Magnetic Resonance Imaging: The RF subsystem

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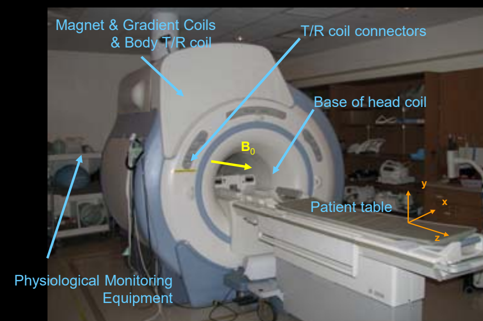
MRI Scanner Components



MR Signal Detection

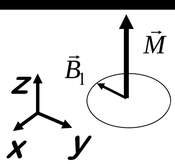
***M*: Magnetization**

$$\vec{M} = M_0 \vec{e}_z$$

f_0: Larmor Frequency

$$f_0 = \frac{\gamma}{2\pi} B_0$$

= 63.86 MHz



B_1 = Transverse Field

$$B_1(t) = \hat{B}_1 \sin(2\pi f_0 t)$$

$\hat{B}_1$ **= 20 μT = 0.2 G**

Contents

- The RF coil
  - Transmit Operation
  - Receive Operation
  - Geometry and B1 Field Distribution
- Matching and tuning
- RF subsystem
  - Transmit
  - Receive

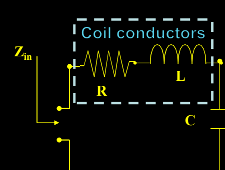
The radiofrequency coil

- ***Functions***
  - Set up uniform transverse RF magnetic field
  - Sense NMR signal
- ***Types***
  - Surface coils
    - Single surface coils
    - Multi-channel arrays
      - Linear arrays
      - Volume arrays
  - Volume coils
    - Linear
    - Quadrature

The radiofrequency coil

- Constructed using conductive wire, rods or tape
- Coil impedance is minimum at resonance

$$Z = R + j\omega L + \frac{1}{j\omega C}$$



The radiofrequency coil

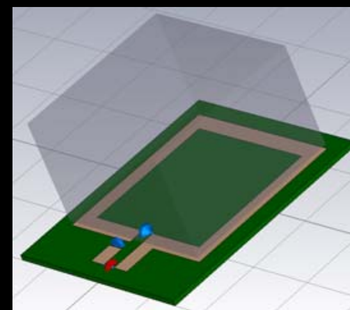
- Principle of operation:
  - Transmit phase:
    - Ampere's circuital law

The integral of the magnetic field around a closed loop that encloses a current carrying conductor is proportional to the magnitude of the electric current in that conductor.

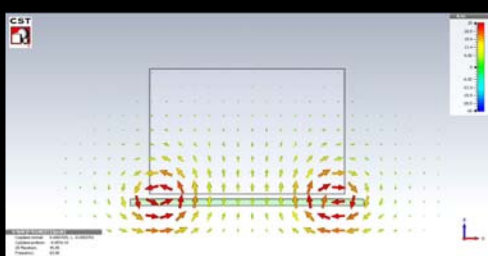
$$\oint_c B.dl \propto I_{cond}$$

Source: Wikipedia

A simple RF Coil



Where should I place my phantom / animal ?

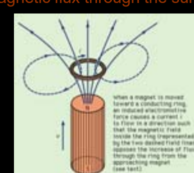


The radiofrequency coil

- Principle of operation:
  - Receive phase:
    - Faraday's law of electromagnetic induction

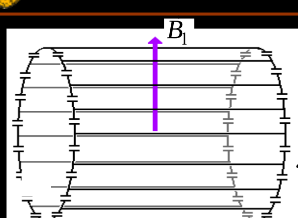
The electromotive force (emf) induced around a closed path is proportional to the rate of change of magnetic flux through the surface bounded by that path.

