MRI in the wild

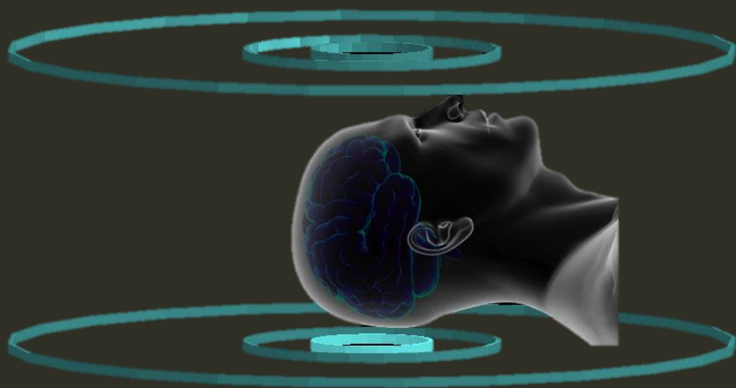
Matt Rosen, Ph.D
MGH/A.A. Martinos Center/Harvard University

Novel Methods for Phytosequestration
ARPA-E Workshop
Chicago, 23 July 2015

MGH/HST Athinoula A. Martinos
Center for Biomedical Imaging
MASSACHUSETTS GENERAL HOSPITAL
Harvard-MIT Health Sciences & Technology

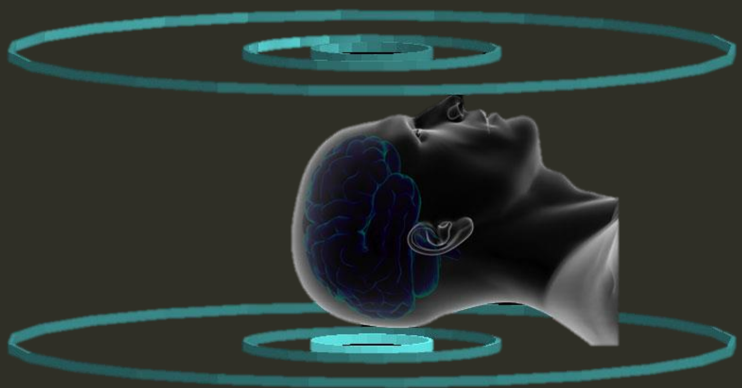
"Wild" MRI?

High-field MRI instruments are of
limited utility in widely deployable contexts



“High-performance” ultra-low field MRI?

What would high-performance ULF MRI look like?



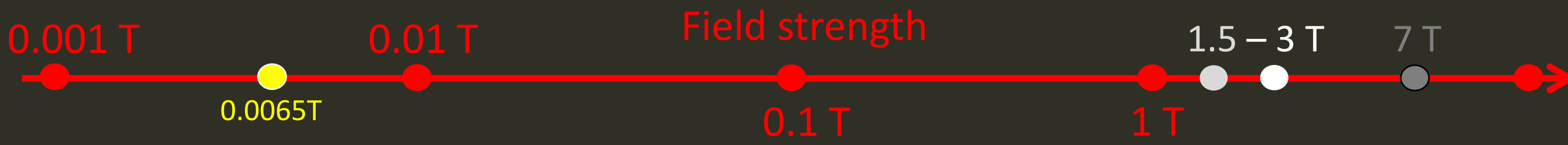
“High-performance” ultra-low field MRI?

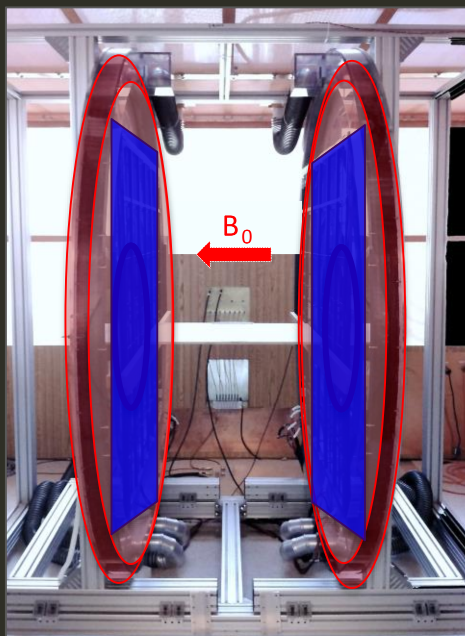
What would high-performance ULF MRI look like?

MGH Connectome scanner : 24 MW

Los Angeles-class nuclear submarine

Ultra-low field MRI?





Custom made
Electromagnet
+
Gradients

6.5 mT

$200k test-bed system

1.5 T – 3T

Cost: ≈ $1 million / Tesla

Weight: 7.3 tons

Cooling: Liquid cryogens / Availability?

Shielding: RF/magnetic

Min. room size: 31m^2 ++

Ultra-low field MRI?

