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Invited presentation 3A-E-O1.1 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015. Not submitted to *IEEE Trans. Appl. Supercond.*

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Deployable SQUID-based magnetic resonance imaging systems

Per Magnelind, Andrei Matlashov, Shaun Newman, Henrik Sandin, Robert Sedillo, Algis Urbaitis, Petr Volegov, and Michelle Espy

EUCAS, Sept. 9, 2015

Outline

- Motivation
- Methods
- Modeling
- Results
- Outlook
- Summary

Single-average slice acquired inside a shielded room

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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 homogeneity
- presence of non-magnetic metal is not an issue
- can be light and made portable

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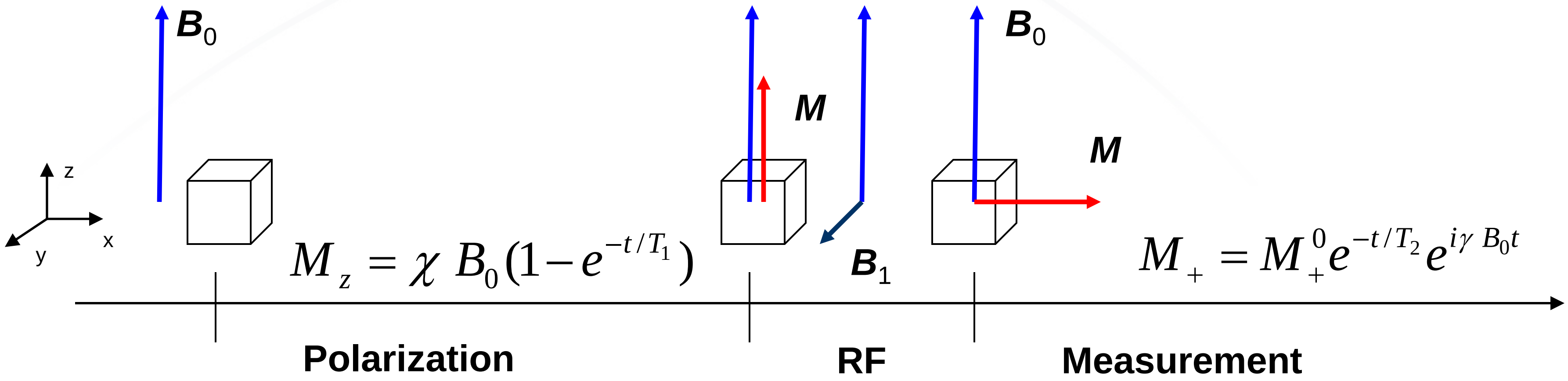
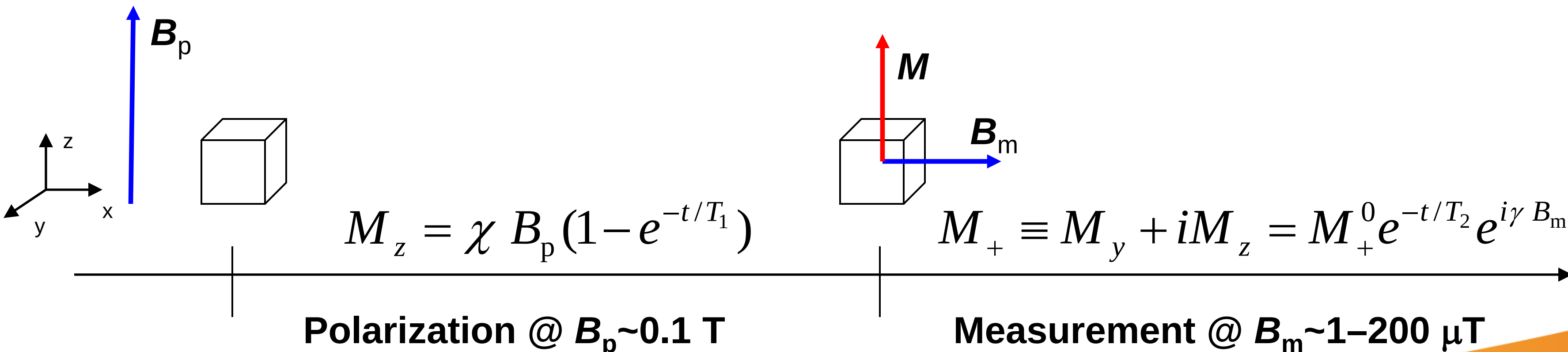
Methods—NMR basics

Conventional NMR:



ULF-NMR: non-adiabatic switching of $\boldsymbol{B}_\mathrm{p}$



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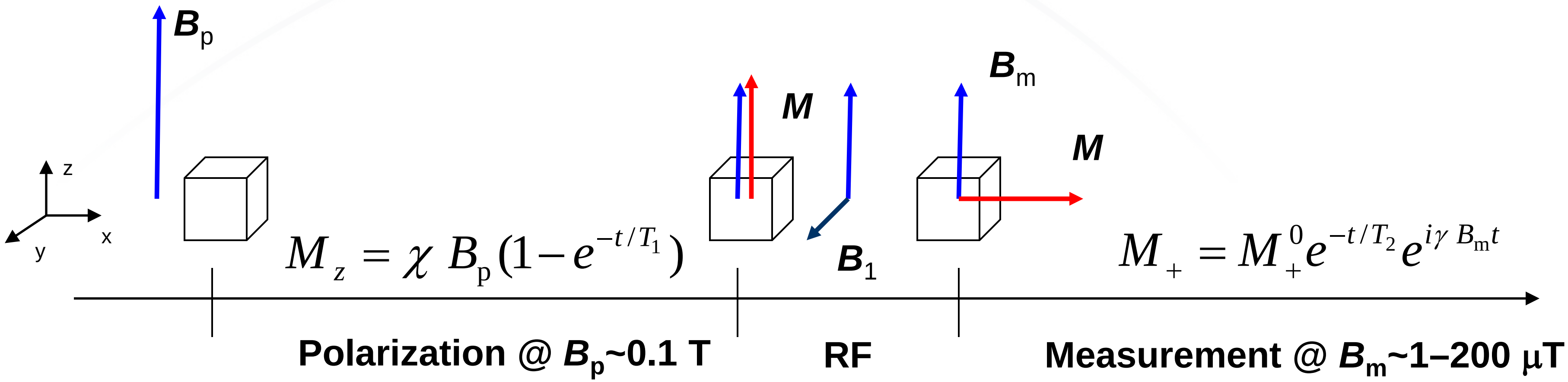
Methods—NMR basics

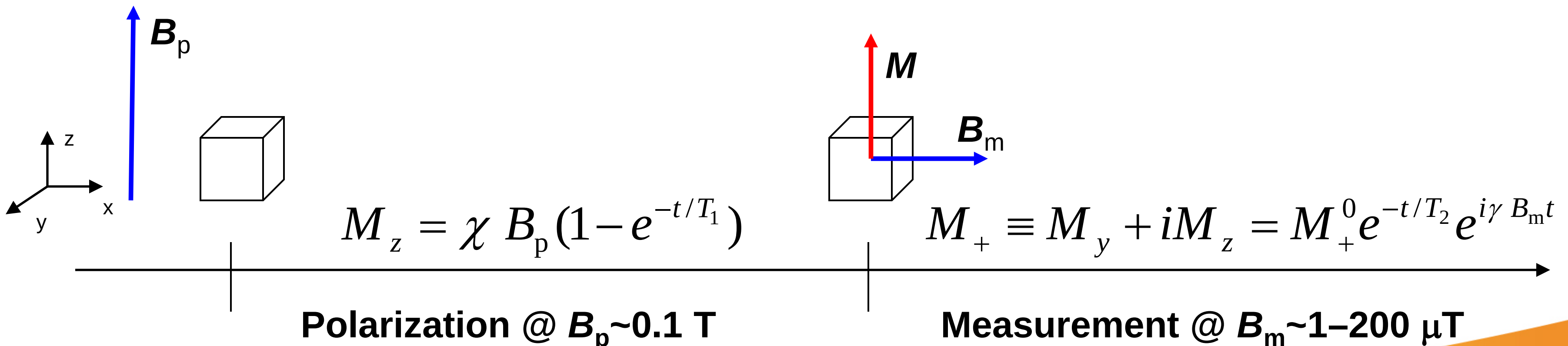
ULF-NMR: adiabatic switching of B_p



$$M_z = \chi B_p (1 - e^{-t/T_1})$$

$$M_+ = M_+^0 e^{-t/T_2} e^{i\gamma B_m t}$$

ULF-NMR: non-adiabatic switching of B_p



$$M_z = \chi B_p (1 - e^{-t/T_1})$$

$$M_+ \equiv M_y + iM_z = M_+^0 e^{-t/T_2} e^{i\gamma B_m t}$$

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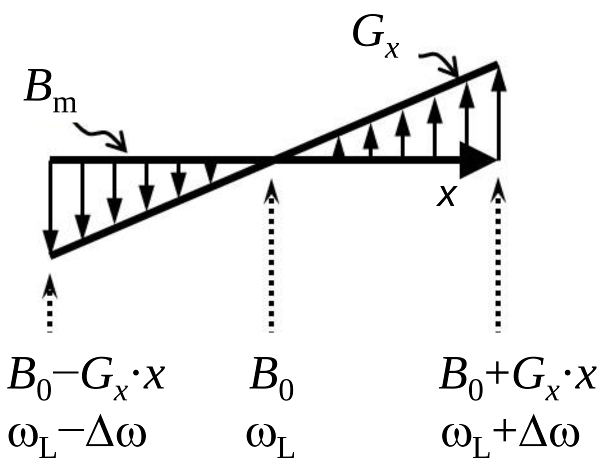
Methods—Gradients