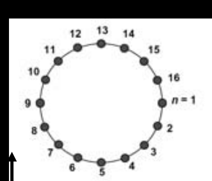
$$\varepsilon \propto -\frac{d}{dt}\iint_S B.dS$$

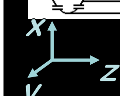


Source: Britannica.com

Birdcage Coil – RF Excitation

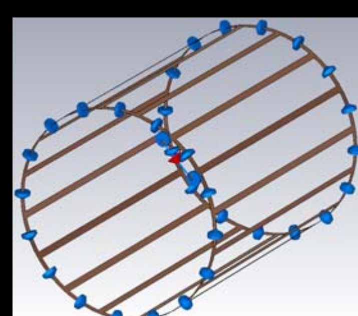




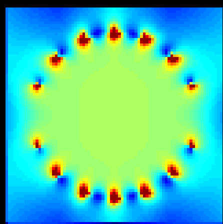


$$J_n = J_s(t)\sin(2\pi(n-1)/N)$$

$$J_s(t) = \hat{J}_s\cos(2\pi f_0 t)$$



Linear Polarized Field



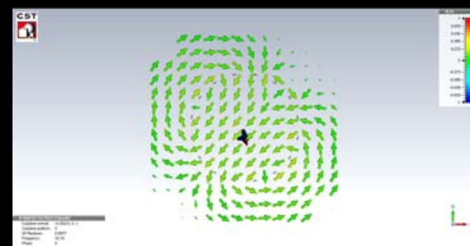
$$J_n = J_s(t)\sin(2\pi(n-1)/N)$$

$$J_s(t) = \hat{J}_s \cos(2\pi f_0 t)$$

$$\vec{H}(t) = \hat{H}\cos(2\pi f_0 t)\vec{e}_x$$

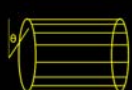
$$H(t) = \frac{\hat{H}}{2}\left(e^{j2\pi f_0 t} + e^{-j2\pi f_0 t}\right)$$

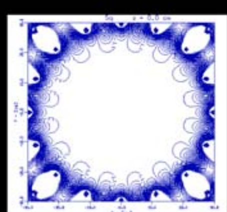
Linear Polarization



The transmit coil…volume coil

- Axial current on infinitely long cylindrical surface whose amplitude varies as the sine of the azimuthal angle produces uniform transverse field
- Birdcage coil: approximation of sinusoidal current distribution





Single feed point: Transverse field is linearly polarized

For circularly polarized field, second feed point placed 90° to first and excited at quadrature phase difference

The birdcage coil (Eddy Boskamp, GE Medical Systems)

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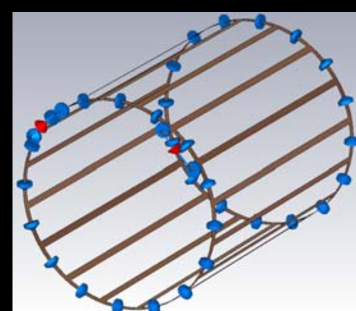
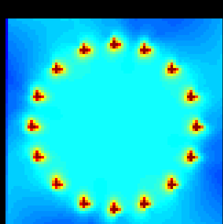


Circular Polarized Field



$$J_n = J_{A,n} + J_{B,n}$$

$$J_{A,s}(t) = \hat{J}_s \cos(2\pi f_0 t)$$

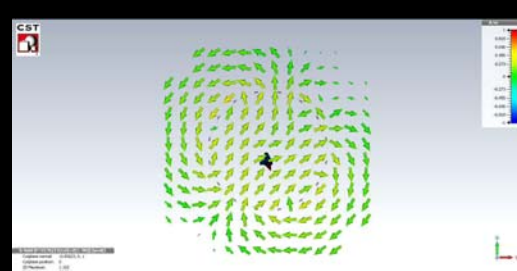
$$J_{B,s}(t) = \hat{J}_s \sin(2\pi f_0 t)$$

$$\vec{H}_x(t) = \hat{H}\cos(2\pi f_0 t)\vec{e}_x$$

$$\vec{H}_y(t) = \hat{H}\sin(2\pi f_0 t)\vec{e}_y$$

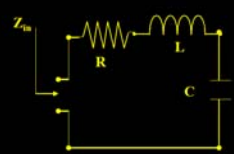
$$H(t) = \hat{H}e^{j2\pi f_0 t}$$

Quadrature Excitation



The radiofrequency coil

- RLC circuit
- Constructed using conductive wire, rods or tape
- R and L are inherent in conductive element
- C is used to resonate the coil
- Coil impedance is minimum at resonance



