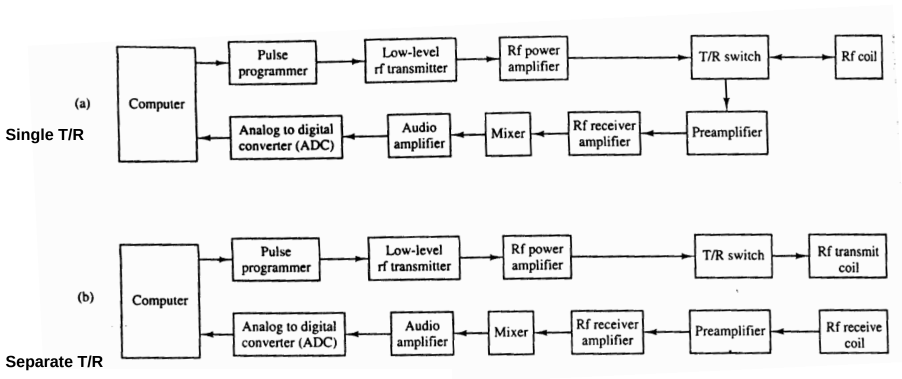
RF Coils

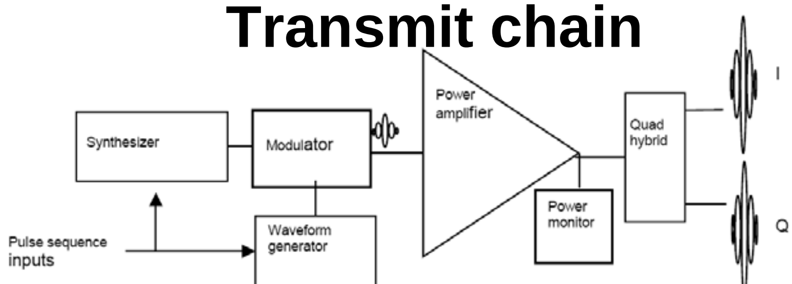
RF System

- RF system can be divided into two parts: transmits and receive.
- The transmit portion sends out high power RF pulses which are applied to the spin system.
- The system generates pulse waveforms which are used to modulate an RF carrier (an RF signal at constant phase and amplitude) with high frequency at the NMR frequency.

RF systems



Transmit chain



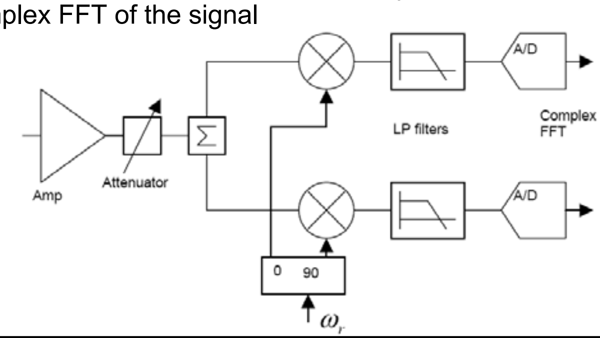
•we generate the carrier frequency of the amplitude modulated pulses. In this case the carrier frequency is of course identical to the ω_0 of the system.
•the frequency may have to be shifted when an off center slice excitation is required. This is the function of the synthesizer.
•Synthesizer**:** delivers an RF signal with a controlled frequency. Subsequently the carrier is amplitude modulated with the RF pulse envelope.
•The shape of the envelope is determined by the pulse sequence and is generated in the waveform generator
•The power amplifier boosts the power level from approximately 10 mW to the order of 16 kW (for a 1.5T system).
•The quad hybrid splits the power into an I and a Q channel, which have a 90 degree phase difference.
•These signals are fed into the quadrature transmit coil, which will convert the power into a circularly polarized RF magnetic field

Quadrature

- Applying a circularly polarized RF excitation could save a factor of 2 in RF energy and receiving
- Apply two linear B_1 excitations at right angles in a plane perpendicular to B_0.
- If the excitations are 90^0 out of phase, a circularly polarized B_1 field results