3 T

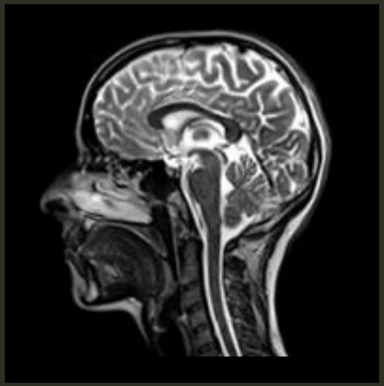
$\times 46^{3/2}$

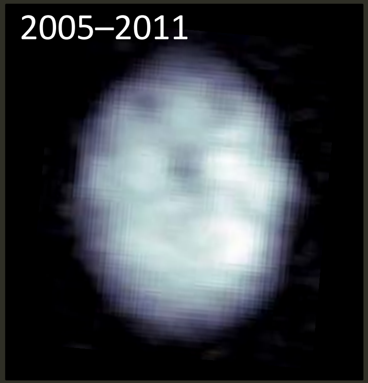
0 SNR

(× 10 000)

0.0065 T

VS





Acquisition time: seconds, minutes…

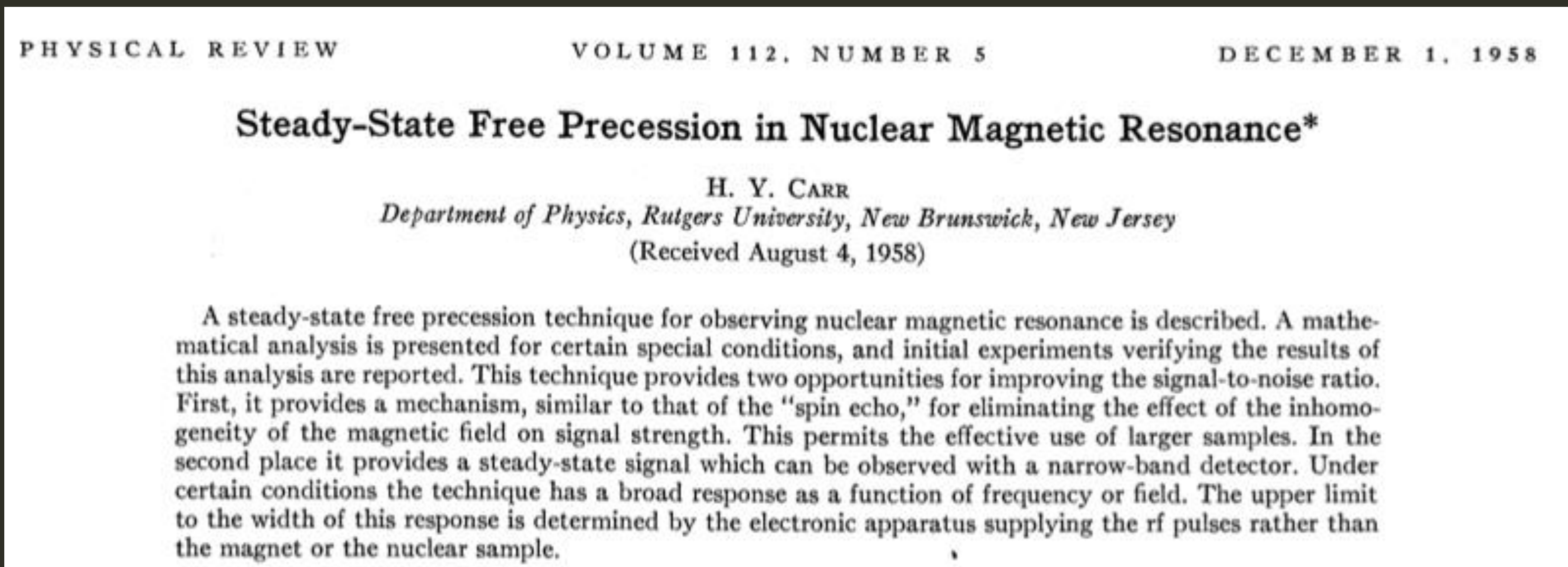
2D Gradient echo – 1 slice – acquired at ULF

Acq. time = 52 min / Voxel size = (3.9 x 7.8 x 15) mm^3

Fast acquisition strategy for ULF MRI

Balanced Steady State Free Precession (b-SSFP):