Frequency encoding



Phase encoding

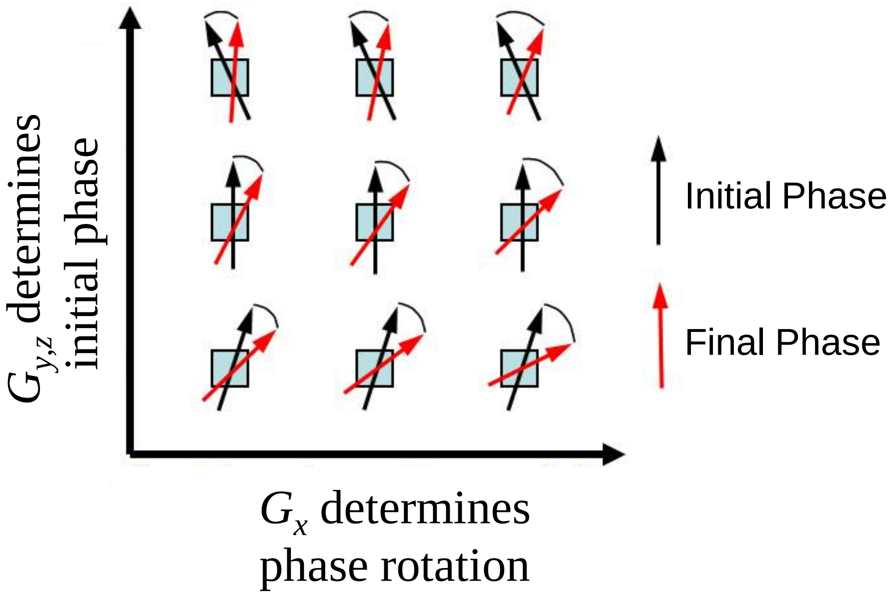


Image (spin density) obtained from 3-D inverse Fourier Transform

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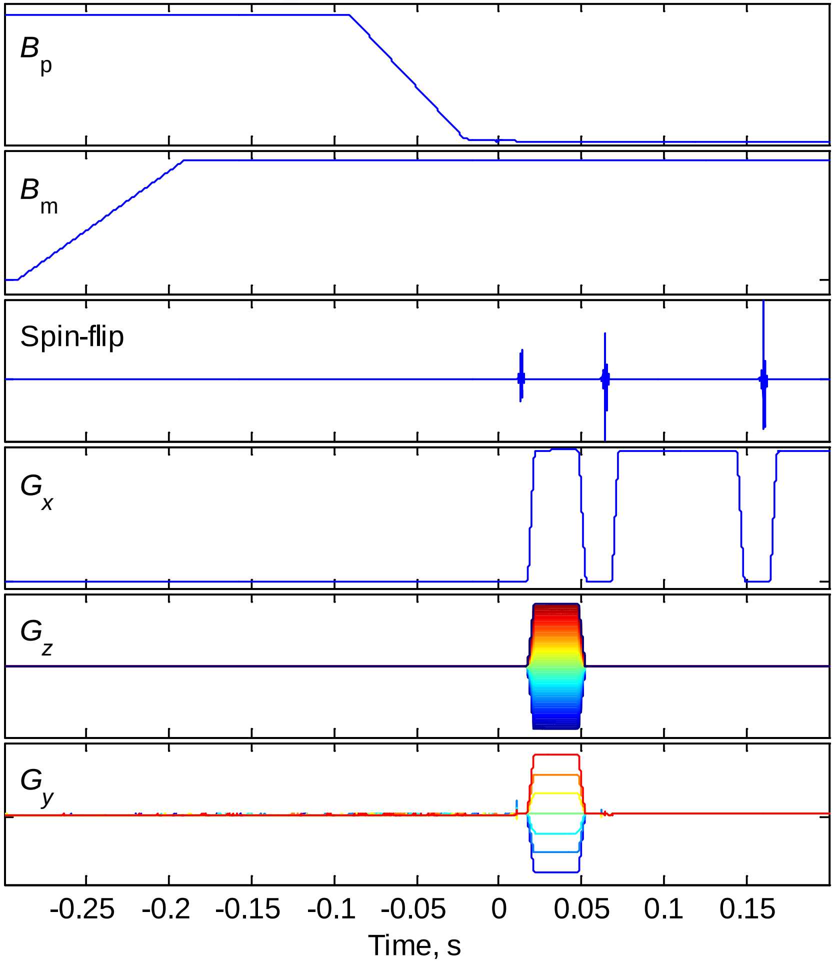
Methods—Pulse-sequence



3D Fourier spin-echo imaging sequence.

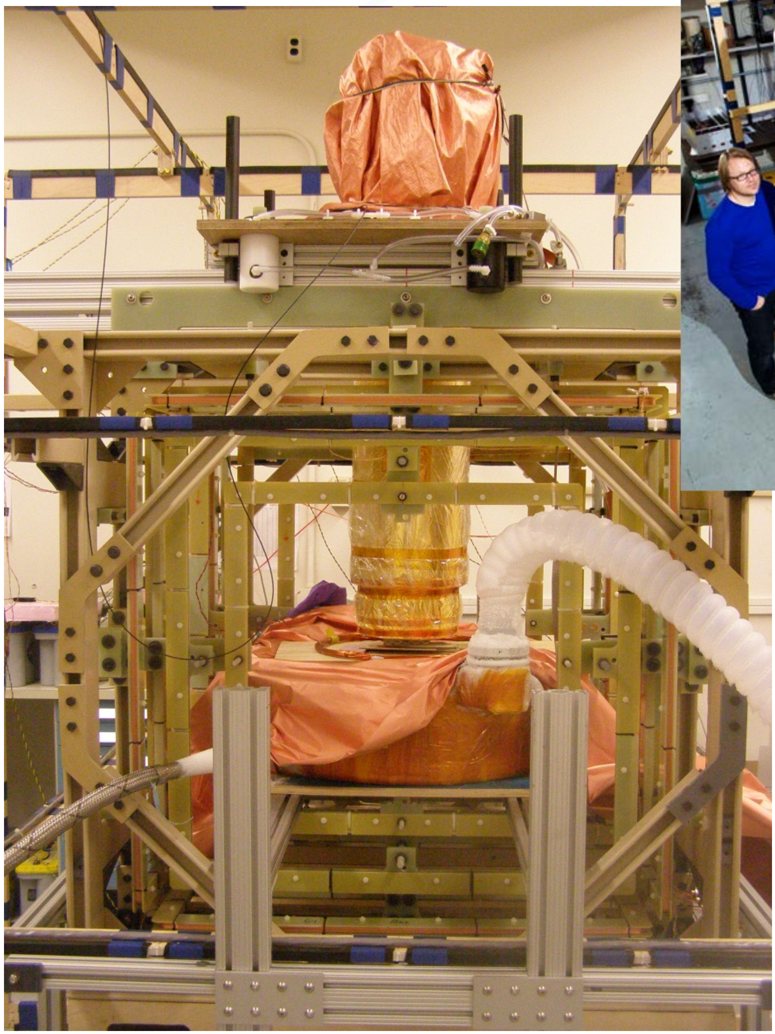
$\boldsymbol{B_p}$: pre-polarization field
≤100 mT, linearly ramped over 70 ms, then ramped to zero adiabatically during 20 ms.

$\boldsymbol{B_m}$: measurement field
190–200 μT (8.2–8.6 kHz).

$\boldsymbol{G_x}$ (readout):	≤248 μT/m	≤11 Hz/mm
$\boldsymbol{G_z}$ (phase, in-plane):	≤222 μT/m	≤9 Hz/mm
$\boldsymbol{G_y}$ (phase, depth):	≤47.6 μT/m	≤2 Hz/mm

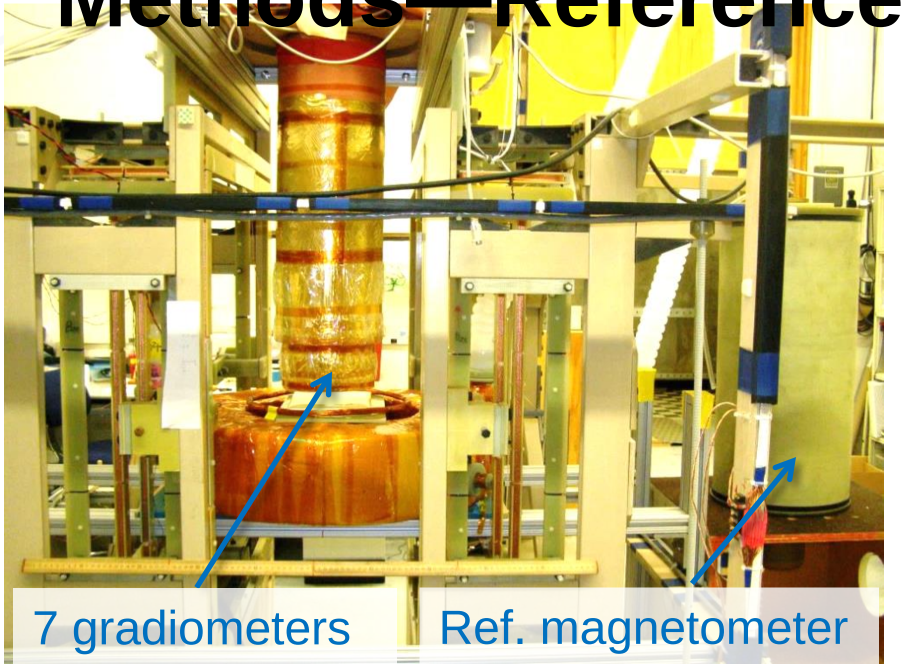
Implemented in a custom LabView VI with a time-slot matrix interface.

Methods—Unshielded System Hardware

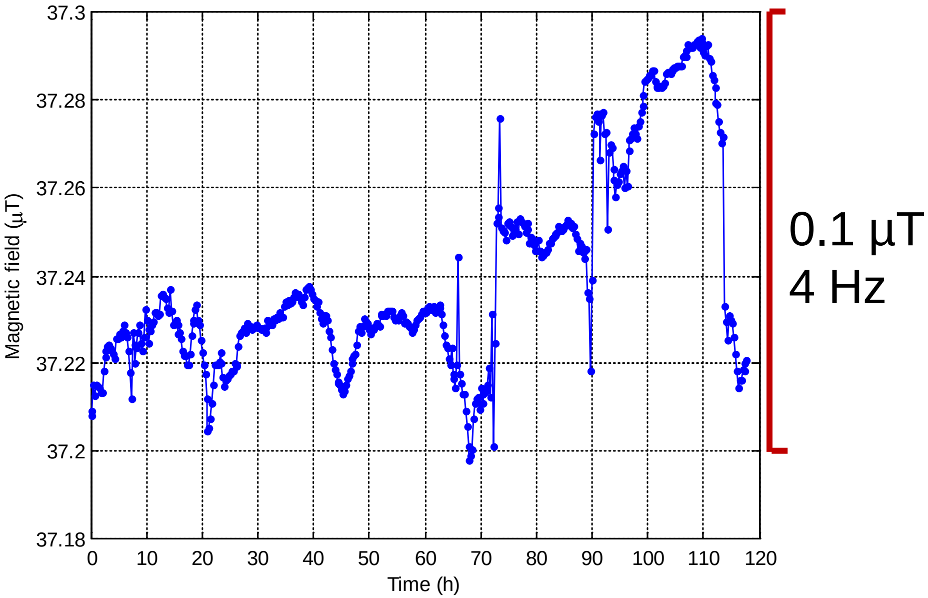


- 3 pairs of square Helmholtz coils cancel the Earth's magnetic field.
- Seven 37 mm 2nd-order gradiometers, 60 mm baseline.
- B_m (~200 μT) continuously on; power supply with a large capacitor.
- Battery-powered current generators for gradients and spin-flip.
- B_p (45–65 mT) was battery-powered and ramped down through banks of solid-state switches.

Methods—Reference Channel



Ambient field deviation in the ULF MRI system location



- Manual ambient DC field compensation.
- A low-frequency dynamic cancellation system is being tested to enable automatic adjustments.
- Electronic compensation and software compensation have been tested and compared.
- In both cases it was possible to suppress noise lines from our NMR signals with a central Larmor frequency of 8.6 kHz.