Receive chain

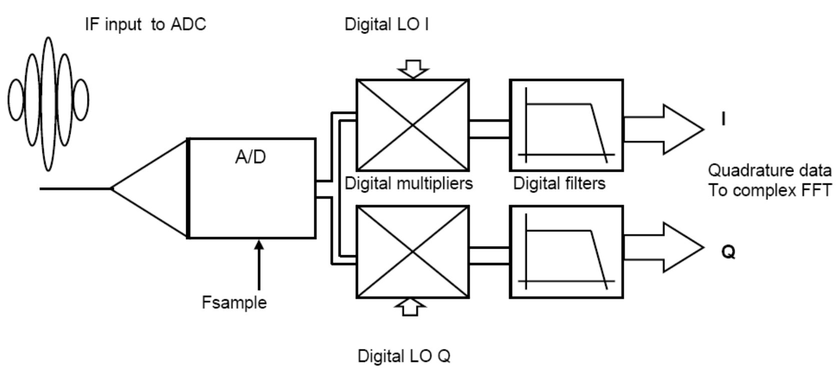
- Once the signal has been detected by the RF coils, it has to be further amplified and / or attenuated such that the signal fills up the ADC, it then has to be converted to baseband using a combination of phase sensitive detectors and/or mixers in a process called Quadrature demodulation
- The signal then passes through a low pass filter and is fed into the ADC, which then connects to the computer for reconstruction using complex FFT of the signal



Receive chain (cont'd)

- The reason for splitting the signal and mixing it with 2 reference signals that are 90 degrees out of phase is to maintain information about the frequency spectrum of the signal.
- after mixing the signal at ω_o with the reference frequency ω_r , the result is a mix of signals at different frequencies, but the term we are interested in is the one at $\omega_r - \omega_0$. A single mixer with a single reference signal does not distinguish between $\omega_r - \omega_0$ and $\omega_o - \omega_r$. By doing the quadrature detection we can distiguish between them.

Digital Receiver



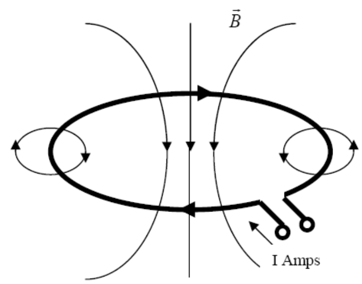
RF coils: Basic Concepts

- The RF coil usually functions as a transmitter to excite the nuclei inside the body, and as a receiver to collect MR signal induced by nuclei during the relaxation process.
- Types of RF coils are categorized as either volume coils or surface coils
  - A volume coil is built to enclose a substantial portion of body such as the torso or the head (have a large FOV but modest signal-to noise-ratio (SNR)
  - A surface coil usually is made of a small metal loop, which is placed up against the portion of the body surface to be examined (have a small (shallow) FOV but a higher SNR).
- These resonators can be characterized by parameters including their inductance (*L*), capacitance (*C*), loss resistance (*R*), quality factor (*Q*), and field patterns (*B1(r)*)

Inductance

- Mutual inductance is defined in terms of "flux linkage", or the magnetic flux through one coil produced by unit current in another coil.
- For a single coil, this is referred to as the self-inductance (inductance) which is a measure of the magnetic flux through a coil produced by unit current in the same coil.

- The amount of energy stored in a resonator can be computed from integrating the flux density over all space. The total magnetic energy stored in an RF coil is given by:



Magnetic flux due to a simple loop inductor

$$W_m = \frac{1}{2}\int_v \frac{1}{\mu}\left|\vec{B}_1\right|^2 dv$$

where μ is the magnetic permeability. For our purposes the volume under consideration is the sample and free space, both of which can be considered to have $\mu=\mu_0= 4\pi\times10^{-7}$ Henries/meter.