- Fast & efficient but demanding
- Refocused quantum control-based acquisition

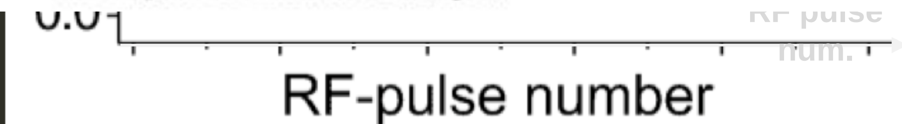


PHYSICAL REVIEW VOLUME 112, NUMBER 5 DECEMBER 1, 1958

Steady-State Free Precession in Nuclear Magnetic Resonance*

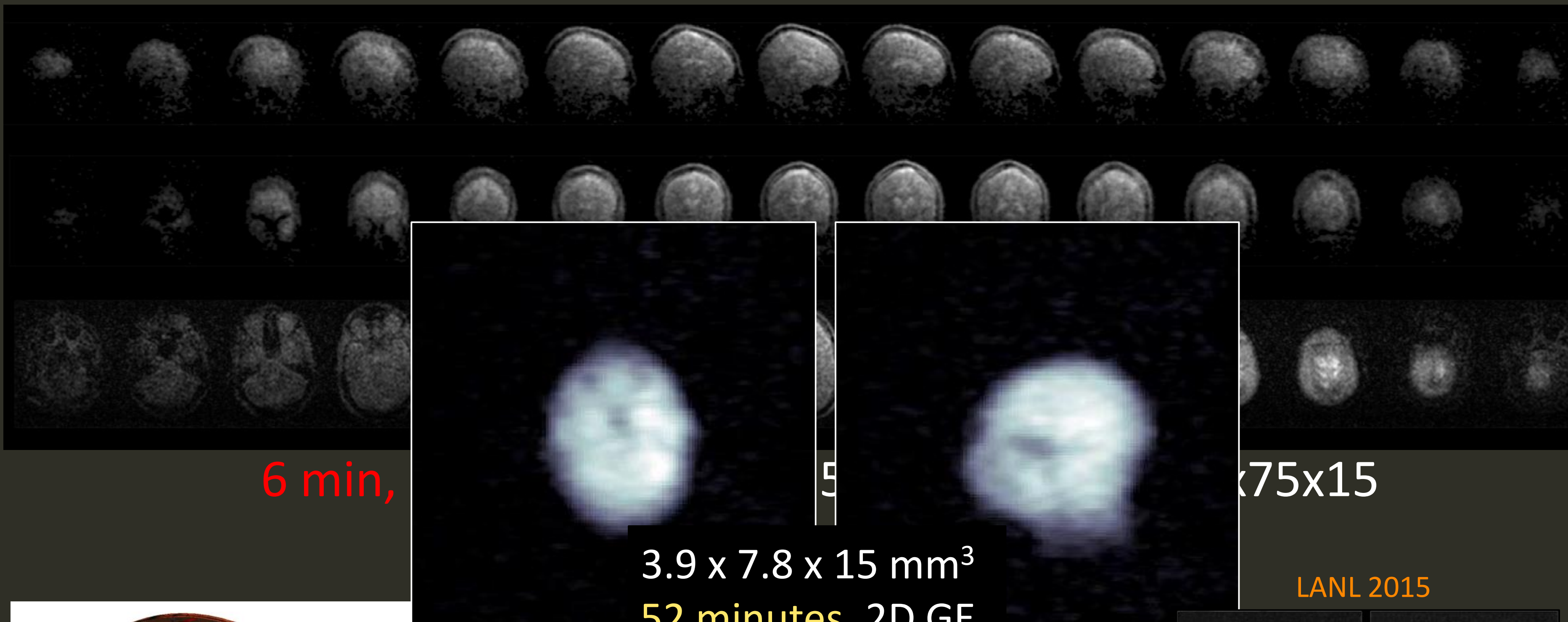
H. Y. CARR
Department of Physics, Rutgers University, New Brunswick, New Jersey
(Received August 4, 1958)

A steady-state free precession technique for observing nuclear magnetic resonance is described. A mathematical analysis is presented for certain special conditions, and initial experiments verifying the results of this analysis are reported. This technique provides two opportunities for improving the signal-to-noise ratio. First, it provides a mechanism, similar to that of the "spin echo," for eliminating the effect of the inhomogeneity of the magnetic field on signal strength. This permits the effective use of larger samples. In the second place it provides a steady-state signal which can be observed with a narrow-band detector. Under certain conditions the technique has a broad response as a function of frequency or field. The upper limit to the width of this response is determined by the electronic apparatus supplying the rf pulses rather than the magnet or the nuclear sample.



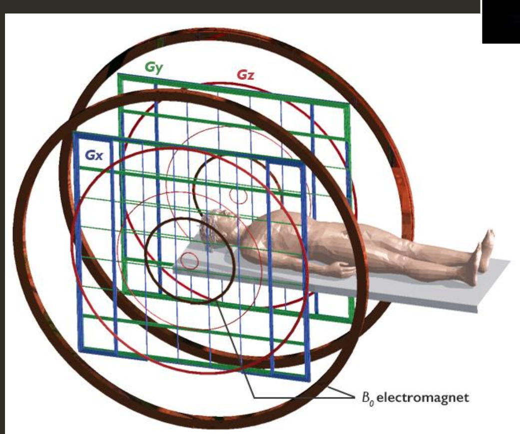
Scheffler *et al.* Principles and applications of balanced SSFP techniques, Eur Radiol (2003) 13:2409–2418

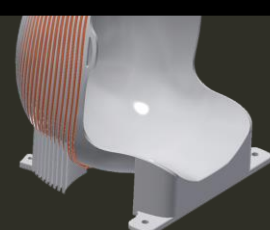
State of the Art: non-cryogenic ULF MRI (6.5 mT)



6 min, 5 x75x15

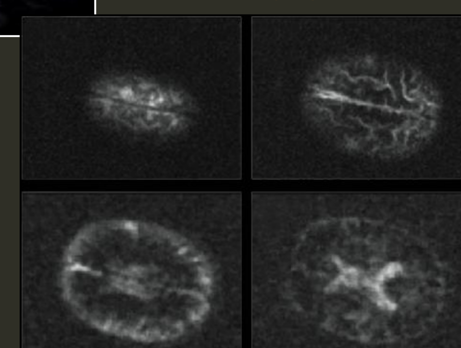
3.9 x 7.8 x 15 mm^3
52 minutes, 2D GE





Custom-fit single channel spiral head coil (276 kHz)

