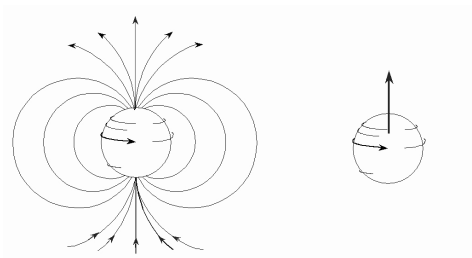
Bioengineering 278
Magnetic Resonance Imaging

Winter 2011
Lecture 1

Topics:

- Review of NMR basics
- Hardware Overview
- Prescan

Spins

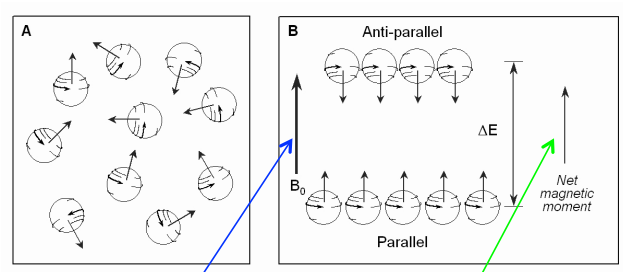


Hydrogen Nucleus = Proton

- Mass
- Spin
- Charge

} Angular Momentum

} Magnetic Moment



$E = \mu_z B_0$

$\Delta E = \gamma h B_0$

$E = -\mu_z B_0$

Boltzmann Distribution

$$\frac{down\_spins}{up\_spins} = e^{-\Delta E/kT}$$

Ratio = 0.99998 at 3T !

Corresponds to an excess of about 20 up spins per million

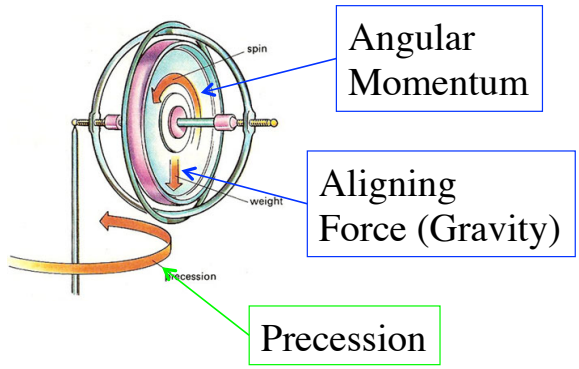
Magnetic Field

Net Magnetic Moment

Equation of Motion for Magnetization Vector **M**

Bloch Equation:

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



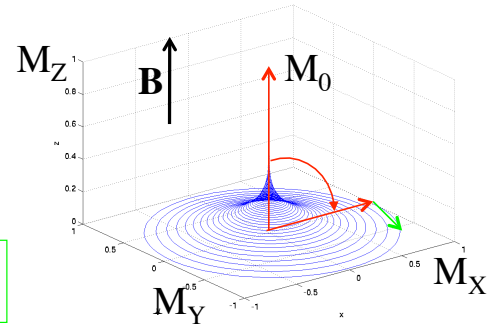
Solution:

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

$$M_{XY}(t) = M(0)e^{-j\omega_0 t}e^{-t/T_2}$$

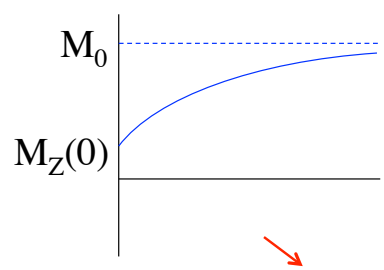
$$\omega_0 = \gamma\mathbf{B}$$

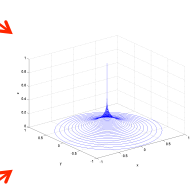
Precession Frequency | Gyromagnetic Ratio (4257Mhz/T) | Magnetic Field