the energy storage due to an inductor, L, can be expressed $W_m = \frac{1}{2}|I|^2 L$

$$L = \frac{1}{|I|^2}\int_v \frac{1}{\mu}\left|\vec{B}_1\right|^2 dv$$

Inductance of a circular coil of radius a and wire radius d, with a >> d.	$L = a\mu \left[\ln\left(\frac{16a}{d}\right) - 1.75 \right]$
Inductance of a rectangular coil with sides d_1 and d_2 and wire radius b, d_1,d_2 >> d.	$L = \frac{\mu}{\pi}\left(d_1 \cosh^{-1}\left(\frac{d_2}{b}\right) + d_2 \cosh^{-1}\left(\frac{d_1}{b}\right)\right)$
Inductance of a solenoidal coil of radius a, length l, and N turns.	$L = \frac{\mu N^2 \pi a^2}{l^2}\left[\left(l^2 + a^2\right)^{\frac{1}{2}} - a\right]$

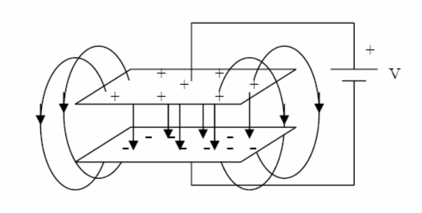
Q:
building a large solenoidal coil

- The impedance due to an inductor is +j *XL* , where the inductive reactance X_L is given by: $X_L = \omega L$
- The resonator has loss term, *R*, due primarily to wire resistance and eddy current losses in the sample.

$$Z = R + jX_L$$

Capacitance

- The total energy stored by a capacitor is given by:



$$W_E = \frac{1}{2}\int_v \varepsilon|E|^2 dv$$

$$W_E = \frac{1}{2}\int_v \varepsilon|E|^2 dv = \frac{1}{2}CV^2$$

where ε is the permittivity of the material, $\varepsilon = \varepsilon_0 = 10^{-9}/36\pi$ *Farads/meter* in air

$$C = \frac{1}{|V|^2}\int_{vol} \varepsilon|E|^2 dv$$

The impedance that a capacitor presents in a circuit is imaginary and negative, given by − *jXc*

$$X_c = \frac{1}{\omega C}$$

Resistance

- Resistance converts current to power loss, resulting in heat and increased pulse widths for a given tip angle. In receiver coils, the received noise is proportional to the coil resistance,

$$V_{noise} = \sqrt{4kT\Delta f R_{coil}}$$

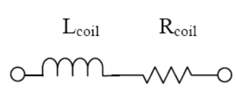
where *k* is Boltzman's constant, *T* is the effective temperature, Δ*f* is the receiver bandwidth, and R_{coil} is the resistance of the coil.

Transmission lines

- Coaxial lines consist of a shield surrounding a center conductor. Equal currents flow on the center conductor and the inside of the shield, with no current on the outside of the shield in a properly designed system.

Quality factor (Q)

- Equivalent circuit for a surface coil



$$Q = \frac{2\pi\,(\text{Energy stored in inductor})}{\text{Energy lost per cycle}}$$

- The energy lost per cycle is obtained by integrating the power loss over once cycle $\pi/\omega\, I^2 R_{coil}$ and the energy stored in the inductor $\frac{1}{2} I^2 L$, giving a quality factor of

$$Q = \frac{\omega L}{R_{coil}}$$

Resonance

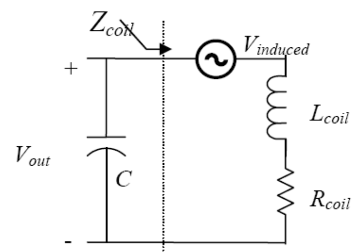
- Surface coils are generally operated as resonant circuits. This is done to provide maximum power transfer between the MR system and the coil.
- A resonant circuit is one in which equal amounts of energy are stored in the electric and magnetic fields, with the energy exchanging repeatedly between the electric and magnetic fields.
- Because electric fields within lossy dielectrics (patients or other samples) increase the coil resistance, the electric fields should be associated with the capacitors used to tune and match the coil rather than the stray electric fields of the coil

Resonance (cont'd)

- the value of capacitance *C* required to resonate an inductor *L* at frequency f_{res} is:

$$C = \frac{1}{(2\pi f_{res})^2 L}$$

- Given the figure, the output voltage, V_{out} , at resonance is given approximately by $V_{out} = QV_{induced}$, where $V_{induced}$ is the open-circuit voltage induced in the coil by the echo or FID.



