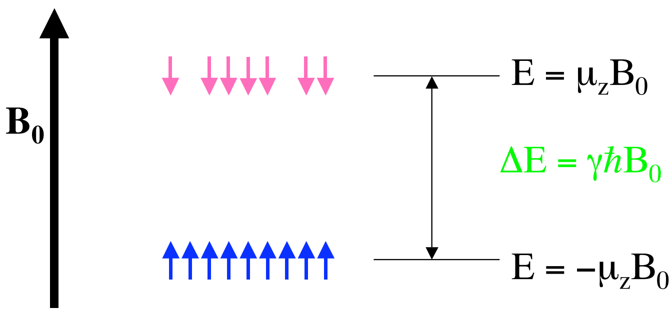
Bioengineering 208
Magnetic Resonance Imaging

Winter 2007
Lecture 1

Topics

- Review of NMR basics
- Hardware Overview
- Quadrature Detection

Boltzmann Distribution



$$\frac{\text{Number of Spins Down}}{\text{Number of Spins Up}} = e^{-\Delta E/kT}$$

Ratio = 0.999990 at 1.5T !!!

Corresponds to an excess of about 10 up spins per million

Magnetization Vector

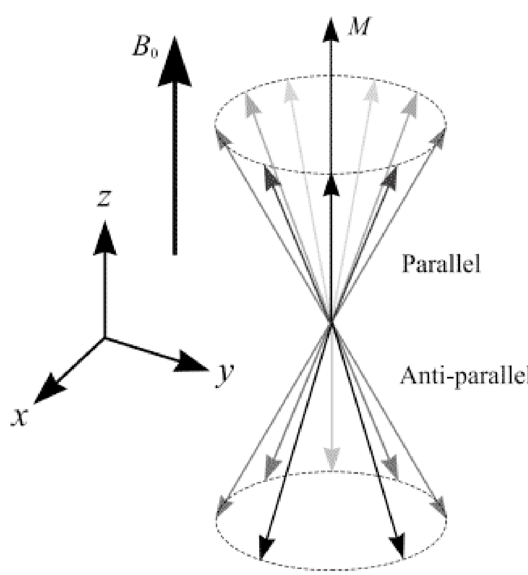
Vector sum of the magnetic moments over a volume.

For a sample at equilibrium in a magnetic field, the transverse components of the moments cancel out, so that there is only a longitudinal component.

Equation of motion is the same form as for individual moments.

$$\mathbf{M} = \frac{1}{V} \sum_{\substack{\text{protons} \\ \text{in V}}} \mu_i$$

$$\boxed{\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{B}}$$



http://www.easymeasure.co.uk/principlesmri.aspx

RF Excitation

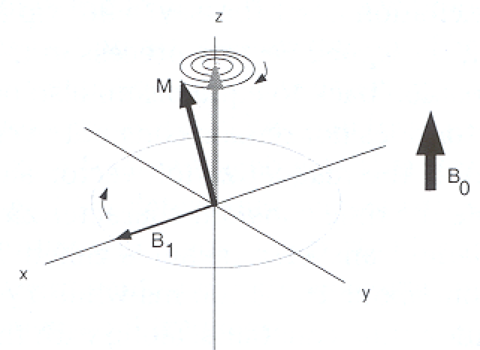


Image & caption: Nishimura, Fig. 3.2

At equilibrium, net magnetizaion is parallel to the main magnetic field. How do we tip the magnetization away from equilibrium?

B_1 radiofrequency field tuned to Larmor frequency and applied in transverse (*xy*) plane induces nutation (at Larmor frequency) of magnetization vector as it tips away from the *z*-axis.
- lab frame of reference

http://www.eecs.umich.edu/%7Ednoll/BME516/

Bloch Equation

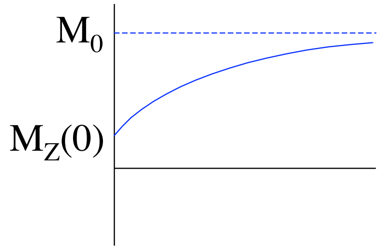
$$\frac{d\mathbf{M}}{dt} = \underbrace{\mathbf{M} \times \gamma \mathbf{B}}_{\text{Precession}} - \underbrace{\frac{M_x \mathbf{i} + M_y \mathbf{j}}{T_2}}_{\text{Transverse Relaxation}} - \underbrace{\frac{(M_z - M_0)\mathbf{k}}{T_1}}_{\text{Longitudinal Relaxation}}$$

$$\omega_0 = \gamma \mathbf{B}$$

i, j, k are unit vectors in the x,y,z directions.

