Magnetic Resonance Imaging at Ultra High Field: Hardware, Methods and Applications

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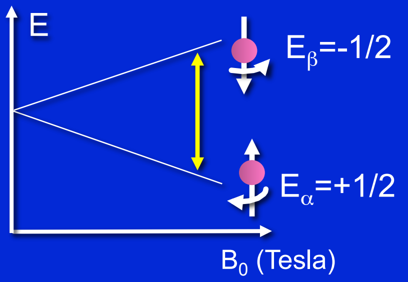
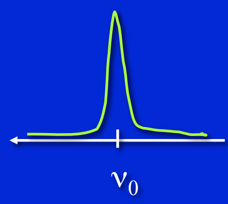
Overview of Talk

- MRI Principles
- UHF MRI Hardware
- MRI Detection/Excitation Methods
- Classification RF Coils
- Virtual lab tour RF surface coils
- Double-tuned RF coils
- Travelling wave detection
- Summary

Principles of MRI



$\Delta E = h\nu_0 = \gamma h B_0 / 2\pi$

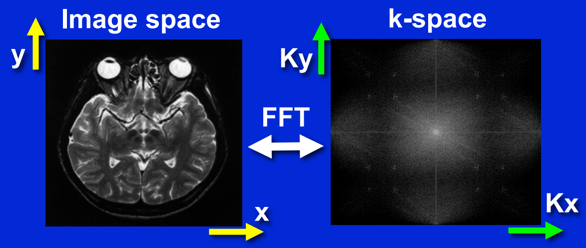


$$\omega_0(\mathbf{r}) = \gamma \cdot \mathbf{B}_0(\mathrm{r})$$

$$\alpha(\mathbf{r}) = \gamma \cdot \mathbf{B}_1(\mathrm{r}) \cdot \mathbf{t}_\mathbf{p}$$

$$k_x(t) = \int \gamma \cdot G_x(t)\, dt$$

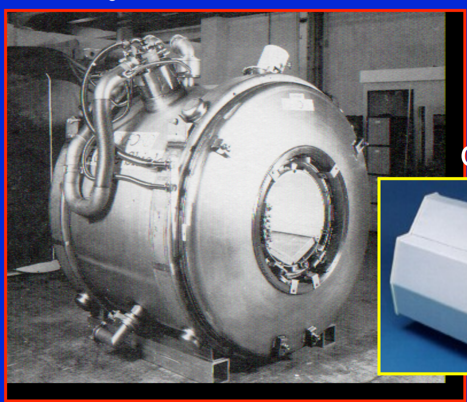
$$k_y(t) = \int \gamma \cdot G_y(t)\, dt$$



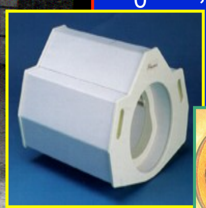
MRI Hardware

- Human Body (spins)
- Superconductive magnet
- (Shim coils)
- Gradient coils (x,y,z)
- Radio frequency coil(s)
- TX/RX electronics

B_0



dB_0/dz, …



B_1

1H, 13C, 23Na, 31P

Common Nuclei/Frequencies

Nuclei	1H	13C	19F	23Na	31P	Electron (EPR/DNP)
gamma (MHz/T)	42.58	10.71	40.06	11.26	17.24	27994
B_0 Field (T)	(MHz)	(MHz)	(MHz)	(MHz)	(MHz)	(MHz)
0.001	0.043	0.011	0.040	0.011	0.017	28
1.5	63.87	16.06	60.08	16.89	25.85	41991
3.0	127.73	32.12	120.16	33.79	51.70	83982
4.0	170.31	42.82	160.22	45.05	68.94	111976
7.0	298.04	74.94	280.38	78.83	120.64	195958
9.4	400.22	100.68	376.52	105.86	162.01	263143
11.7	498.15	125.25	468.64	131.76	201.65	327530