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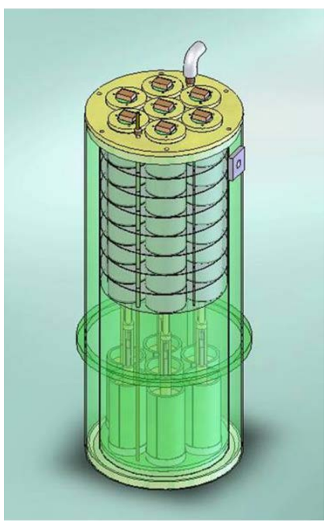
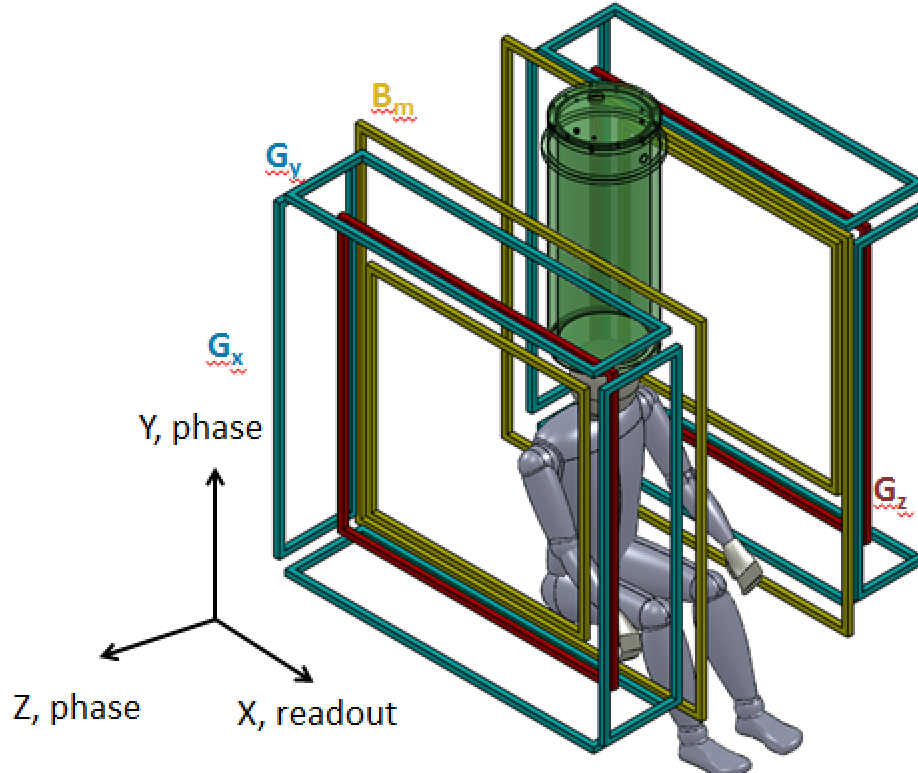
Methods—Shielded System Hardware

- Wall-powered field generation
- 2nd-order gradiometers, 90 mm diameter & baseline
- Sensors co-exist with 100 mT B_p
  - Pb-Bi shields
  - 2nd-feedback
  - Compensation



Pb-Bi shield



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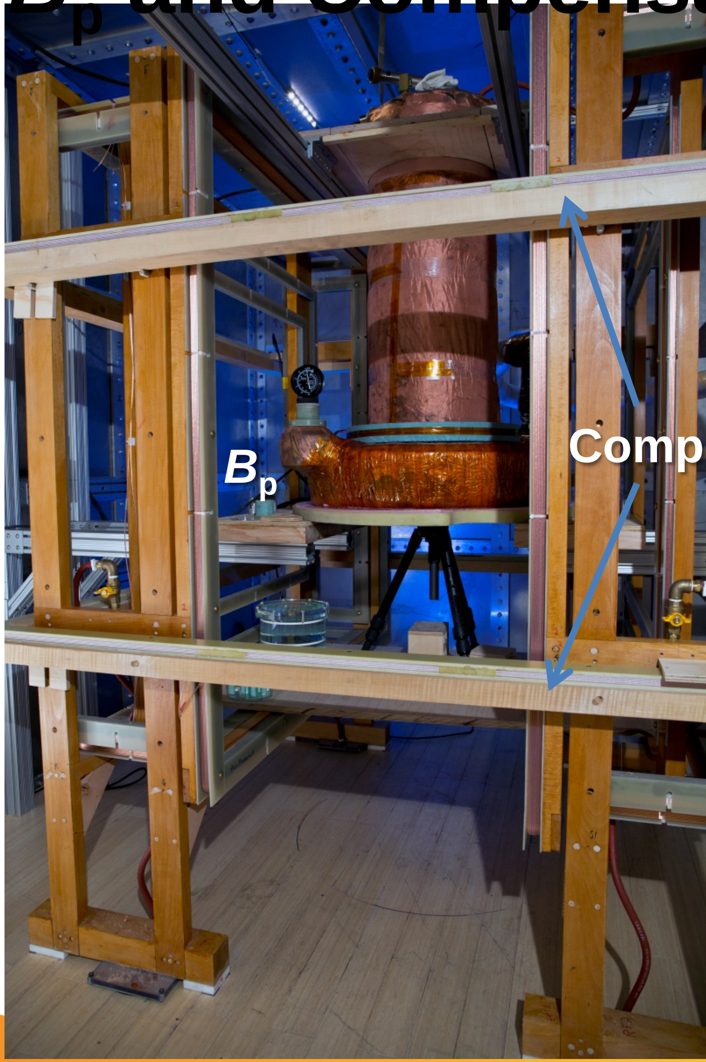
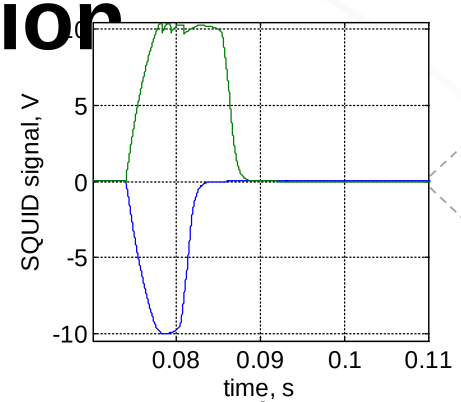
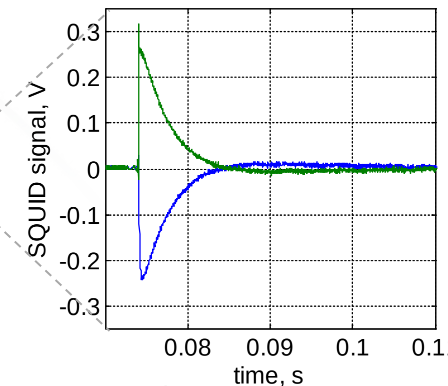
Methods— B_p and Compensation

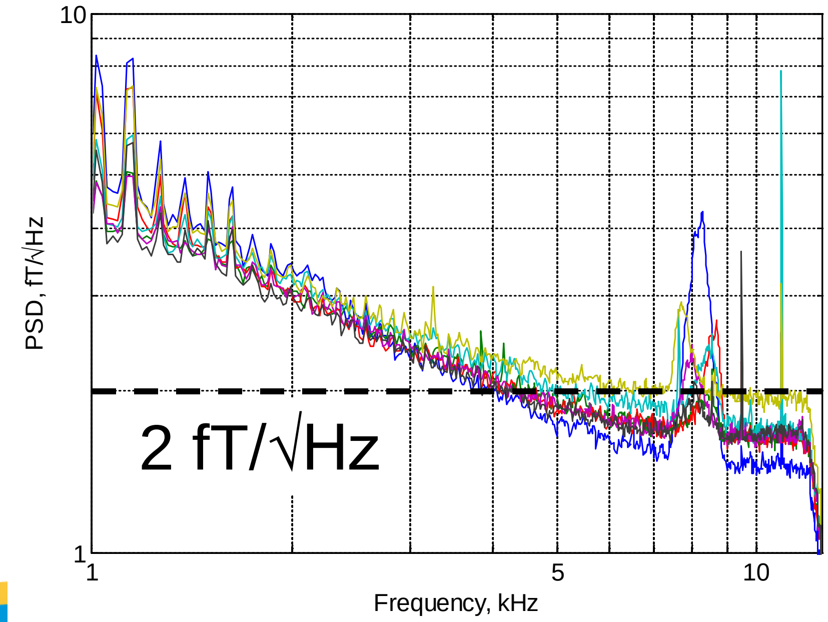




SQUIDs reach output limit w/o 2nd-feedback



With 2nd-feedback dynamic range maintained



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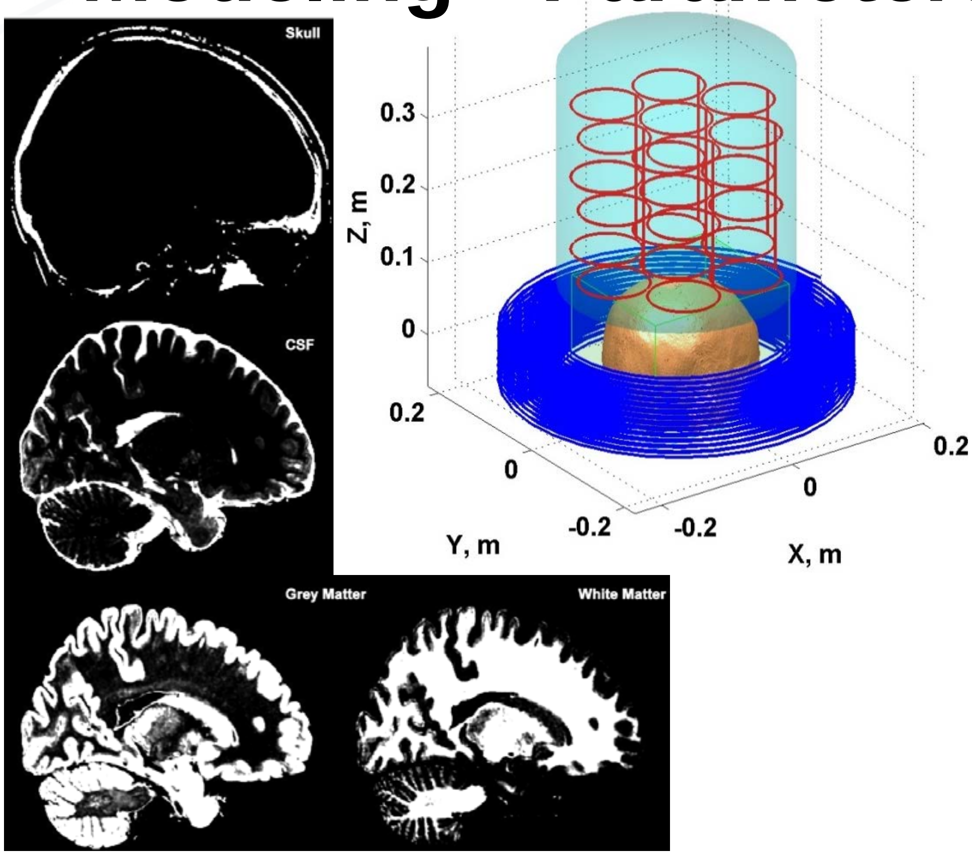
Modeling—Parameters etc.



- Implemented in Matlab
- Bloch equations for NMR calculations
- Biot-Savart and reciprocity used for field calculations

	Tissue name	PD (%)	T_1 (ms)	T_2 (ms)
1	CSF	100	4360	329
2	GREY MATTER	86	635	83
3	WHITE MATTER	77	360	70
4	FAT	100	350	70
5	MUSCLE	100	120	47
6	MUSCLE/SKIN	100	120	47
7	SKULL	0	0	0
8	VESSELS	0	0	0
9	CONNECTIVE	77	500	61
10	DURA MATER	100	2569	329
11	BONE MARROW	77	500	70

Eleven high-resolution (0.5×0.5×0.5 mm^3) volumes describing content of a voxel
Montreal Neurological Institute, McGill University
B Aubert-Broche, AC Evans, and DL Collins, *NeuroImage*, **32**(1), 138–45, 2006.