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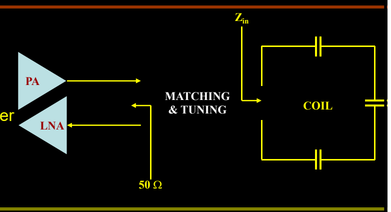
Matching and Tuning

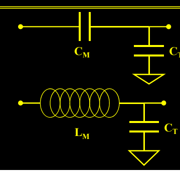
- Matching
  - PA, LNA are 50 Ω systems
  - Match coil Z to 50 Ω for max power transfer
- Tuning
  - Tune coil to desired center frequency



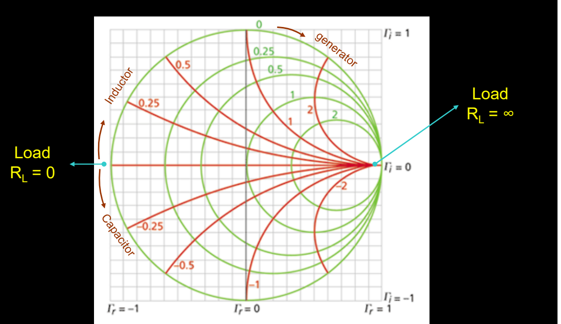
Most commonly used for MR coils:

2 element 'L' matching networks

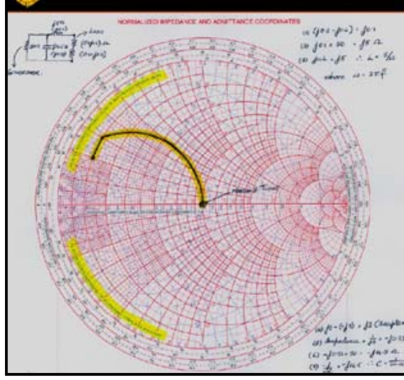
C_T tunes the coil; C_M or L_M match to 50 Ω



The Smith Chart



The Smith Chart



- Load impedance $Z_L = (5+j10)\Omega$
- Generator impedance $Z_G = 50\Omega$
- Characteristic impedance, $Z_0 = 50\Omega$

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RF coil…Match & Tune procedure

- Measure coil impedance
  - Careful about choosing the measurement plane!
- Determine series coil capacitance
  - If coil inductance is too large, reduce it to a manageable value
- Determine parallel matching capacitance
  - Impedance measurement close to the 50Ω impedance circle
- Determine series tuning capacitance
  - Final tuning/matching by adjusting the series/parallel capacitor

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The transmit coil

- High homogeneity: Uniform flip angle

$$\alpha(\vec{r}) = \gamma \int_0^{\tau} B_1(\vec{r},\tau)\,d\tau$$

$$S(\vec{r}) \mu \left(\sin\{\alpha(\vec{r})\}\right)^3 \quad \text{Spin Echo Sequence}$$

$$S(\vec{r}) \mu \sin\{\alpha(\vec{r})\} \quad \text{Gradient Echo Sequence}$$

- High sensitivity and Q: minimum power requirement

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Flip angle variations

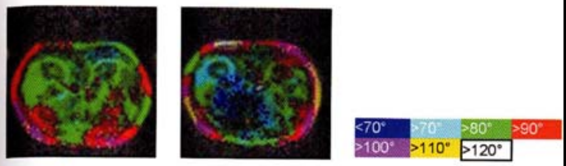
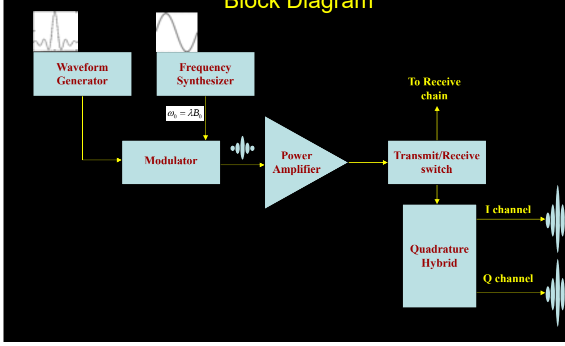


Figure 15.4
Flip angle distribution due to an inhomogeneous B_1 field in a human object at 63 MHz **(left)** and 126 MHz **(right)**.