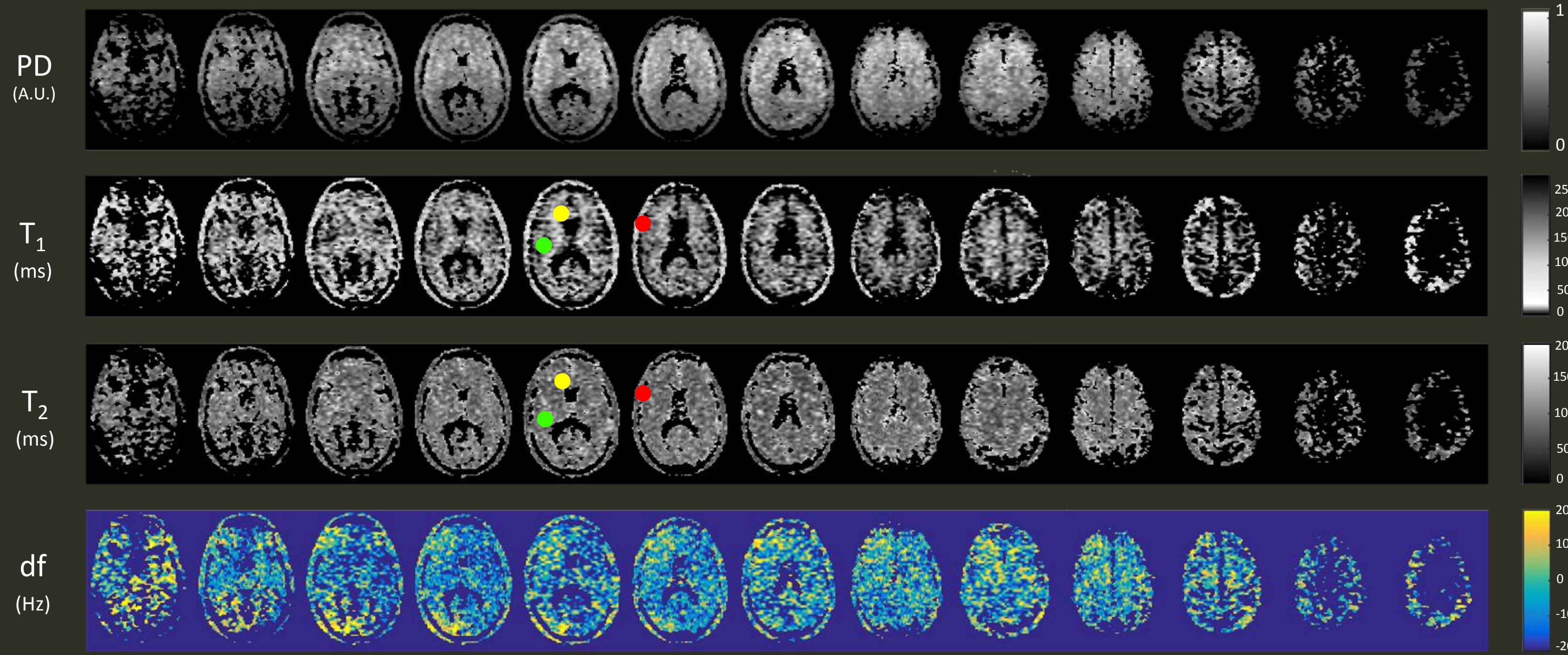
LANL 2015



2 x 2.4 x 15 mm^3 (5 slices)
67 min

3D MR fingerprinting *in vivo* at 6.5 mT

Stochastic Bloch trajectory-based imaging:



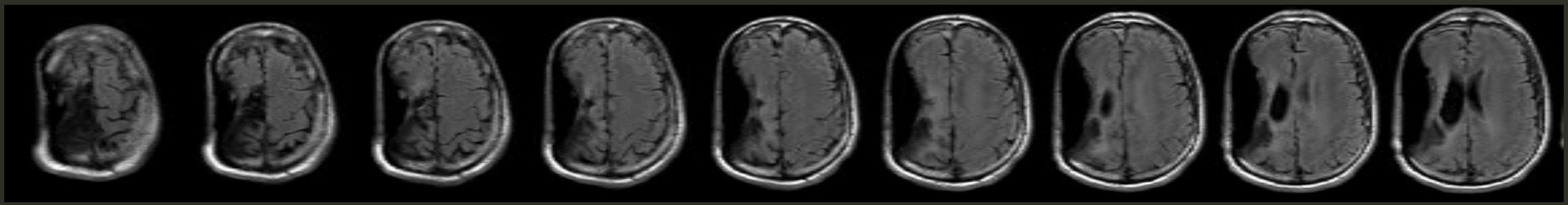
Optimized 20 point trajectory
3x3x10 mm^3
NA: 1
Total acquisition time: 14min