- Consider a simple surface coil with an inductive reactance of 90 ohms and a Q of 100. Assuming low-loss capacitors, the coil resistance is found from the Q and the coil reactance to be

$$Q = \frac{\omega L}{R} = \frac{X_L}{R} \Rightarrow R = \frac{X_L}{Q} = \frac{90}{100} = 0.9\Omega .$$

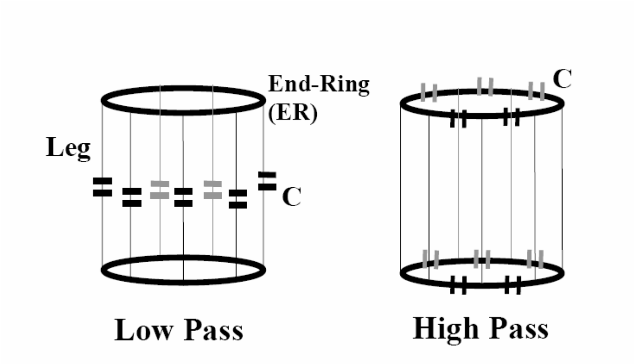
- The current through the resistance in the 1kW RF pulse is

$$P = \frac{1}{2} I^2 R \Rightarrow I = \sqrt{\frac{2P}{R}} = \sqrt{\frac{2000W}{0.9\Omega}} = 47.1A$$

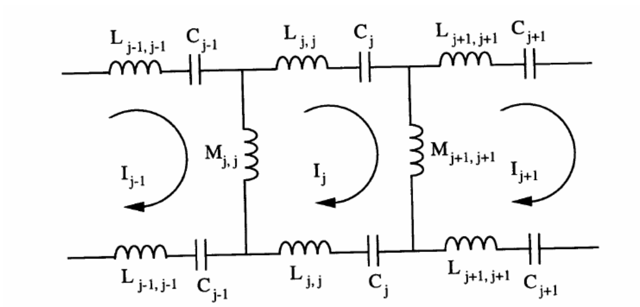
The Birdcage Coil

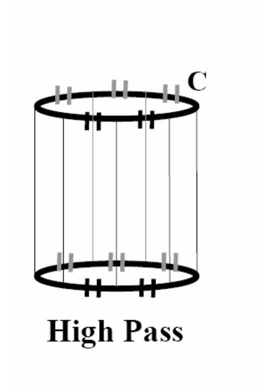
- They can provide a homogeneous field inside a large imaging volume and good SNR
- Coils are built with a set of desired capacitance values, a finite number of legs, and two end-rings (ERs) which all together approximate a continuous conducting surface
- The coils are driven in linear mode or in quadrature mode which provides a square root of two increase in SNR

- Depending on the positions of capacitors, birdcage coils have high-pass and low-pass modes



High pass

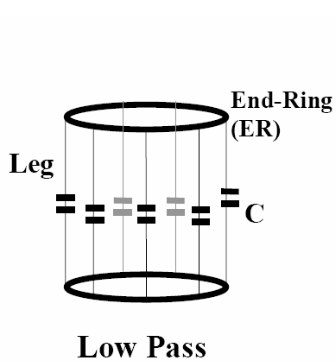


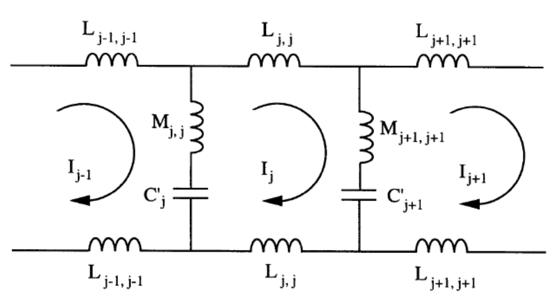


$$\omega_m = \left[C\left(L + 2M\sin^2\frac{\pi m}{N}\right)\right]^{-1/2} \quad \left(m = 0, 1, 2, \ldots, \frac{N}{2}\right).$$