Relaxation: Z-component

$$M_z(t) = M_0 + (M_z(0) - M_0)e^{-t/T_1}$$

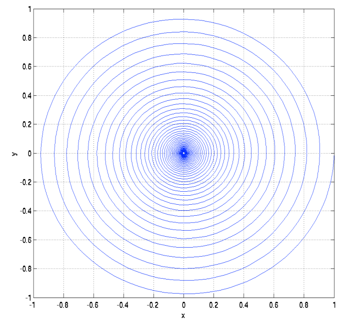


Relaxation: Transverse Component

$$M \equiv M_x + jM_y$$

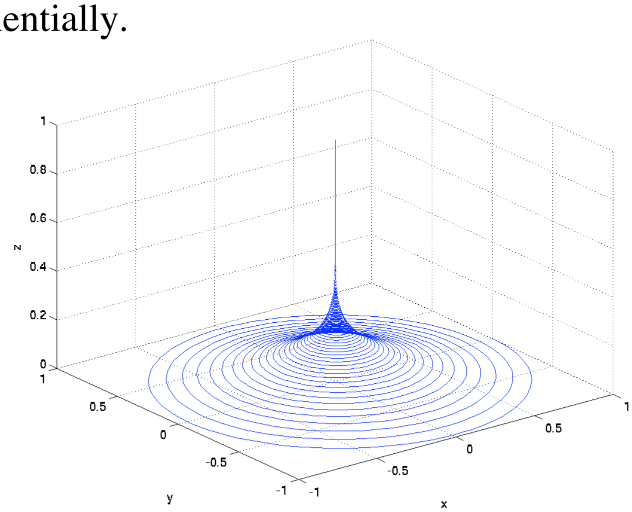
$$dM/dt = d/dt\left(M_x + iM_y\right)$$
$$= -j\left(\omega_0 + 1/T_2\right)M$$