BENEFITS OF HIGH FIELD MRI

- Higher signal to noise ratio
- Improved spatial resolution
- Shorter scan times
- Greater spectral dispersion
- Larger BOLD contrast
- Special applications
  - (^{23}Na, ^{17}O, etc)

$$\nu_0 = \frac{\gamma}{2\pi} B_0 \quad \textbf{(proton)}$$

B_0 (T)	ν_0 (MHz)
1.5	64
3	128
7	298
8	340
9.4	**400**

Design Criteria for High Field RF Coils

1. **Coil issues:**
   - Self-resonance frequency
   - Increased radiative losses
   - Lumped vs distributed models
2. **Sample issues:**
   - Electric and magnetic losses
   - RF penetration effects
   - RF standing wave effects

$$\nu_0 = \frac{\gamma}{2\pi} B_0 \quad \text{(proton)}$$

B_0 (T)	ν_0 (*MHz*)	$\lambda_0 / 2\,(cm)$
1.5	64	234
3	128	117
7	298	50
8	340	42
9.4	400	36

Signal-to-noise-ratio and RF coils

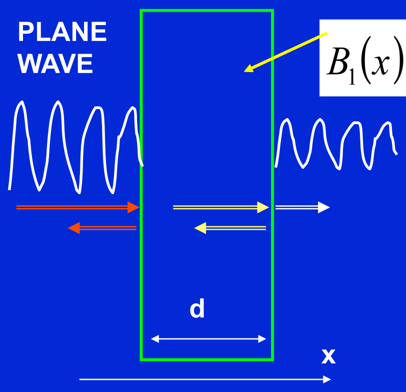
$$\mathrm{SNR} \propto \frac{\mathbf{M}_{\mathbf{xy}} \cdot \left(\frac{\mathbf{B}_{1,\mathbf{xy}}}{\mathbf{I}}\right)}{\sqrt{\mathbf{T}_{\mathbf{coil}} \cdot \mathbf{\Delta f} \cdot \mathbf{V}_{\text{coil effective}}}}$$

$$\mathrm{SAR}_{\mathrm{WB}} = \frac{\text{Total RF Energy Dissipated in Sample (J)}}{\text{Exposure Time (s)} \cdot \text{Sample Weight (Kg)}} \cong \frac{\sigma \cdot |\vec{E}|^2}{2 \cdot \rho}$$

$$\sigma = \text{conductivity}\left(\text{Siemens}/\text{m}\right);\ \rho = \text{material density}\left(\text{kg}/\text{m}^3\right)$$

- **Basic design goals:**
  - minimise B_1 spatial variations over ROI
  - maximise B_1 amplitude per unit current (reciprocity)
  - minimise losses in the RF coil (cool)
  - minimise losses in the sample (volume)
  - minimise Specific Absorption Rate (SAR)
  - and many others!!!

Analytical Model Dielectric Slab



$$B_1(x) \propto \sqrt{e^{-2\alpha x} + \Gamma_S^2 e^{+2\alpha x} + 2\Gamma_S \cos(2\beta x)}$$

- α=attenuation constant
- β= propagation constant
- Γs=reflection coefficient

↓

- ω=Larmor frequency
- ε=permittivity of dielectric
- σ =conductivity
- d=slab thickness

Stratton, EM Theory, McGraw-Hill, 1941

Balanis, Advanced EM, Wiley, 1989

Analytical Model Dielectric Slab

B1 distribution is a combination of RF standing wave and RF penetration effects

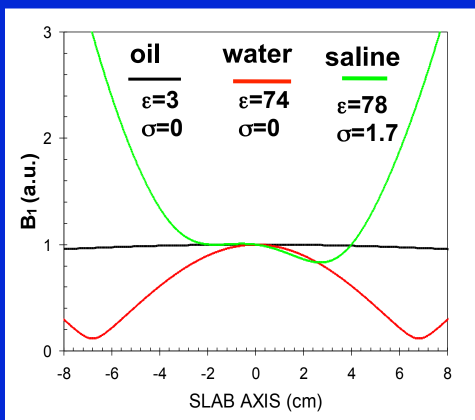
d=16 cm
@ 3 Tesla (128 MHz)