Where $C_{j} = C_{j-1} = C_{j+1}$ …
$L_j = L_{j-1} = L_{j+1}$…..
$M_{j,j} = M_{j+1,J+1}$

Low Pass





$$\omega_m = \left\lfloor C\left(M + L\Big/2\sin^2\frac{\pi m}{N}\right)\right\rfloor^{-1/2} \quad \left(m = 0, 1, 2, \ldots, \frac{N}{2}\right).$$

Optimum Current Distribution

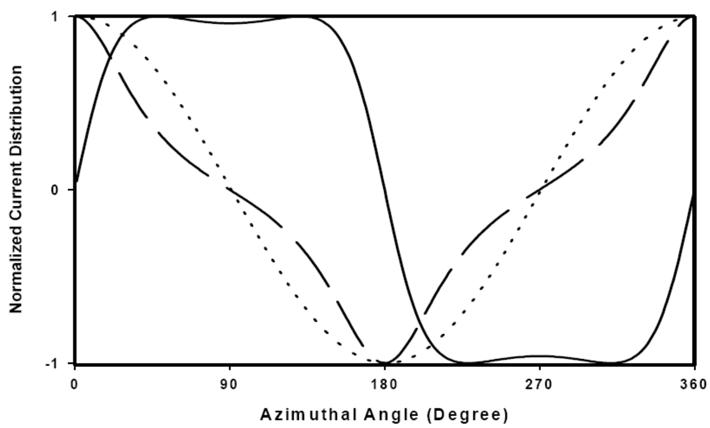
- Theoretically, when the current distribution on a cylindrical conducting surface satisfies the sinusoidal angular dependency, a homogenous magnetic field can be created inside this conductor
- For a N-leg cylindrical birdcage coil, the current in the legs can be assigned proportionally to *sin*(*n*θ) or *cos*(*n*θ), where the values of θ are increased from 0 to 2π by 2π/N. The discrete legs correspond to a sampling of a continuous current distribution.
- The highest resonant frequency occurs when *n* = N/2, where adjacent legs have currents with opposite phase.

- The optimum current distributions for an elliptical birdcage coil to create a homogeneous **B1** field directed in the short-axis ($I_{short\text{-}axis}$) and long-axis ($I_{long\text{-}axis}$) directions have been derived

$$I_{short-axis}(\theta) = I_o \frac{B^2\cos\theta}{B^2\cos^2\theta + A^2\sin^2\theta}$$

$$I_{long-axis}(\theta) = I_o \frac{A^2\sin\theta}{B^2\cos^2\theta + A^2\sin^2\theta}$$

where *A* and *B* are half the long and short axes respectively, θ is the azimuthal angle of the leg position, and I_o is the maximum current intensity.



A sinusoidal optimum current distribution for the cylindrical birdcage coil (dot). The optimum current distribution for an elliptical coil with field orientation in short-axis direction(dash) and long-axis direction (solid) is shown.

RF shield

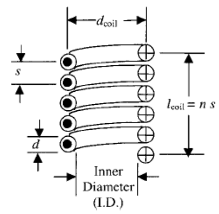
- A RF shield is usually placed between the birdcage coil and gradient coils to isolate the coil from the environment, which is usually assumed as a part of the RF coil.
- The RF shield is used to prevent the interactions between the RF coil and imaging gradient and shim coils when we collect the MR signal.
- The shield must be opaque to RF fields but transparent to the gradient fields.

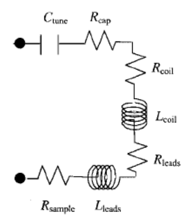
Solenoidal Coil

$$\text{SNR} \propto \frac{\omega_0^2 B_{xy}}{\sqrt{R_{\text{nmr}}}}$$

$$R_{\text{nmr}} = R_{\text{coil}} + R_{\text{leads}} + R_{\text{cap}} + R_{\text{sample}}$$

$$B_{xy} = \frac{n\mu_0}{d_{\text{coil}}\sqrt{1 + \left(\frac{l_{\text{coil}}}{d_{\text{coil}}}\right)^2}}$$





Equivalent-circuit model for assessing the relative SNR performance of the NMR receiver circuit.

