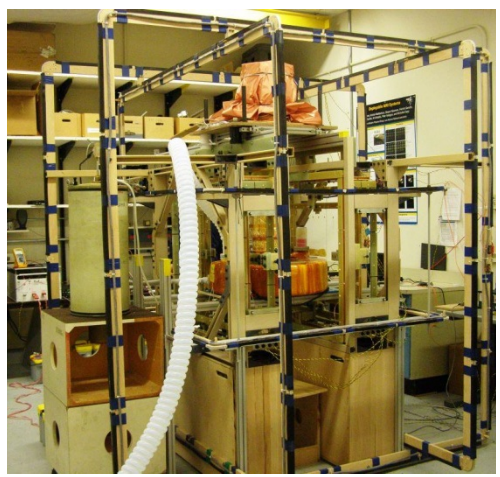
The phantom consisted of seven 24 mm diameter and 20 mm tall cylinders with pure water located on hexagonal corners with one cylinder in the center. The distance between their centers was 35 mm.

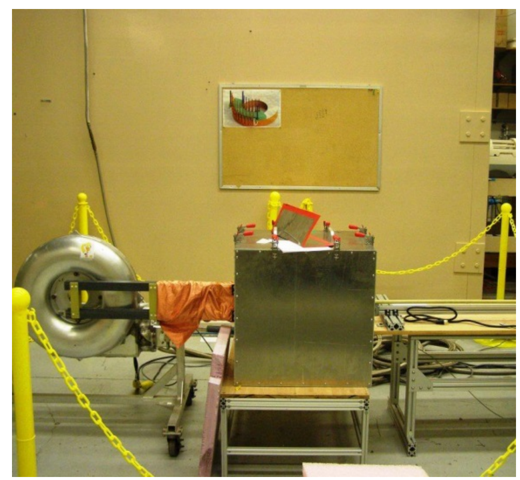
Experimental Surroundings



A busy road is placed 15 m away from the MRI system location.







1T magnet with a pulsed-tube cryo-cooler that generates a lot of noise at 1-10 kHz range (from its power supply)

It located 10 m away from MRI system.

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Summary

- SNR of ULF MR Images can be accurately predicted using computer simulations.
- The possibility of providing ULF MRI using moderately balanced SQUID-based gradiometers in unshielded environment has been experimentally demonstrated.
- We proposed a simple and very effective method for high frequency noise cancellation that allows ULF MRI systems to work in noisy urban locations.
- We've built a prototype of an unshielded ULF MRI system that can be used for quick internal bleeding diagnostic in emergency situations.