λ/2≈117 cm in air

λ/2≈68 cm in oil

λ/2≈14 cm in water

Alecci *et al*, MRM 46:379 (2001)



3T Radial B_1: Phantoms

Good agreement FD-TD calculation and experiment

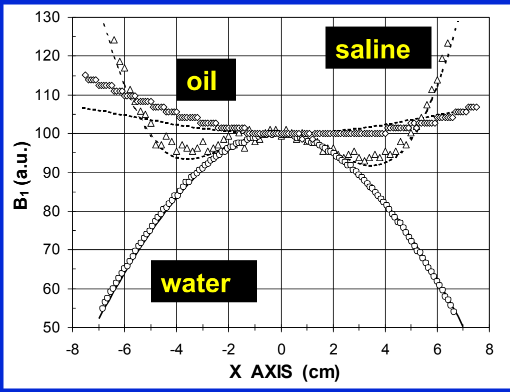
B1 distribution is sample dependent

ΔB1 oil≈10%

Δ B1 water≈50%

Δ B1 saline≈30%

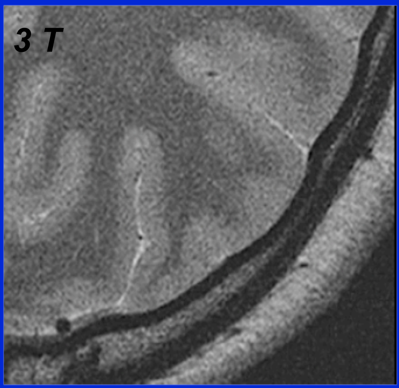
Alecci *et al* MRM 46:379 (2001)

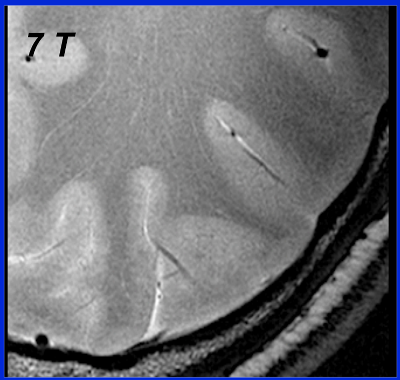


1H UHF MRI in Humans

UHF (>4T) allows SNR improvement

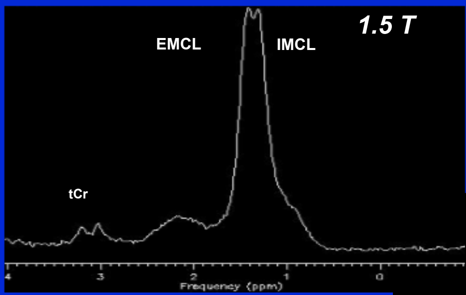
human brain

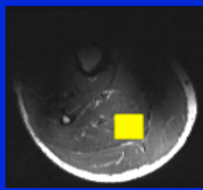




1H UHF MRS in Humans

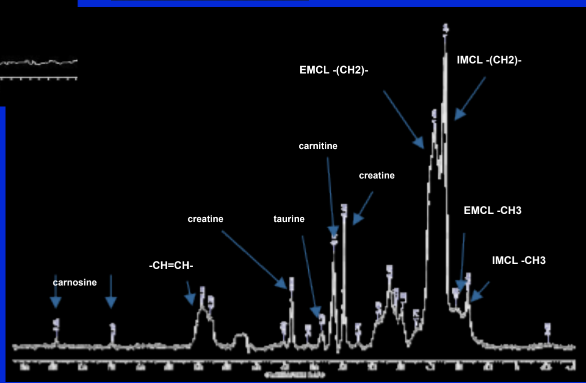
UHF (>4T) allows spectral resolution improvement