RF subsystem…The transmit chain

Block Diagram



The receive coil

- SNR optimization*

$$SNR \sim \sqrt{\frac{Q_L}{V_{eff}}} \qquad \frac{1}{Q_L}=\frac{1}{Q_0}+\frac{1}{Q_{pat}} \qquad V_{eff}=\int \frac{B_1^2}{B_{1(ROI)}^2}\,dV$$

  - Patient losses should dominate
  - $Q_0 > 5Q_L$
  - Coil should fit anatomy of interest
- Loss mechanisms
  - Coil losses
  - Dielectric losses
  - Radiation losses
  - RF eddy current losses

High SNR
Not very homogeneous sensitivity

* From Lecture notes on RF subsystem by Dr. Ed Boskamp

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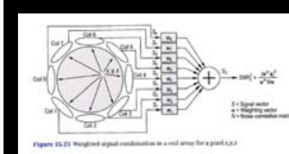
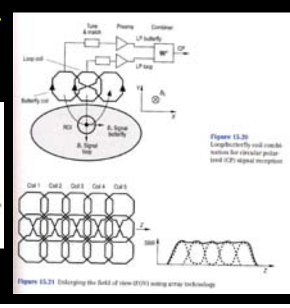
Receive Coil

High SNR
Not very homogeneous sensitivity

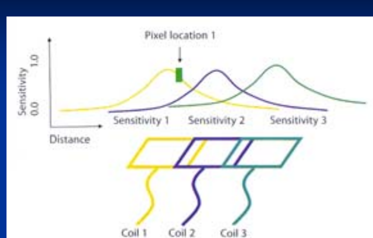
- Optimize coil fill factor





Alexey Samsonov, PhD, UW Madison

Multichannel Reception

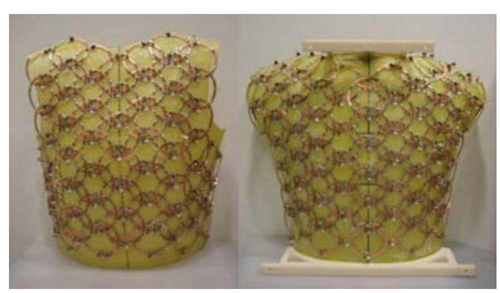


- Receive channels a.k.a. receivers, coil elements
- Elements sensitive to signal from limited regions
  - depth of penetration is on the order of the coil diameter

Parallel Imaging in Clinical MR Applications, Springer, 2007

Phased Array

128-Element Cardiac Array



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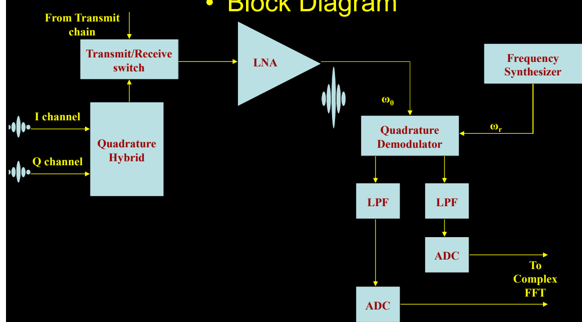
Parallel MRI: Challenges

- Generally, Signal-to-Noise Ratio is degraded
- Hardware issues
  - Multi-channel receiver hardware
  - Multi-element coil systems
  - Dedicated image reconstruction system

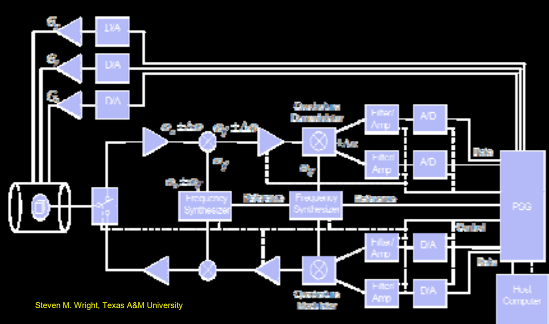
90 Channel Array from MGH

RF subsystem…The receive chain

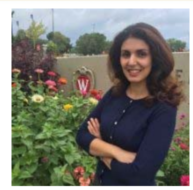
- Block Diagram



Block diagram of the MR system



Steven M. Wright, Texas A&M University



- Bahar Behzadnezhad
- PhD candidate in Electrical Engineering
- Mentors:
  - Nader Behdad, Dept. of ECE
  - Alan McMilan, Dept. of Radiology