	T_1	T_2
• Gray matter	172ms	85ms
• White matter	127ms	76ms
• Scalp	91ms	69ms

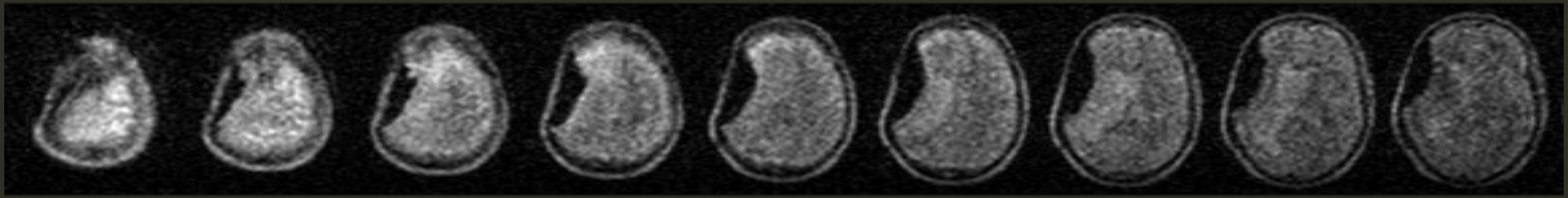
Quantitative image contrast!

Non-cryogenic ULF MRI (6.5 mT):
Ultra-low field vs. high field in clinical TBI

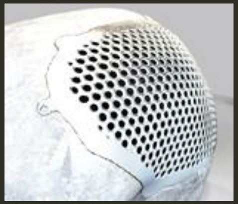
3 T

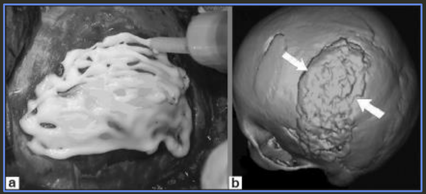


6.5 mT



Traumatic skull cranioplasty w/ titanium mesh & MMA implant





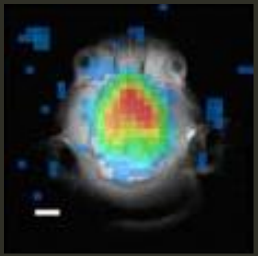
High field: T2 FLAIR
ULF: 3D b-SSFP, 3x3x8.5 mm, 15 slices
NA=140, α=84^{o}, Matrix: 64x75x15, 28 min.

What do we measure in MRI?

- Nuclear (Boltzmann) polarization: $P \sim \mu B / k_B T$
- Magnetization per unit volume ~ $\rho \mu P$

Direct detection:

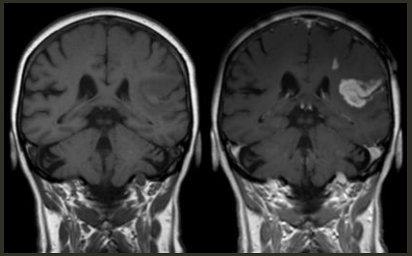
- Liquids, *solids* (thermally polarized)
- …& gases (non-Boltzmann "hyperpolarization")
- Not just ^{1}H!
- ^{3}He, ^{129}Xe, ^{13}C, ^{23}Na, ^{29}Si….



Rosen et. al 1997

Indirect detection:

- Paramagnetic things (Gd) via nuclear relaxation
- Free radicals (Bohr magnetons) via polarization transfer (DNP)



BBB leakage in stroke

Physics: Overhauser techniques transfer electron polarization into long-lived nuclear polarization