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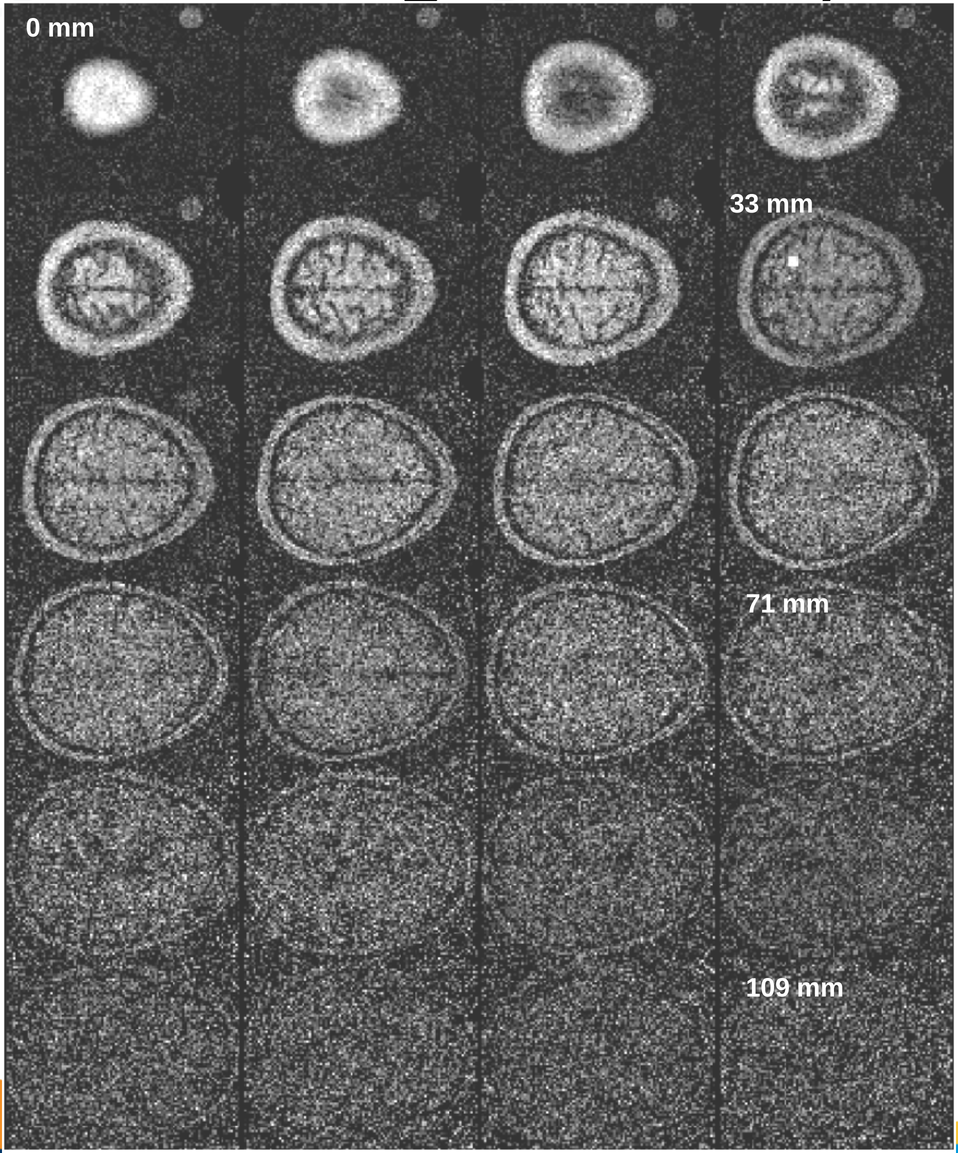
Modeling—100 mT, 2 fT/√Hz



Imaging parameters:

B_p: **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: 7.0 Hz/mm
Phase gradient, G_y: 7.0 Hz/mm
Phase gradient, G_z: 3.0 Hz/mm
Voxel size: 2.0 × 2.0 × 4.8 mm^3

Noise: **1.80** fT/√Hz

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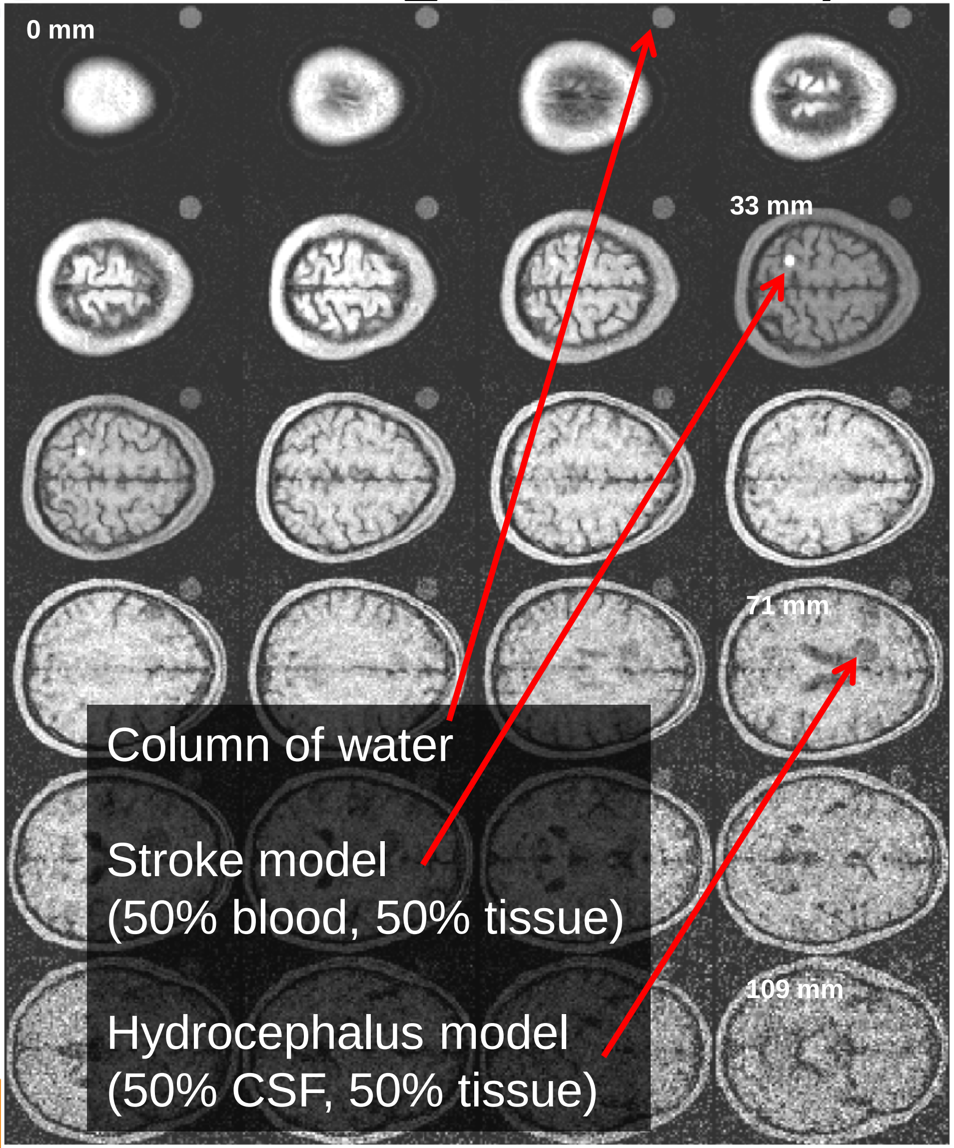
Modeling—250 mT, 1 fT/√Hz



Imaging parameters:

B_p: **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: 7.0 Hz/mm

Phase gradient, G_y: 7.0 Hz/mm

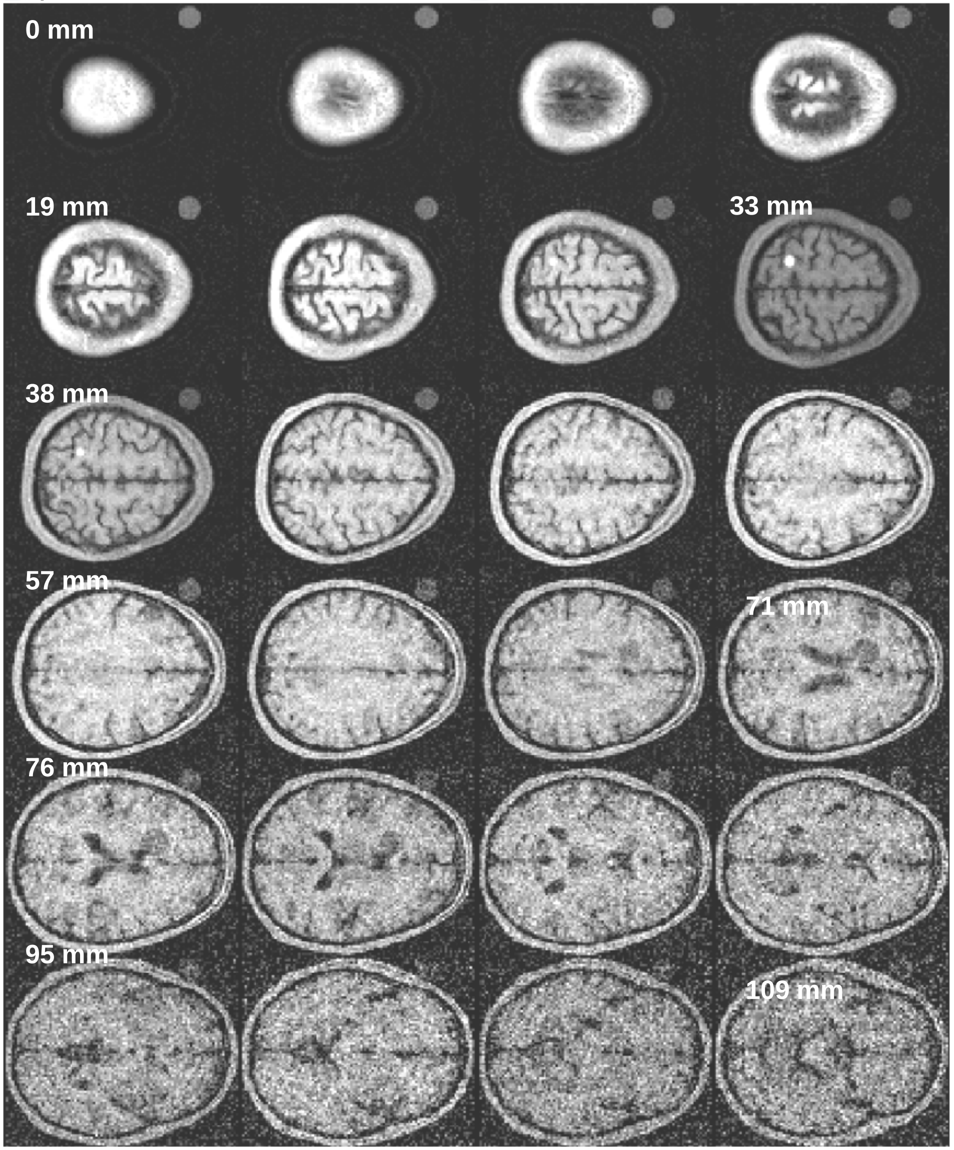
Phase gradient, G_z: 3.0 Hz/mm

Voxel size: 2.0 × 2.0 × 4.8 mm^3

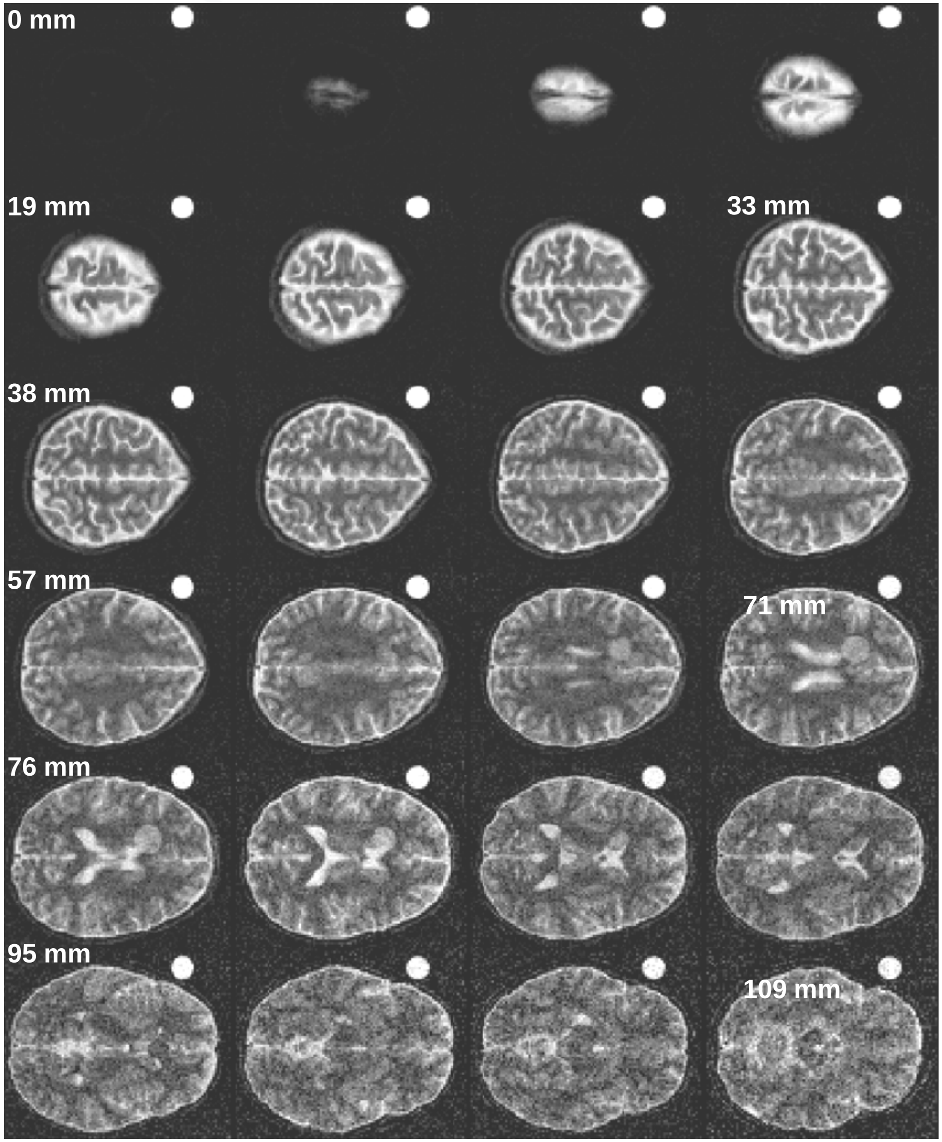
Noise: **0.90** fT/√Hz

Modeling—Contrast (Inversion Recovery)

t_p = 750 ms, t_{inv} = 750 ms

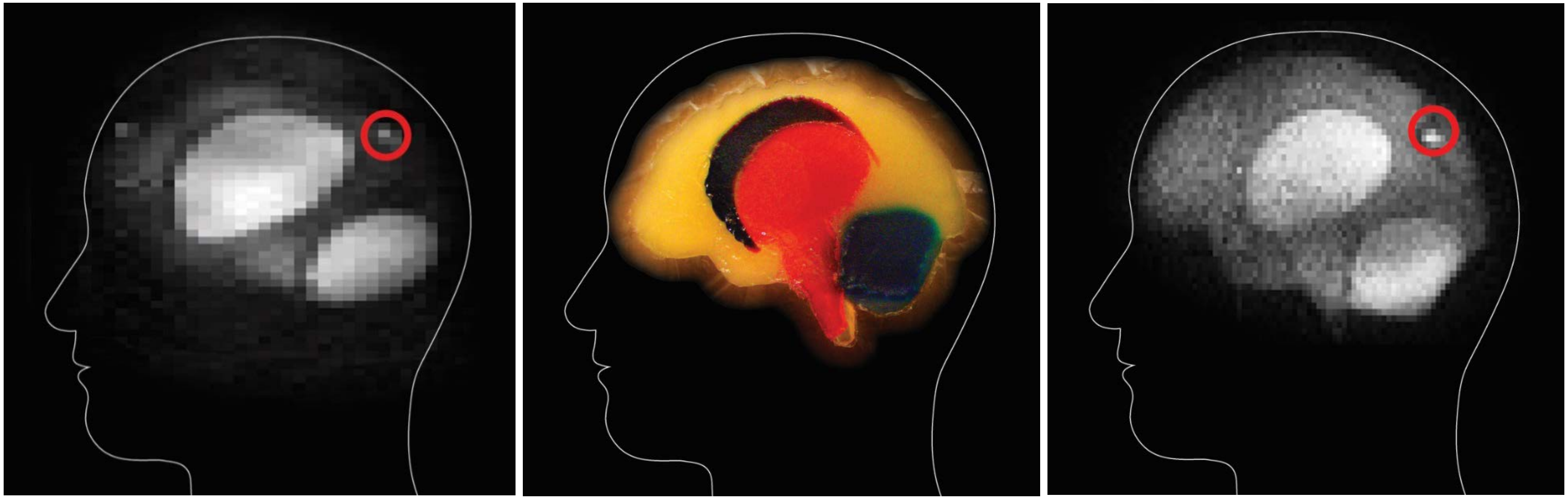


t_p = 2750 ms, t_{inv} = 100 ms



Results—Unshielded

Unshielded MR-image (4 averages; 65 mT) | **Gelatin-agar phantom** | **Shielded MR-image** (1 average; 100 mT)



2D imaging sequence: t_p = 1 s, t_{enc} = 100 ms, t_{read} = 200 ms.

Phase encoding: 57 steps, $|G_z|_{max}$ = 1.62 Hz/mm.

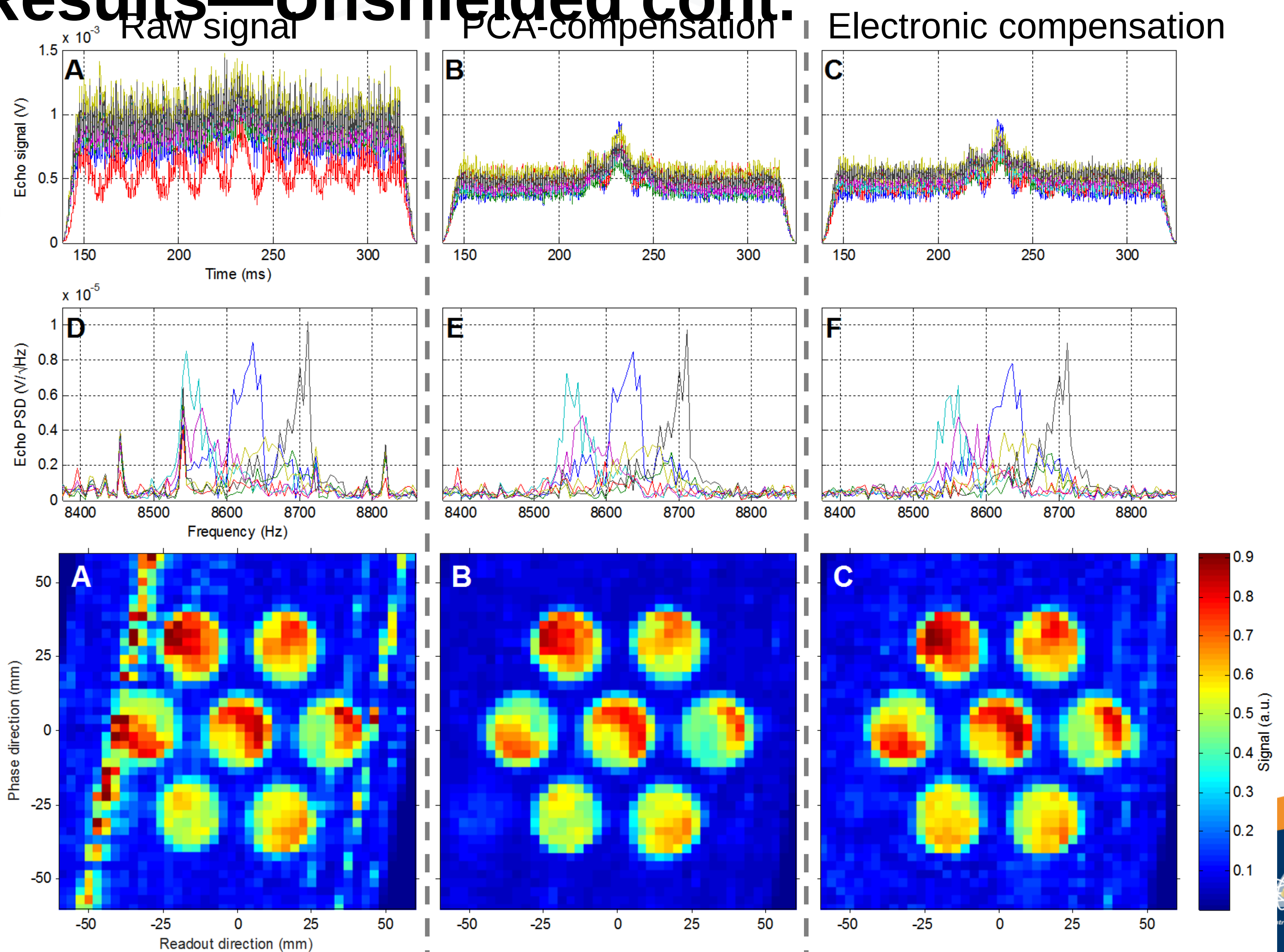
Frequency encoding (readout), G_x: 1.63 Hz/mm.

Resolution: ~3×3 mm^2.

Spin-flip pulses: hard, 4 ms.