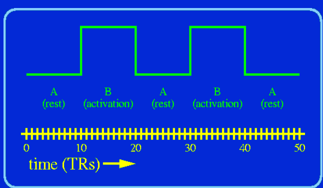
human calf muscle

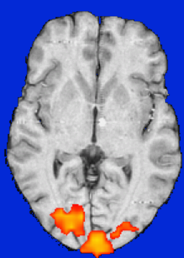
7 T

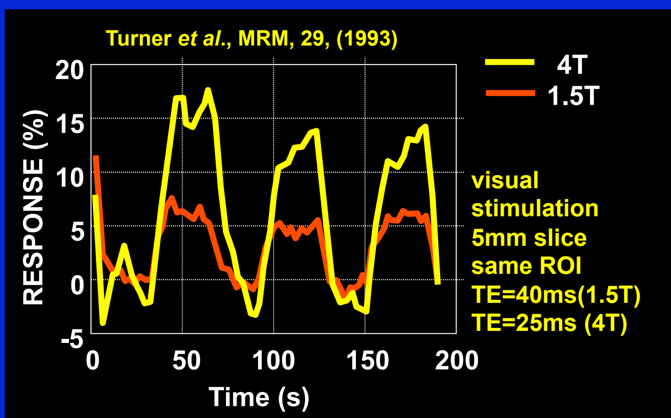


UHF fMRI BENEFITS

Functional MRI in visual cortex

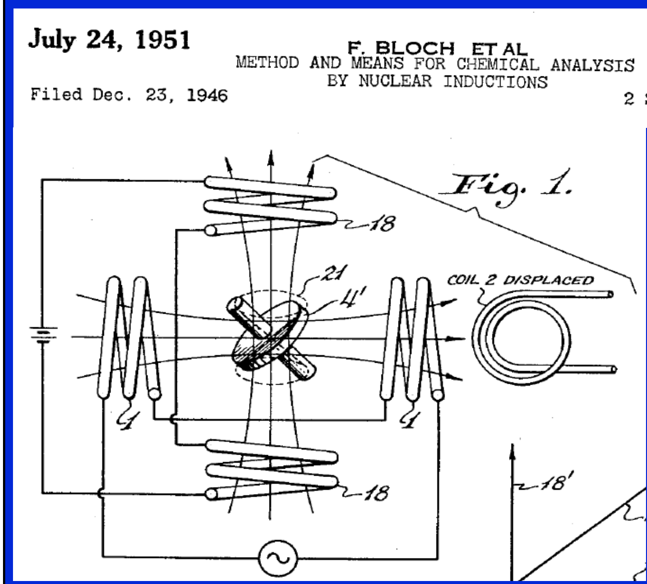






Basic RF coils

Crossed- RF Coils NMR Detection



B-H-P, Phys Rev 1946

Traditional RF coils form standing radio-frequency waves in the sample.

The magnetic component B1, in TX mode causes nutation of the magnetization M and in RX mode governs the probe's receive sensitivity

MRI Signal Detection/Excitation Methods

- **Standard MRI signal detection** is based on Faraday induction via the use of one (or more) RF coil (tuned circuit) positioned in close proximity of the sample under investigation
- **Alternative Principles:**
  - Superconducting Quantum Interference Devices (Day, PRL 1972)
  - Dielectric resonators (Balaban et al, JMR 1990)
  - Hall Probes (Boero et al, Appl Phys Lett 2001)
  - Structured Materials Flux Guides (Wiltshire et al, Science 2001)
  - Atomic Magnetometers (Savucov et al, PRL 2005)
  - Magnetoresistive Elements (Verpillat et al, PNAS 2008)

COMMON FEATURE:

they rely on close coupling between the detector and sample

- **Novel Principles:**
  - Parallel Receive (pRX) (Pruessmann et al, MRM 1999, Sodickson et al, MRM 1997)
  - Parallel Transmit (pTX) (Sotgiu et al, MRI 1988, Katscher et al, MRM 2003)
  - Traveling Wave Detection (Brunner et al, Nature 2009)

Function of RF coil

TX: high efficiency in transmission, i.e. shortest 90° RF pulse with availabe input peak RF power

RX: high efficiency in signal reception, i.e. highest signal-to-noise ratio

Principle of reciprocity

↓

Maximize the measured voltage for a given precessing magnetization

&

minimize the noise from the coil, the sample and the environment

A resonant RLC circuit offers the maximum output at the resonance frequency and a reduced output at lower/higher frequencies (band pass).