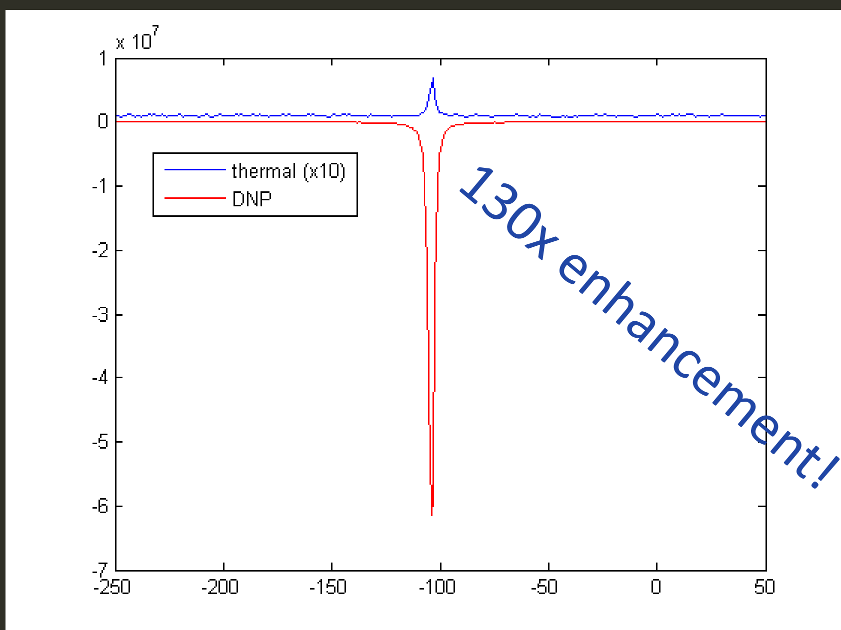
The Overhauser effect

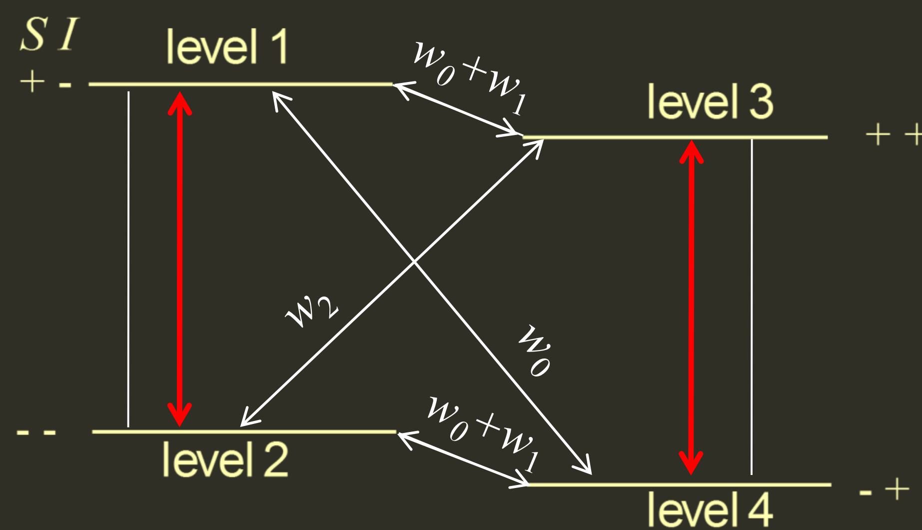
$$H = \hbar\gamma_S\left(\mathbf{S}\cdot\mathbf{H}_0\right) + \hbar\gamma_I\left(\mathbf{I}\cdot\mathbf{H}_0\right) + \gamma_S\gamma_I\hbar^2\left[\frac{8\pi}{3}\left|\psi(0)\right|^2\left(\mathbf{I}\cdot\mathbf{S}\right) - \frac{3\left(\mathbf{I}\cdot\mathbf{r}\right)\left(\mathbf{S}\cdot\mathbf{r}\right)}{r^5} + \frac{\mathbf{I}\cdot\mathbf{S}}{r^3}\right]$$

Zeeman interaction

Scalar | Dipolar

Time dependent coupling



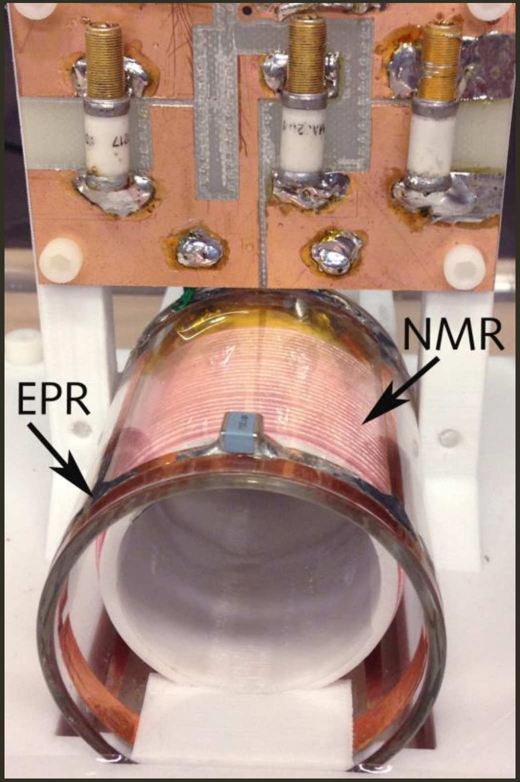


Rates depend on dynamics, H_0, & [e^-]

Hardware: free radical imaging at 6.5 mT

NMR (276 kHz)

Johnson noise dominated

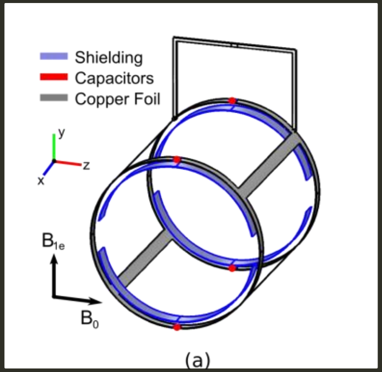


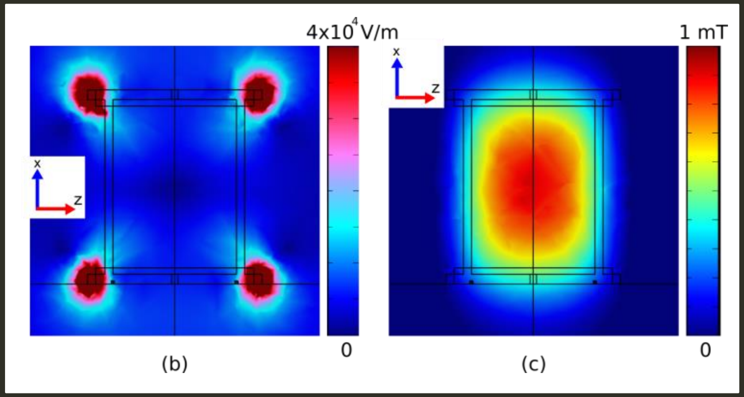
Litz wire
BW=3KHz
Q=92

EPR (141 MHz)