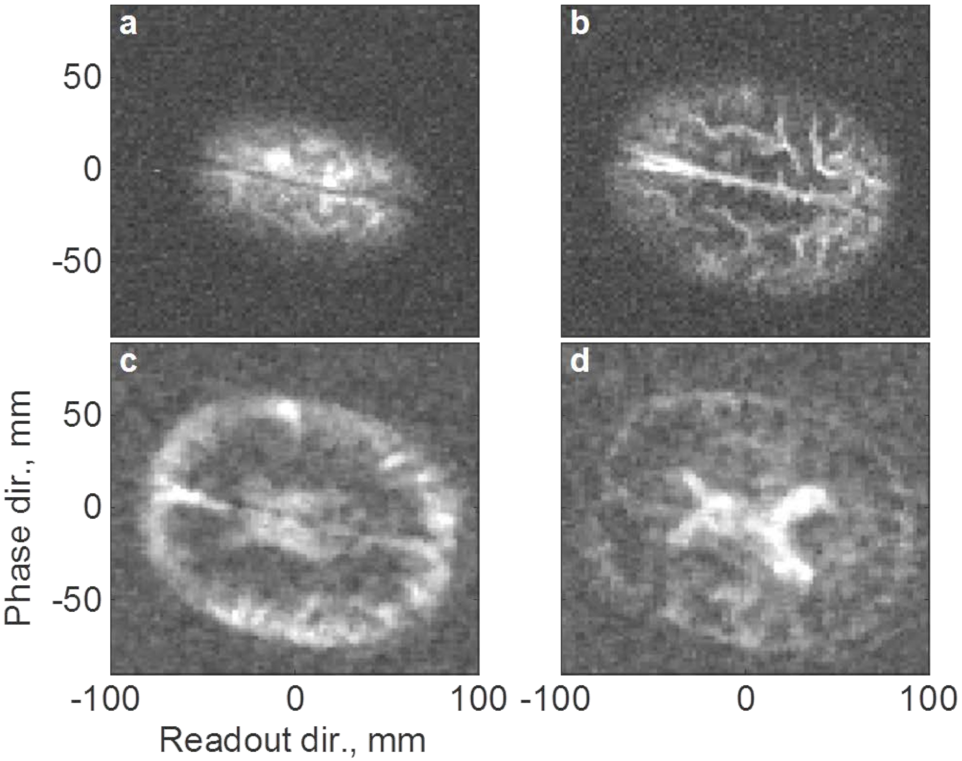
Gelatin-agar mixtures:
T_2 ~ 120 ms for the surrounding
T_2 ~ 300 ms for inclusions

Results—Unshielded cont.

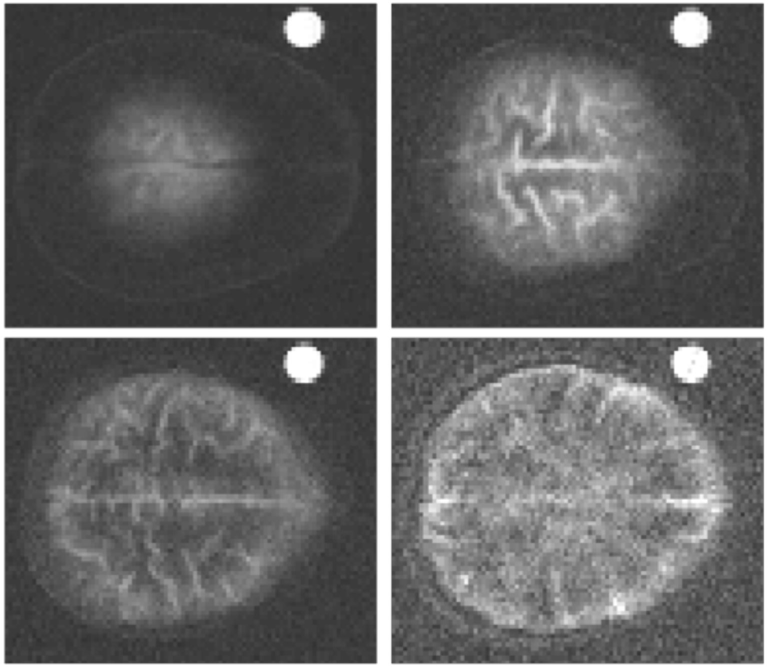


Results—Inside MSR

4 s polarization (67 min.; 5 slices total)



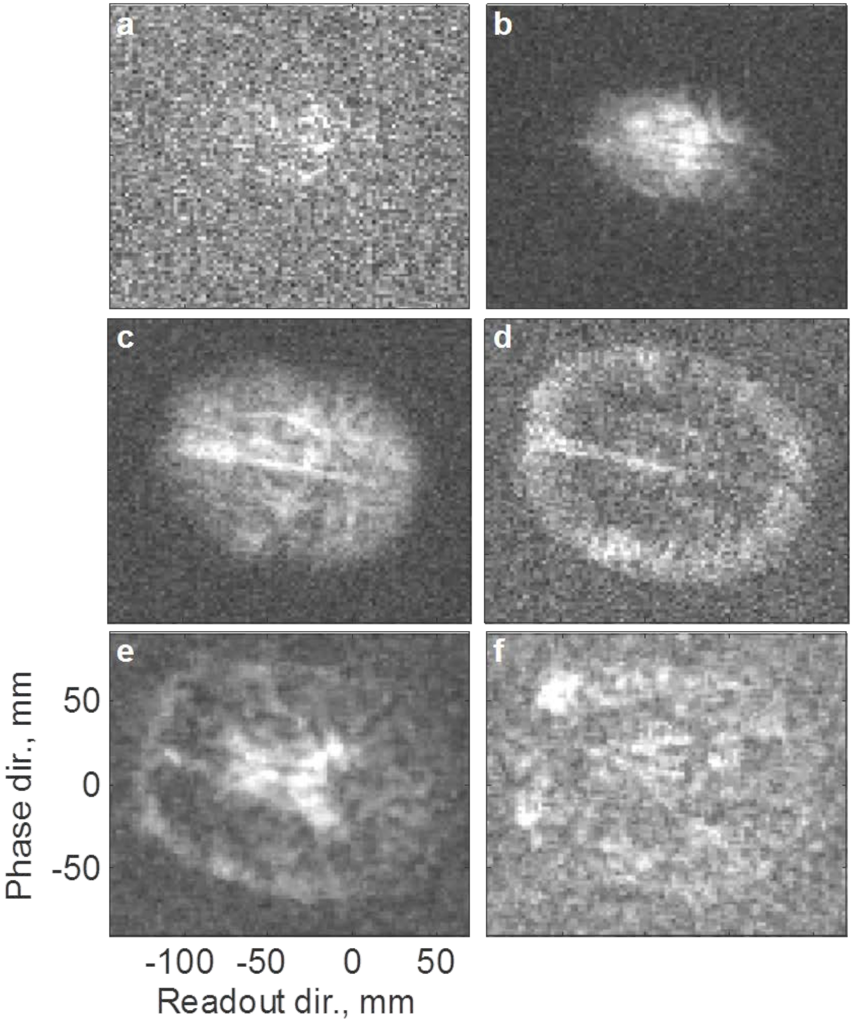
Simulation



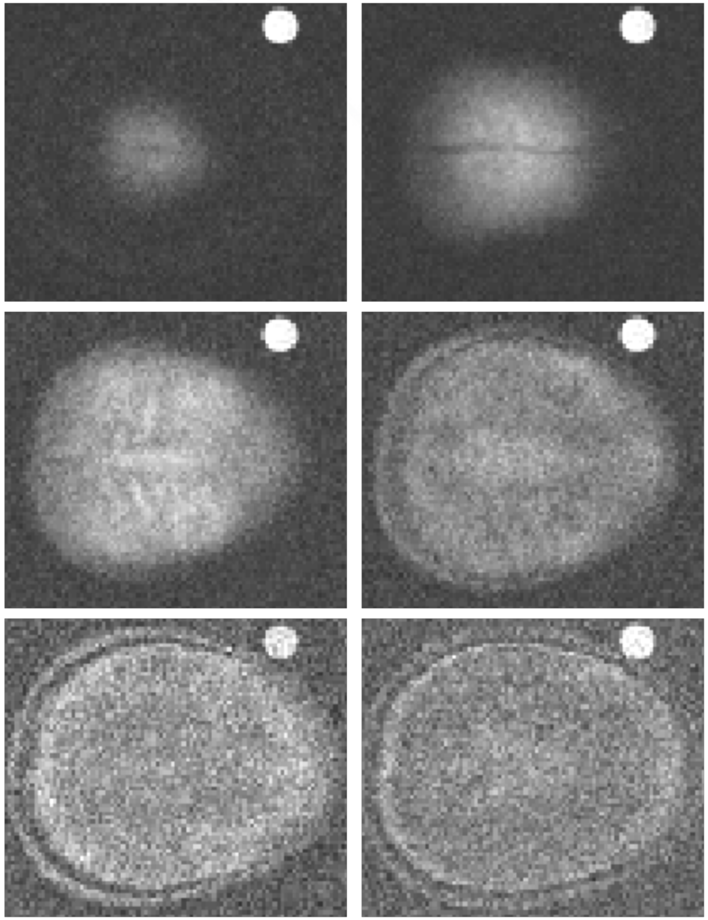
15 mm slices

Results—Inside MSR

3.5 s polarization (80 min.; 7 slices)



Simulation



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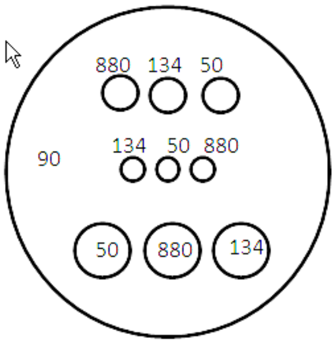
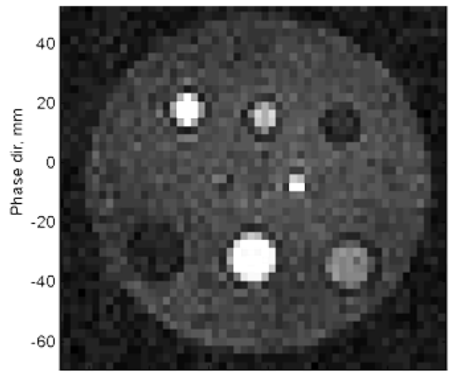
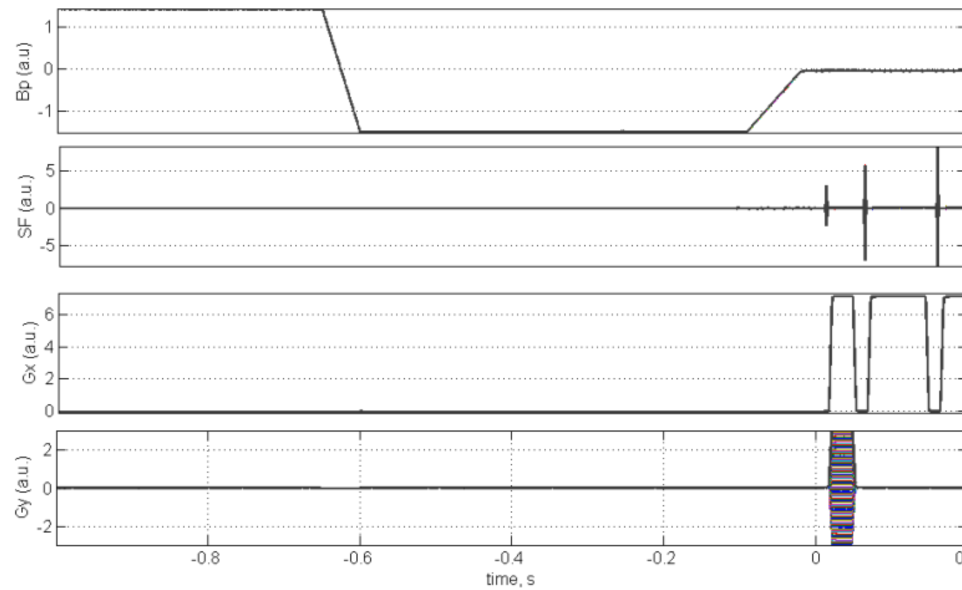
Results—Inside MSR, contrast