$$M(t) = M(0)e^{-j\omega_0 t}e^{-t/T_2} \qquad \omega_0 = \gamma\mathbf{B}$$

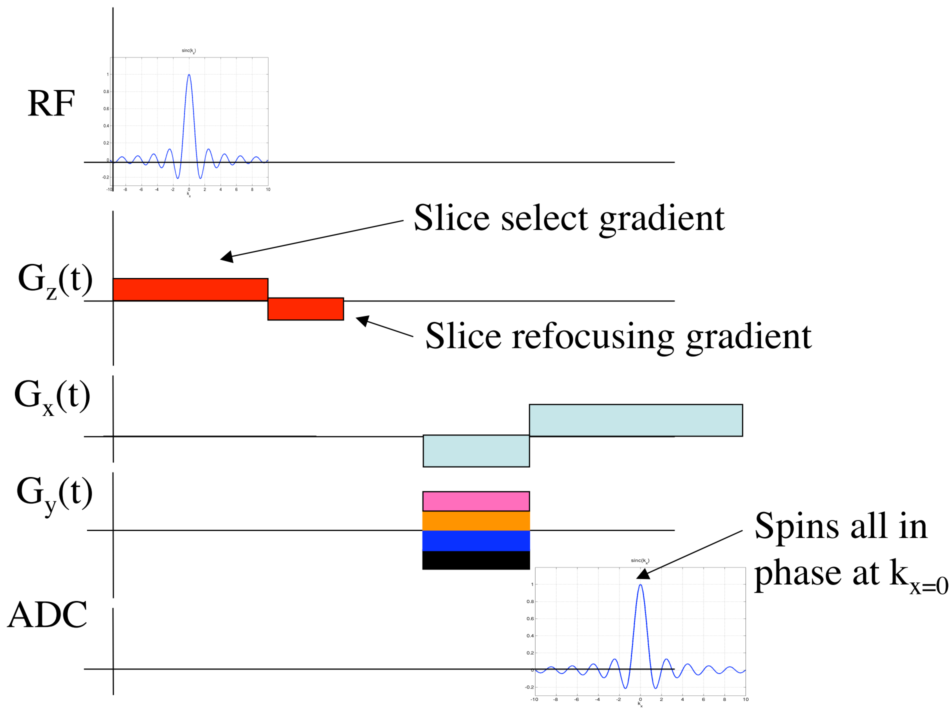


Relaxation: Summary

1) Longitudinal component recovers exponentially.
2) Transverse component precesses and decays exponentially.



Gradient Echo



Small Tip Angle Example

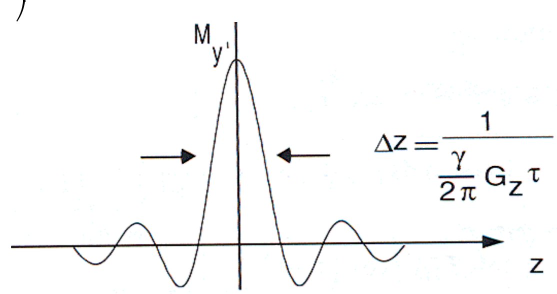
$$B_1(t) = B_1 rect\left(\frac{t-\tau/2}{\tau}\right)$$

$$M_r(\tau,z) = jM_0 \exp(-j\omega(z)\tau)\int_0^\tau \exp(j\omega(z)s)\omega_1 rect\left(\frac{s-\tau/2}{\tau}\right)ds$$

$$= jM_0 \exp(-j\omega(z)\tau/2)F_{1D}\left(\omega_1 rect\left(\frac{t}{\tau}\right)\right)\Big|_{f=-(\gamma/2\pi)G_z z}$$

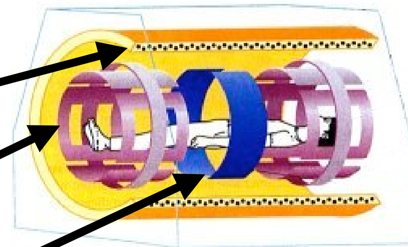
$$= jM_0 \exp(-j\omega(z)\tau/2)\omega_1\tau \operatorname{sinc}(f\tau)$$

$$= jM_0 \exp(-j\omega(z)\tau/2)\omega_1\tau \operatorname{sinc}\left(\frac{\gamma G_z \tau}{2\pi}z\right)$$



Nishimura 1996

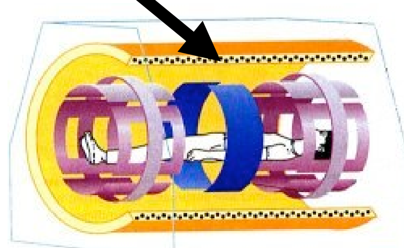
Hardware Overview



<u>Three fields:</u>

- Main Field (B_0)
  - Polarize Spins
- Gradient Fields ($G_{[XYZ]}$)
  - Map space into frequency
  - $\frac{\partial B_Z}{\partial [XYZ]}$
- RF Fields (B_1)
  - Change the latitude or zenith angle of ('tips') spins

Main Field (B_0)



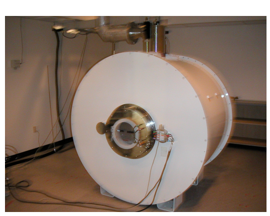
<u>How do we decide on B_0?</u>

$$\Delta E = \gamma h B_0$$

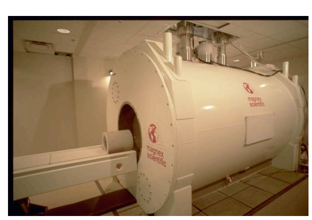
$$M_0 \propto \Delta E$$

$\therefore$ Bigger is better!

3T Human @UCSD.