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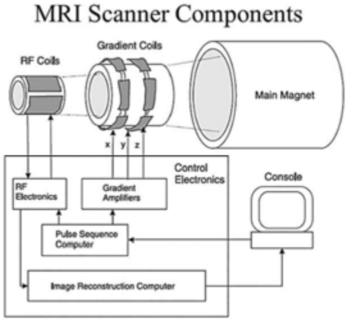
MRI Scanner Components



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Proton Imaging Frequencies in MRI

Magnetic Field Strength	Frequency
0.8 T	34.06 MHz
1.5 T	63.86 MHz
3 T	127.72 MHz
7 T	298.01 MHz

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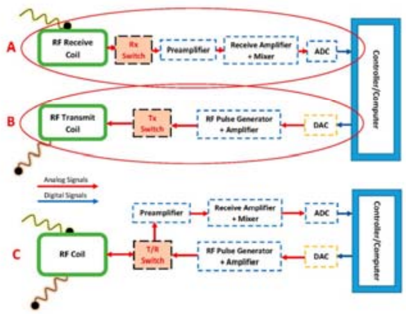
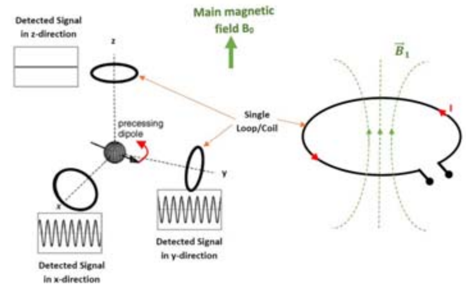
Modes of Operation

TX, RX, TX/RX

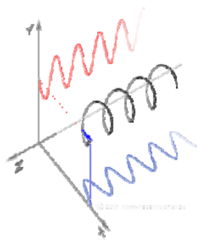


Mode of Operation

Linear, Circular



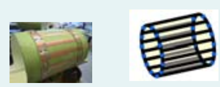
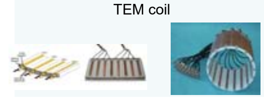
Wave Polarization



A circularly polarized wave as a sum of two linearly polarized components 90° out of phase

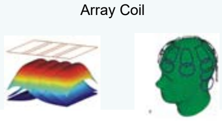
Types of RF Coils

Volume coils (Birdcage coils, TEM coils)

	🙂	🙁
Birdcage Coil 	Excellent transmit magnetic field homogeneity below 3T for a large FOV	Poor SNR significant coupling between the patient and the coil at high frequencies
TEM coil 	Homogeneous magnetic field at high frequencies (7T and above)	Poor SNR

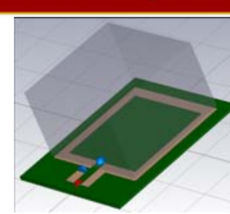
Types of RF Coils

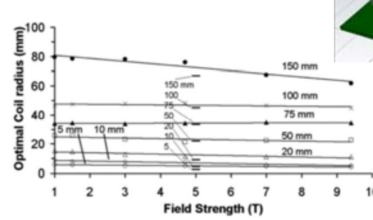
Surface Coils

	🙂	🙁
Single element 	High SNR for receive	Poor field homogeneity for transmit for larger FOV
Array Coil 	High SNR Large FOV	Design Complications Coupling between elements