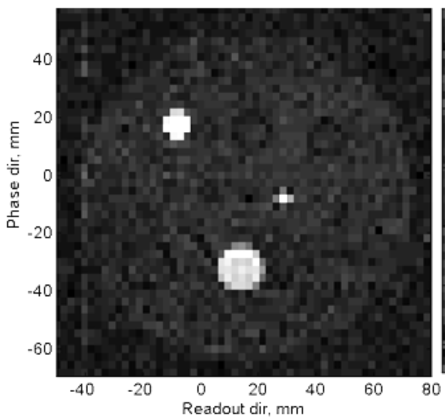


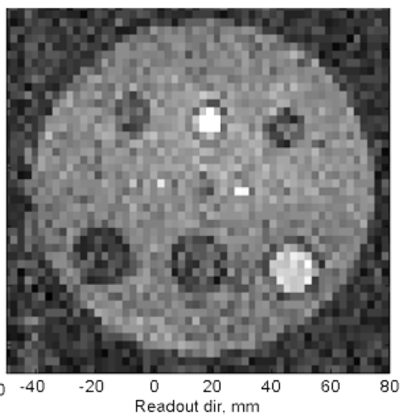
4 sec polarization
and no inversion



Pulse-sequence



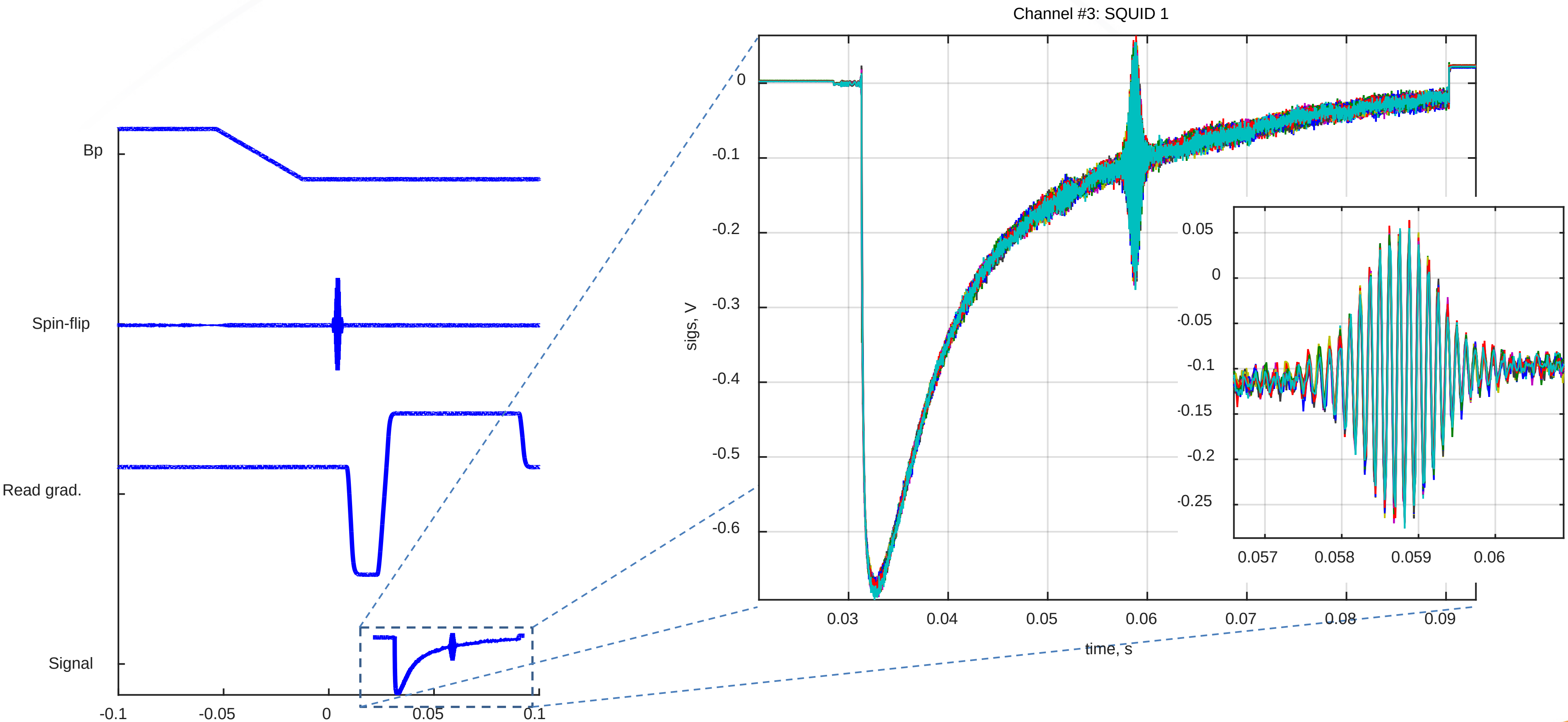




4 s polarization and
0.1 s inversion

0.5 s polarization and
0.5 s inversion

Outlook—Shorter TE (Imaging Sooner)



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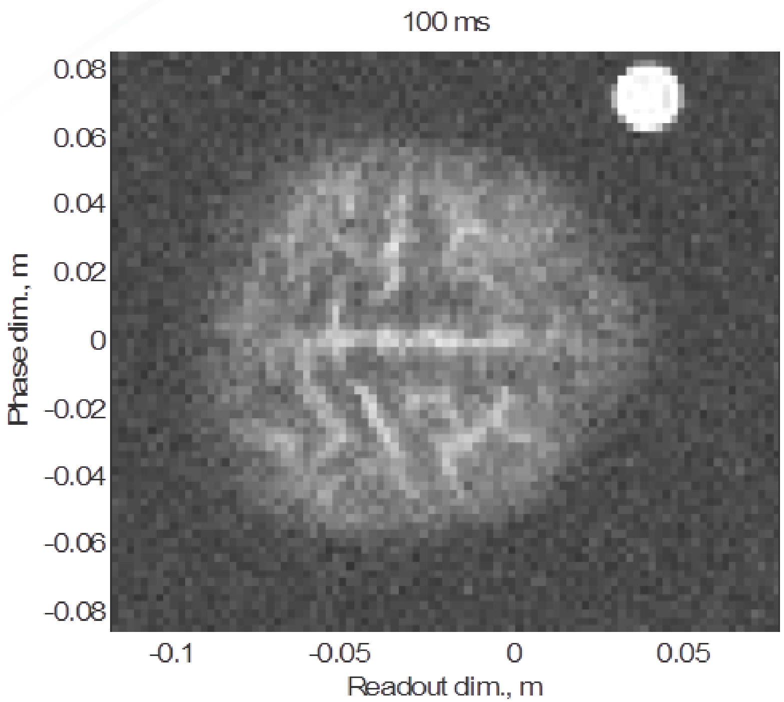
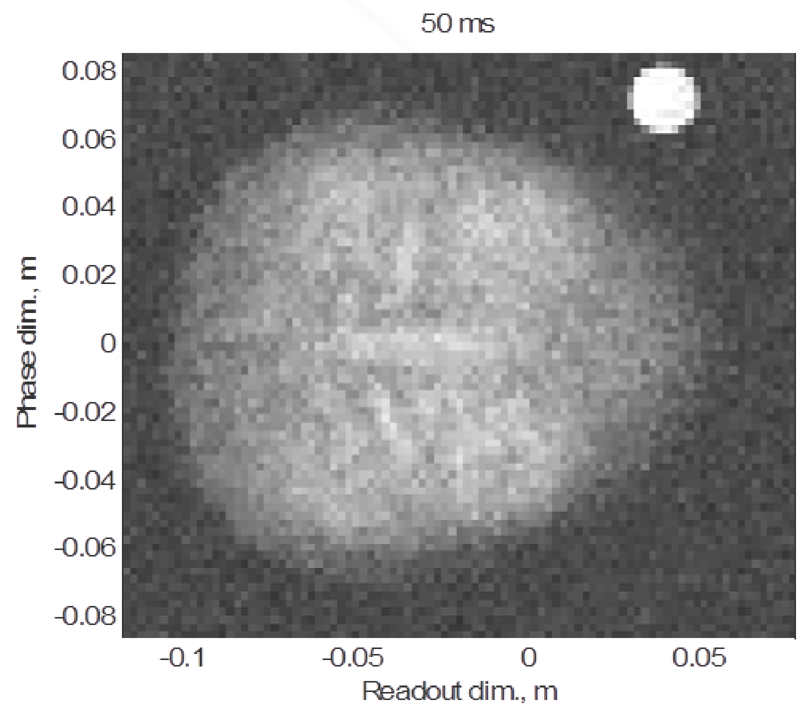
Outlook—Shorter TE (simulations)





- Signal from more tissues
- Signal in subsequent echoes

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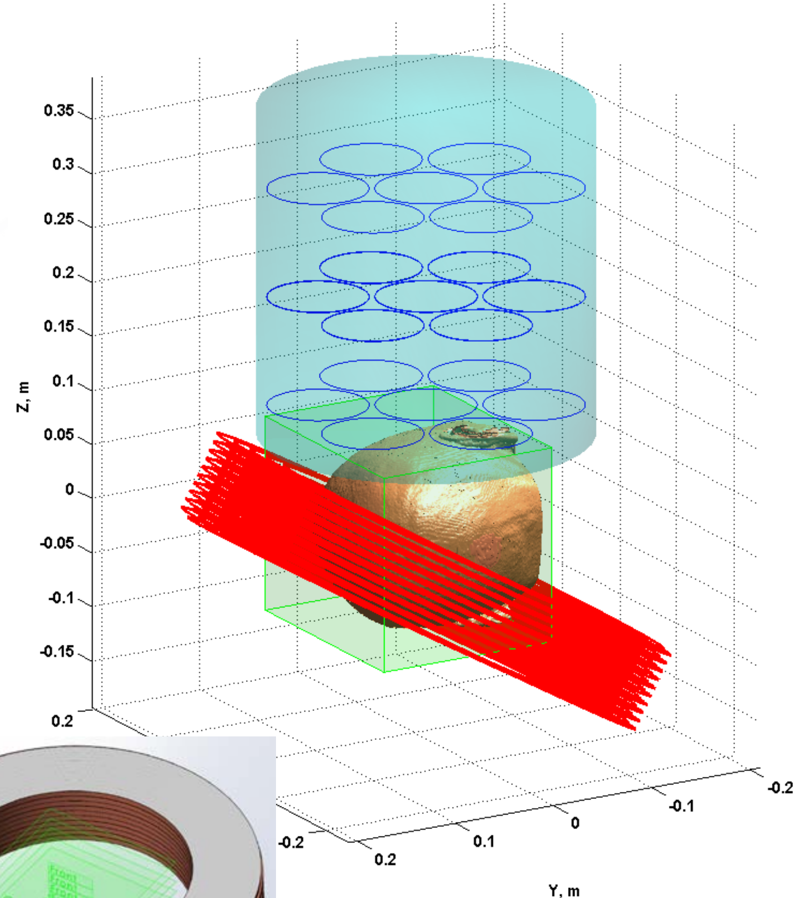
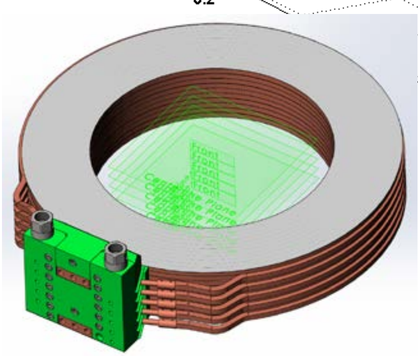
Outlook—New 250 mT B_p Coil