Coil Interface

- Purpose of the system interface: spin magnetic moment induces voltage in a nearby coil. The induced voltage must be transferred to the MR system receiver, safely and with as little reduction in SNR as possible
- It is necessary to transfer the spin signal voltage and the noise originating with the coil/sample system without addition of noise.
- Coil/sample define the maximum achievable SNR and preamplifiers can only degrade it from there.

Noise figure

- Noise figure is a figure of merit used to characterize preamplifiers and receivers in general.
- Consider a “black box”, which amplifies whatever signal (and noise) that enters it by a gain factor G. The noise figure is then defined as the total noise power out of the box, divided by the Gain*(input noise power).
- The expression for total noise figure of a series of elements can be expressed as

$$NF = 10\log(1 + NF_1 + \frac{NF_2}{G_1} + \frac{NF_3}{G_1 * G_2} + ..)$$

Matching/Tuning

- Coils should be matched to 50 ohms in order to maximize power delivery to the preamplifier load even though modern preamplifiers have input impedance close to 3 ohms real for the following reasons:
  - test equipment (network analyzers) are designed to measure accurately at this impedance.
  - 50 ohm coaxial cable is standard and matching the transmission line to the impedance at one end reduces reflection losses in the cable
  - the preamplifier is noise matched (has minimum noise figure) when the source is 50 ohms

RF Decoupling

- Since coils are sensitive to a RF magnetic field), then their use as receive-only coils requires isolation from the excitation coil, and in general switches (mainly diodes) are used to turn the receive coil off during transmission with the excitation coil.
- Cable shield traps: decouple the cable shields from induced current. Cable shield traps are used to limit the currents induced on the outside of coil cables by body coil excitation.

Safety Issues in RF Coil Design

- Whole-body and localized heating are the primary safety issues associated with radio frequency (RF) coils used in magnetic resonance (MR).
- Heating depends on ambient temperature, RF power deposited per unit mass, relative humidity, airflow rate, blood flow, and patient insulation.
- The specific absorption ratio, *SAR*, is the power absorbed per unit mass. It serves as a crude measure of heating potential

The International Electrotechnical Commission (IEC) published a widely used MR safety standard. When environmental temperature ≤ 24 °C and the relative humidity ≤ 60 %,

Configuration	Whole-Body SAR[1,2] (W/kg)	Head SAR[1] (W/kg)	Peak SAR[1] (W/kg)	Partial Body SAR[1] (W/kg)	Local Head SAR[1] (W/kg)	Local Trunk SAR[1] (W/kg)	Local Extremity SAR[1] (W/kg)	Short Term SAR[3] (W/kg)
FDA_IEC (NORMAL MODE)	2	3.2	n/a	equation[4]	10	10	20	3 x Long Term SAR
FDA_IEC (1st CONTROLLED MODE)	4	3.2	n/a	equation[5]	10	10	20	3 x Long Term SAR
FDA_IEC (2nd CONTROLLED MODE)	IRB Limit[6]	IRB Limit[6]	IRB Limit[6]	IRB Limit[6]	IRB Limit[6]	IRB Limit[6]	IRB Limit[6]	IRB Limit[6]

notes:
1. SAR averaged over sliding six minute window
2. For environmental temperatures > 24°C, Whole-Body SAR is reduced 0.25 W/kg/°C. For each 10% increment that relative humidity exceeds 60%, the derating temperature (25 °C) is lowered 0.25 °C.
3. Short Term SAR is averaged over a 10 second sliding window

HW

- Design a birdcage coil that resonate at 63.85 and 500.1 MHz with a diameter of
  - 10 mm and length 25 mm
  - 200 mm and length 200 mm

  Plot the current distribution for
    - different number of legs and capacitance values
    - With/ without shielding