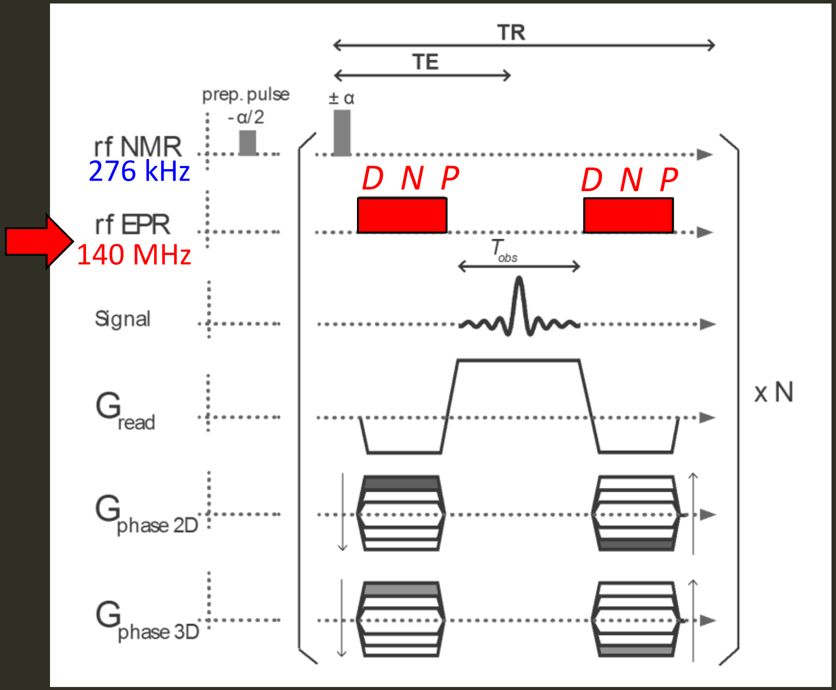
Modified A-G resonator

—High ESR homogeneity
—Suppressed E-field (SAR)

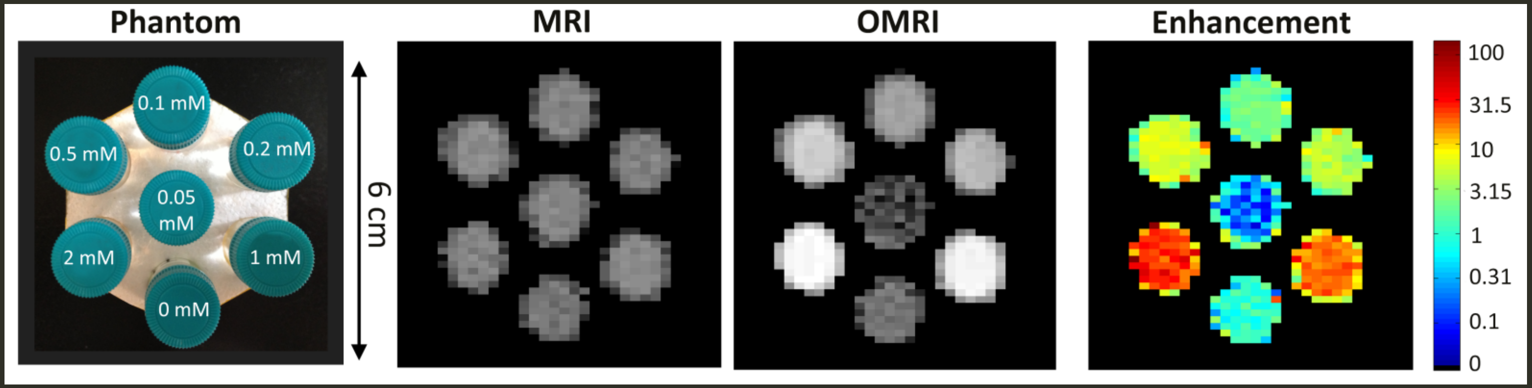




High speed 3D free radical imaging



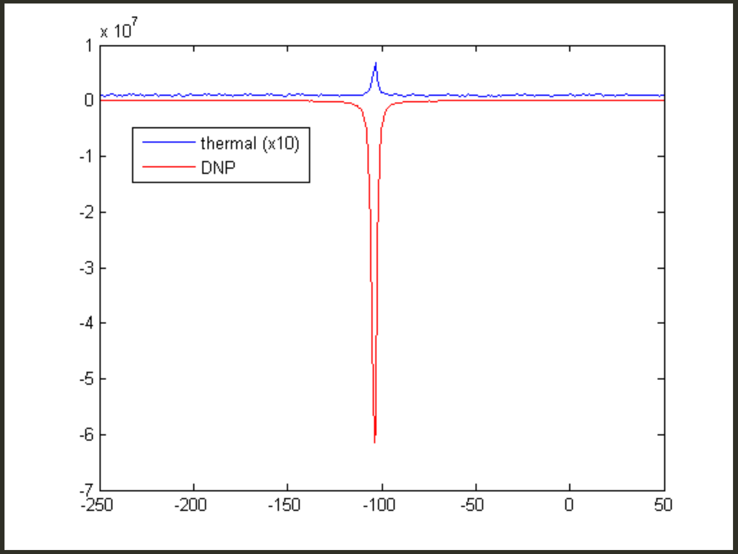
b-SSFP based OMRI
Embedded ESR pulse
No additional sequence time