7T Rodent @UCSD

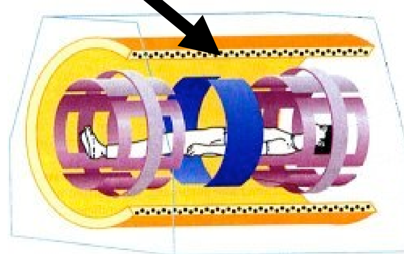


7T Human @U.Minn.

9.4T Human @UIC

 Slide Credit: T.T. Liu

Main Field (B_0)



Energy in a Magnetic Field:

$$E = \frac{1}{2\mu_0}\int B^2 dV$$

For B=3T over 1m^3:

$$E = \frac{1}{2(1.25\times 10^{-6})}9 = 3.6MJ$$

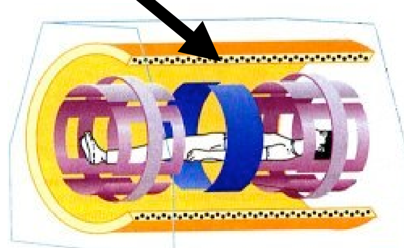
= dropping a 1000Kg car from 360m high

Heat of Vaporization of He = 2.5*KJ*/*l*

During a quench, R goes from 0 to ~100Ω, I~100A, so P=I^2R~1MW

∴ A quench can boil off 3.6MJ/2.5KJ/*l*=1400*l* of Helium *in 3.6MJ/1MW ~3.6s !!!*

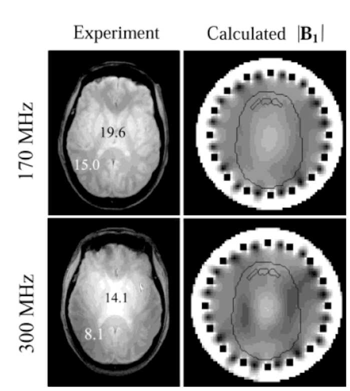
Main Field (B_0)



Wavelength (λ) of RF:

In Vacuum:
5m @ 60MHz (1.5T)
1m @ 300MHz (7T)

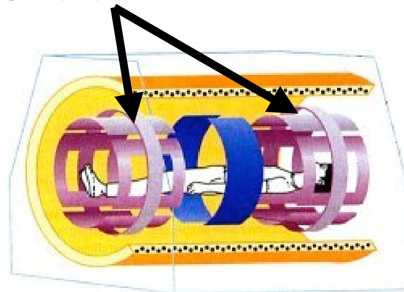
In Brain:
12cm @ 300MHz (7T)[1]



When λ is not large compared to object, standing waves form. This is referred to as Dielectric Resonance. RF inhomogeneity during receive is fixed by scaling, but RF transmit inhomogeneity is much more difficult to address.

[1]Vaughan et al, MRM 46 p24 2001

Gradient Fields



$$G_X \equiv \frac{\partial B_Z}{\partial X} \qquad G_Y \equiv \frac{\partial B_Z}{\partial Y} \qquad G_Z \equiv \frac{\partial B_Z}{\partial Z}$$

<u>How big do gradient fields need to be?</u>

- Shortest soft tissue $T_2^* \sim 1\text{ms}$
- For 0.2mm resolution in 1ms:

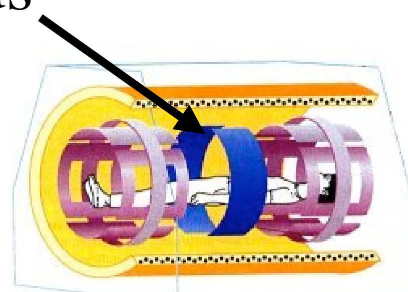
$$G = \frac{K_{\max}}{\gamma T} = \frac{(0.5/0.2mm)}{(4257Hz/G)(1ms)} \approx 5G/cm$$

- To fill 1m^3 with 5G/cm gradients in 0.2ms requires:

$$P = \frac{E}{T} = \frac{1/2\mu_0 \int B^2 dV}{T} \approx \frac{1/2\mu_0 (B_{RMS}(5G/cm))^2 (1m^3)}{0.2ms} \approx 500KW \longrightarrow \boxed{\text{About 3 simultaneous Rolling Stones concerts}}$$