Field @ head center: ~250 mT
Field @ head edge: ~180 mT

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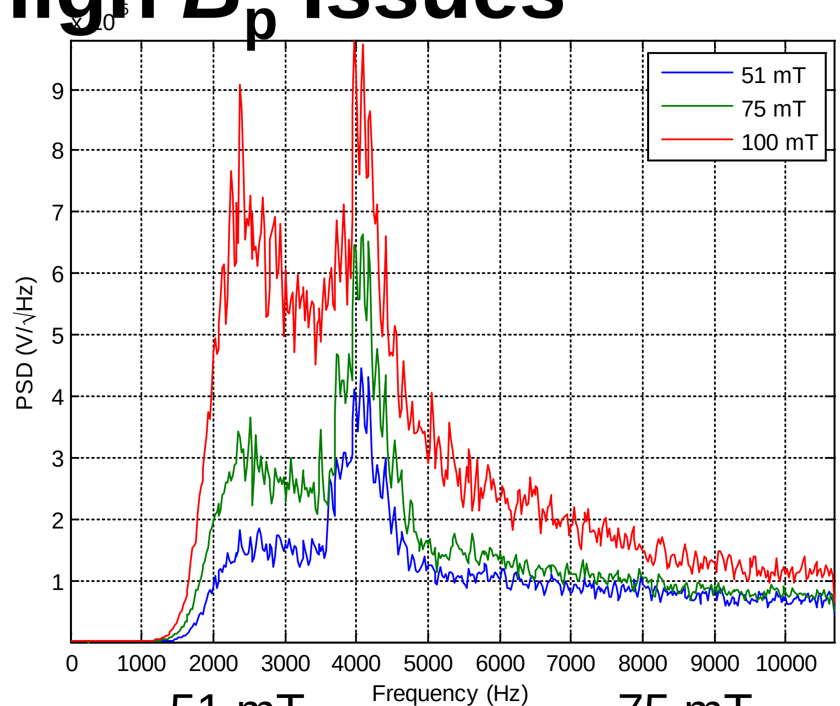
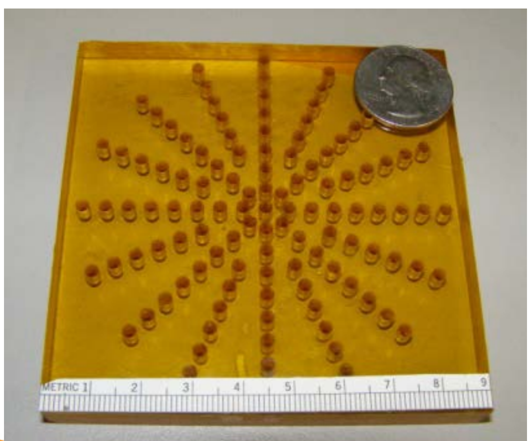
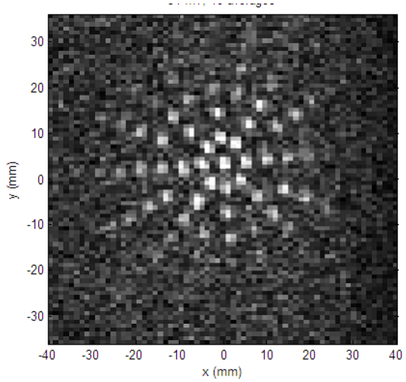
Outlook—High B_p Issues



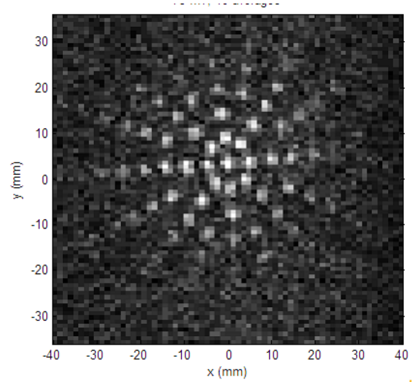
Data from the Nb-gradiometers in the unshielded system



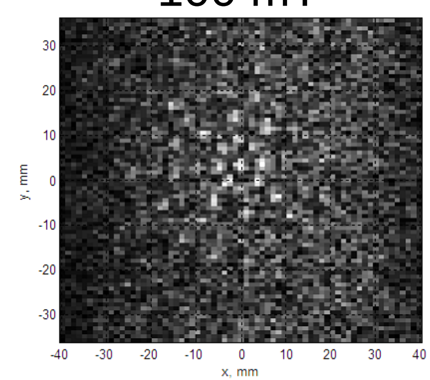
51 mT



75 mT



100 mT



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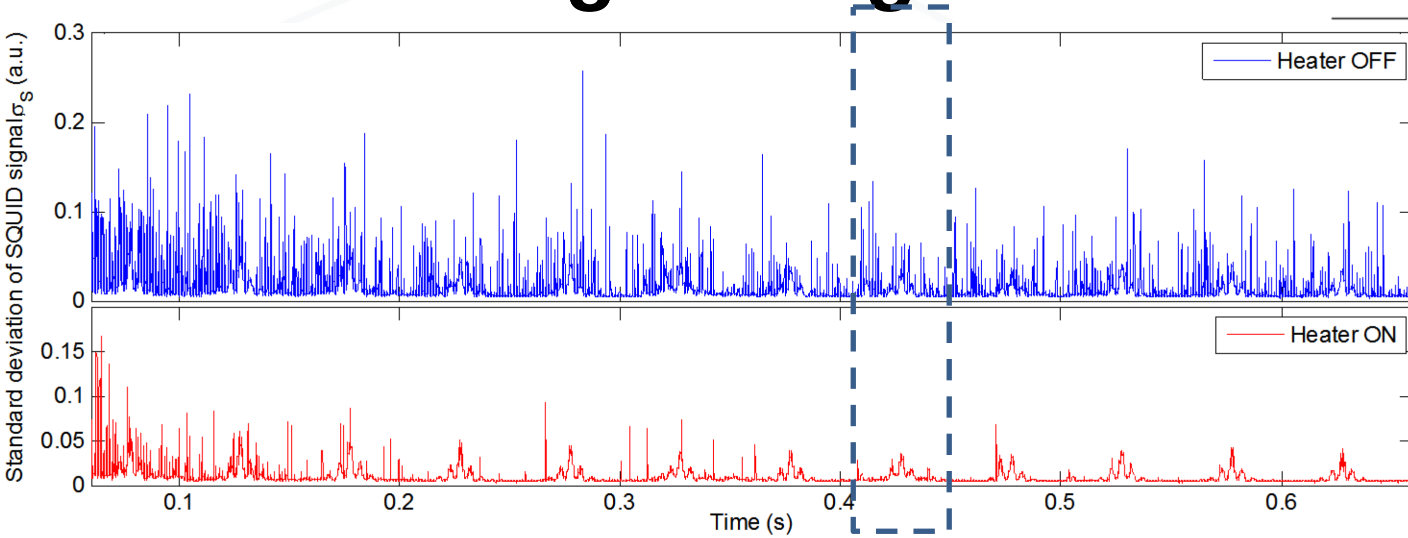
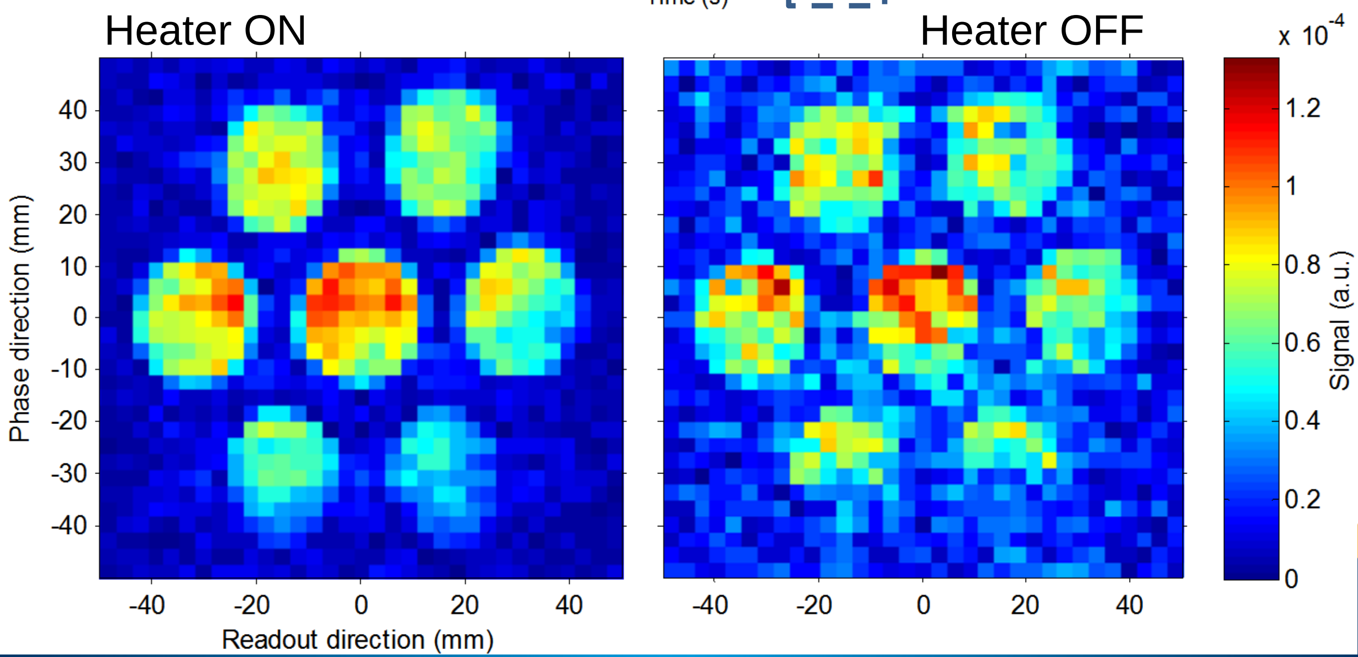
Outlook—Heating of Ta-grads





Summary

- The shielded system works robustly with filtered amplifiers for all fields and gradients
- We need to increase B_p but not increase noise
- Improve duty-cycle to decrease imaging time
- Unshielded imaging with static Earth's field compensation and reference channel de-noising demonstrated
- Promising preliminary results from heating of Ta-gradiometers obtained

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Thank you for your time and attention!