Images acquired at 6.5 mT: NMR: 276 kHz, ESR: 140 MHz, 2 mM TEMPOL in H2O

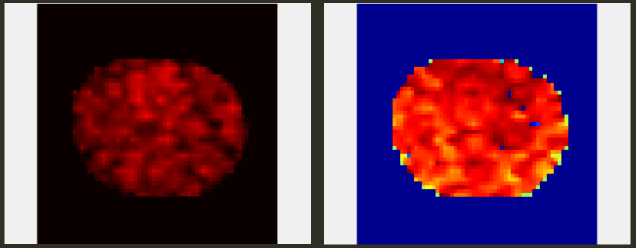
Dynamic *in vivo* OMRI

Proof of concept in healthy rat



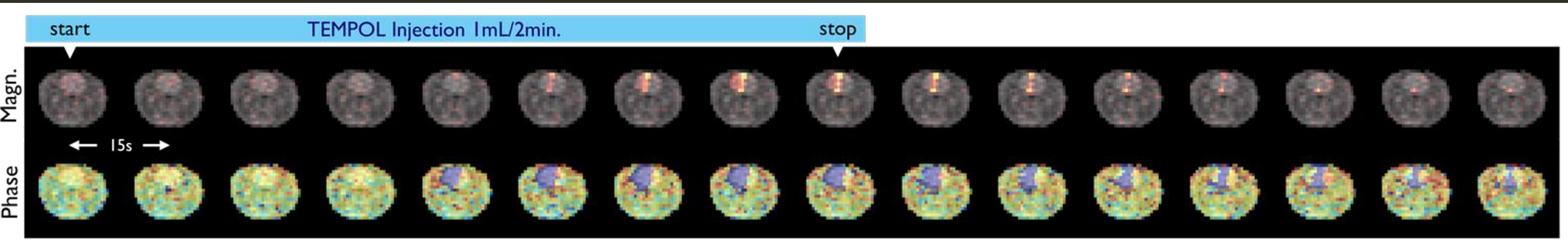
OMRI

Central slice in rat head – axial view



magnitude

phase



Matrix : 128 x 35 x 11

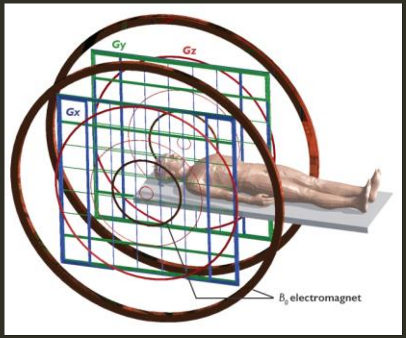
Resolution: 1.7 x 2.2 x 4.2 mm^3

1 full 3D OMRI scan (11 slices) = 10 s + 5 s pause

16 dynamic scans: 4 min total imaging time

Carotid injection: 1 mL in 2 min, 150 mM TEMPOL

Conclusions

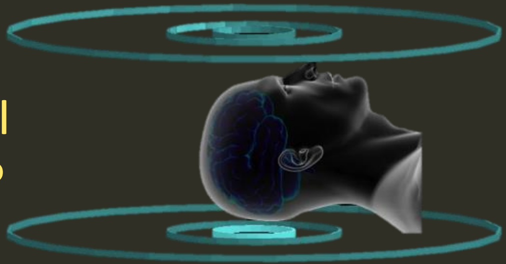


- MRI is possible outside the scanner suite
  - Not limited to brain imaging!
  - Not limited to existing scanner footprint
  - Understand impact of time/resolution tradeoff
  - Next revolution in heath care? Cost!

Eg. highly optimized tradeoff between resolution, speed, specificity, cost?

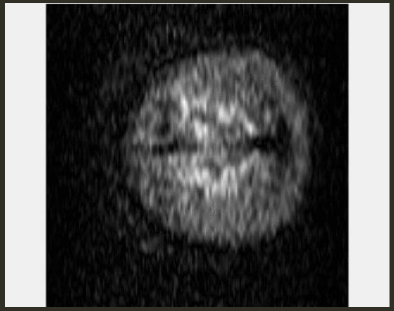
Stethoscope ($50)

- Free radical sensitive MRI is possible
  - Hyperpolarization via *in vivo* DNP & high speed ULF MRI
  - Free radical tracer agents? Redox/metabolic processes?



High-speed, inexpensive “medium resolution” MRI in the wild:

How would you use a tool like this?



Brandon Armstrong
Oliver Baltay
Matt Christensen
Clarissa Cooley
Stephen DeVience
Cris LaPierre
Najat Salameh
Mathieu Sarracanie
Jason Stockman
David Waddington

Thomas Witzel
Cenk Ayata
Fannie Herisson
Ron Walsworth

Funding: DoD/DMRDP
NIH NINDS

MGH/HST Athinoula A. Martinos
Center for Biomedical Imaging

MASSACHUSETTS GENERAL HOSPITAL
Harvard-MIT Health Sciences & Technology