- Modern gradient systems are also up against dB/dt limits for peripheral nerve stimulation (~50T/s)
- For diffusion or ultrashort T_2^* imaging, more G would help a lot

RF Fields



<u>How big do RF fields need to be?</u>

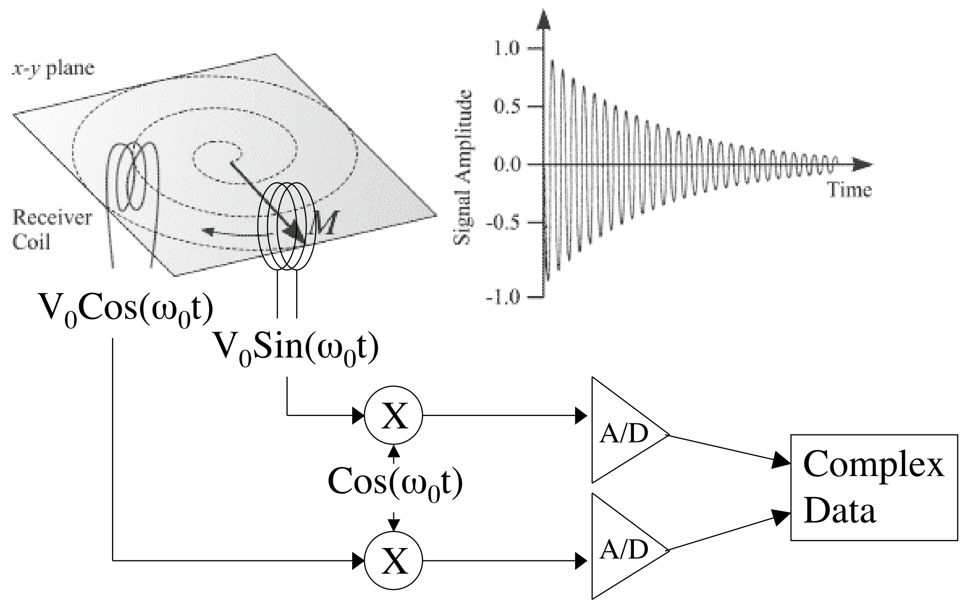
- Shortest soft tissue $T_2^* \sim 1\text{ms}$
- To flip spins by 90° (0.25 rotations) in 0.2ms:

$$B_1 = \frac{0.25}{\gamma T} = \frac{0.25}{(4257Hz/G)(0.2ms)} \approx 0.24G$$

- RF power absorption by the body is a complex function of frequency, conductivity, and geometry, but at 0.24G, approximately 200W/Kg are deposited in human tissue at 3T. Thus, for a 100Kg person, the RF system must supply 20KW of deposited power, or about 40KW of total power, assuming 50% losses to the coil, cabling, reflections, and radiation.