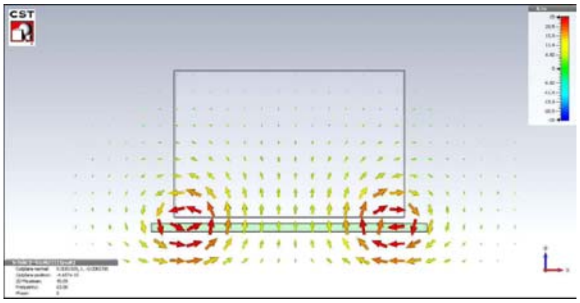
Single Loop RF Coil

For a target depths of interest, determined with full-wave simulations





B1 Field distribution



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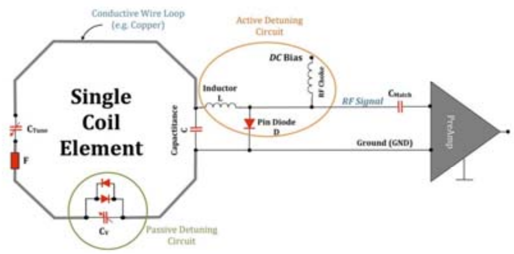
Single Element Circuit Schematic

A typical circuit schematic for a receive-only coil element



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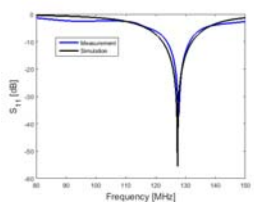
Measurements



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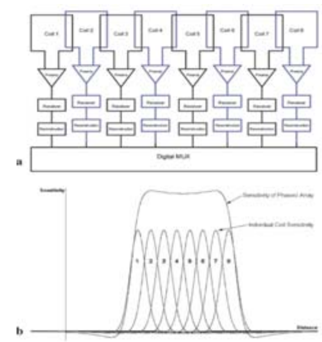
Coil Array



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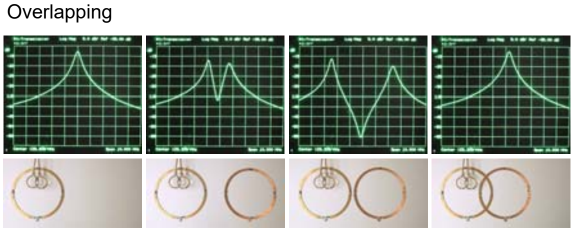
Decoupling

Overlapping



- Capacitive decoupling
- Preamplifier decoupling

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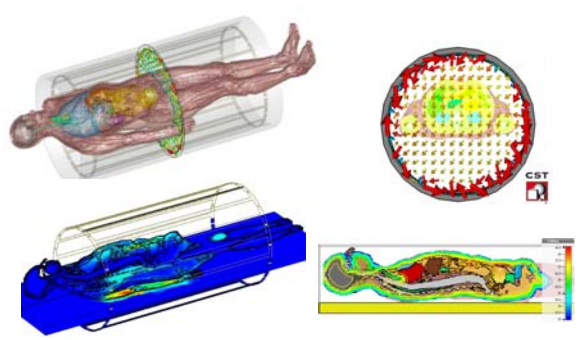
Specific Absorption Rate (SAR)



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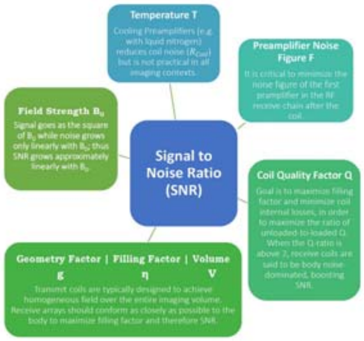
SNR



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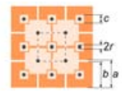
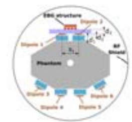
New Developments and Outlook

- METAMATERIALS
  - Find artificially designed materials to tackle the high SAR levels, image inhomogeneity





- WIRELESS TECHNOLOGY

As the amount of receivers keeps increasing, the issue of cabling is a challenge
  - High interaction between cables
  - Space
  - Weights

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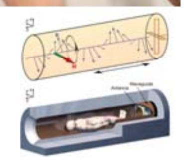
New Developments and Outlook

- Flexible and Adaptive RF Coils
  - Close fit to the subject
  - Higher SNR

- Traveling Wave Imaging
  - Higher field homogeneity at higher frequencies (7T and above)



- Multituned RF Coils
  - Tuned to several frequencies
  - Detect other nuclei other than hydrogen

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