Classification RF Coils (1)

- Operating field
  - Ultra Low Field (1μT-0.1T), Low Field (0.1T-1.5T), High Field (3T-4.0T), Ultra High Field (4.7T-11.7T)
- Modality
  - Single Tuned (1H), Double Tuned (1H & 23Na), Triple Tuned (1H&13C&31P)
- Geometrical Design
  - Surface, Volume, Phased-Array, RX-Parallel-Imaging elements (RX-PI), TX-Parallel-Imaging elements (TX-PI), Combined TX/RX-PI
- Practical features
  - Materials, TX/RX mode, TX-only, RX-only, Linear/Circular Polarization, Shielded/Unshielded, Quality Factor, Self-Resonance Limit, Eddy Currents, Radiation Losses, SAR

Classification RF Coils (2)

- Applications
  - Research, Pre-clinical, Clinical
- Organ/Tissue Districts
  - Whole Body, Brain, Neck, Cardiac, Shoulder, Wrist, Knee, Calf, Fingers, Endorectal, etc.
- Structural/Functional Use
  - Anatomy, Functional, Spectroscopy, Perfusion, DNP
- Quality Control/Safety Aspects
  - RF Artifacts, Periodic Ceck /Calibration, Positioning of coil(s), Calibration based on individuals (male, female, child, obese), SAR requirements, MR Thermometry

Double-Tuned
UHF RF Coils

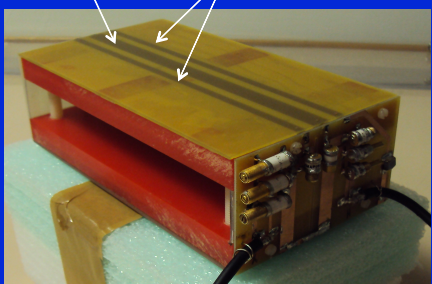
4T Double-Tuned Microstrip RF Coil Prototype

Vitacolonna et al, Proc. ISMRM 2009

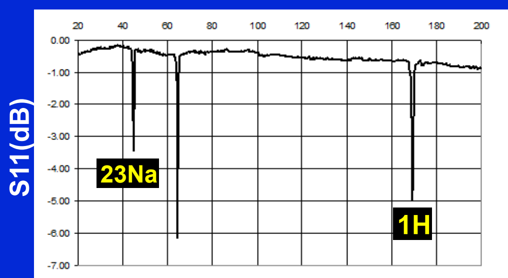
f_{1H}=168.3 MHz ⟶ λ_{1H} = 1.8 m

f_{23Na}=44.5 MHz ⟶ λ_{23Na}=6.7 m

1H **23Na**



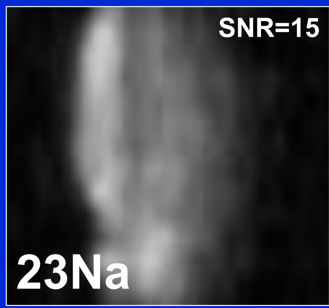
- **1H channel:** one microstrip; width=10 mm; CL=11 pF
- **23Na channel:** two microstrips, width=5 mm; separation=20mm; CL=68 pF
- **Air/Plastic gap**=35 mm
- **Copper ground:** 100 mm x 190 mm



4T Double-Tuned MRI

Vitacolonna et al, Proc. ISMRM 2009

FOV=192*230 mm^2
Resolution=128*153
Slice thickness=1.5 mm
NEX=1
TA=5 min



FOV= 192*192mm^2
Resolution=128*65
Slice thickness=3 mm
NEX=32
TA=7 min

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