Quadrature Reception

Original quadrature detection: separate coils and A/D for I and Q

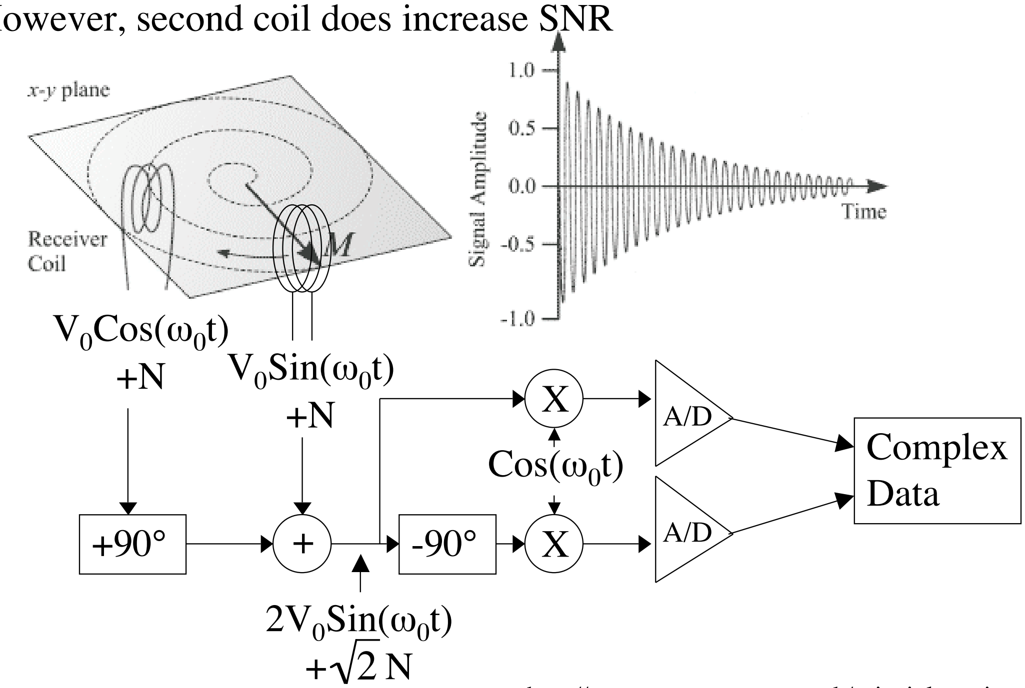


E. Wong, BE208, UCSD Winter 2007

http://www.easymeasure.co.uk/principlesmri.aspx

Quadrature Reception

Because ω_0 >>bandwidth, 2 coils are not needed for phase detection.
However, second coil does increase SNR



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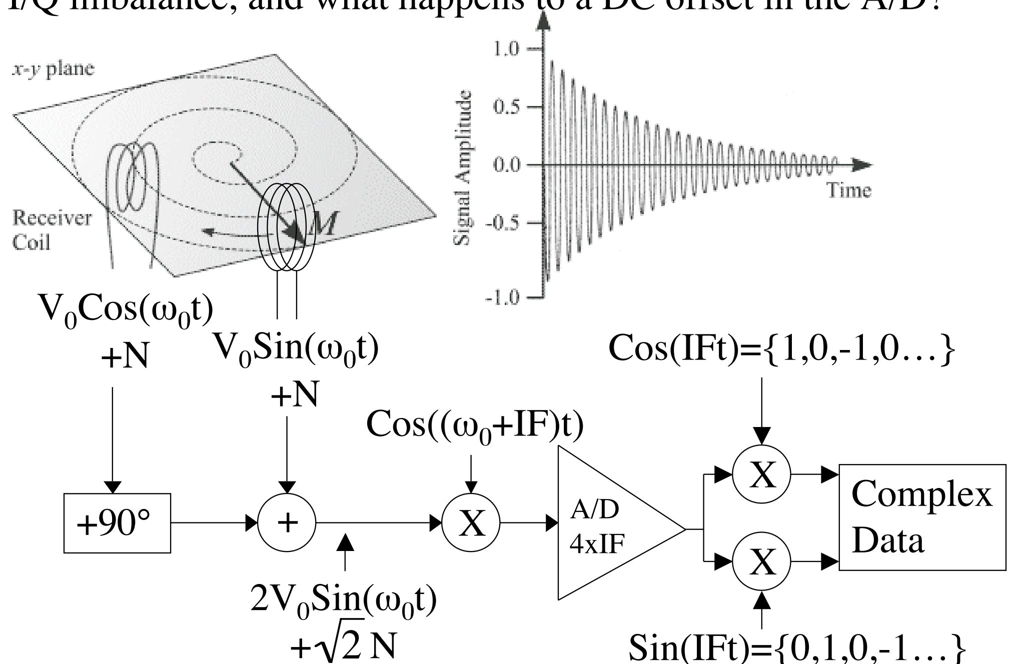
Quadrature Reception

Digital quadrature requires 2x faster sampling, but eliminates I/Q imbalance, and what happens to a DC offset in the A/D?



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Quadrature Reception

<u>Summary:</u>

1. Quadrature RF coil is NOT needed to detect MR signal phase.
2. Quadrature RF coil improves SNR by $\sqrt{2}$
3. Digital quadrature detection:
    1. Eliminates I/Q imbalance
    2. Moves DC offset in ADC to edge of image
    3. Requires 2x higher sampling rate than separate I/Q