Relaxation: Z-component

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





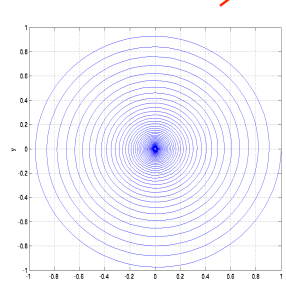
Relaxation: Transverse Component

$$M \equiv M_x + jM_y$$

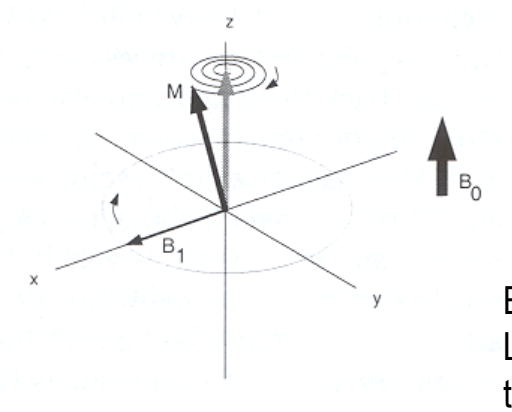
$$dM/dt = d/dt\left(M_x + iM_y\right)$$

$$= -j\left(\omega_0 + 1/T_2\right)M$$

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



RF Excitation



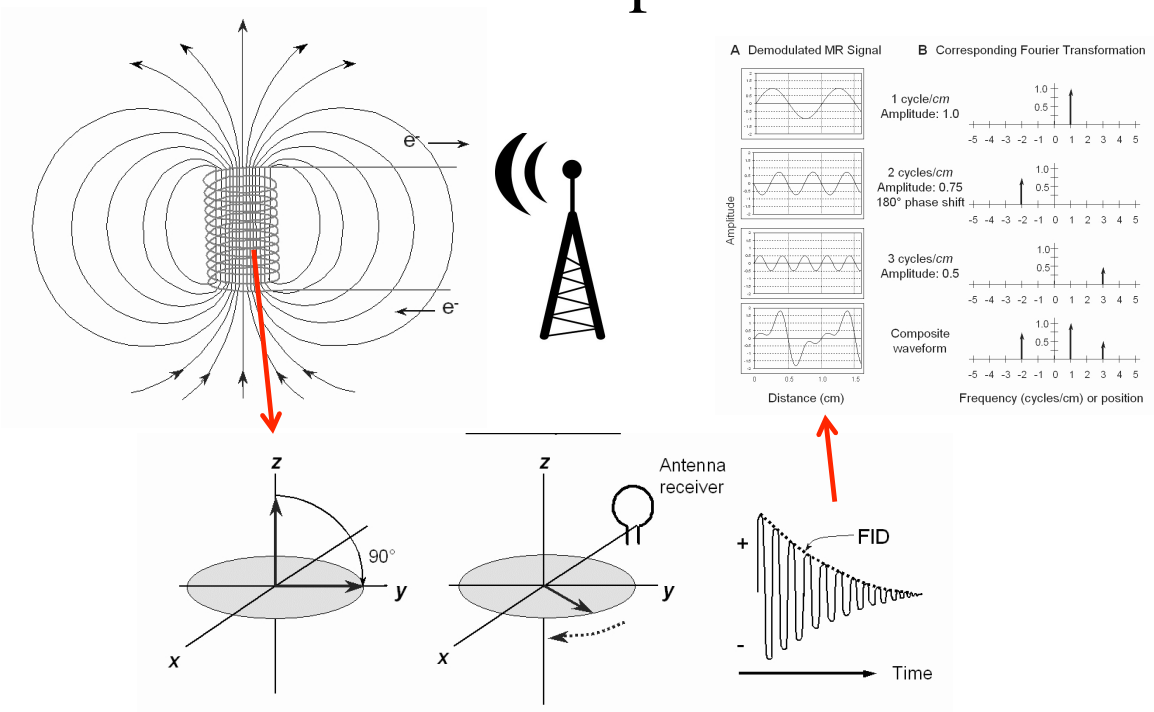
Laboratory Frame
Nishimura, Fig. 3.2

Bloch equation says that magnetization will precess around the applied field.

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-mrsrl.stanford.edu/~wro/defense/animations/

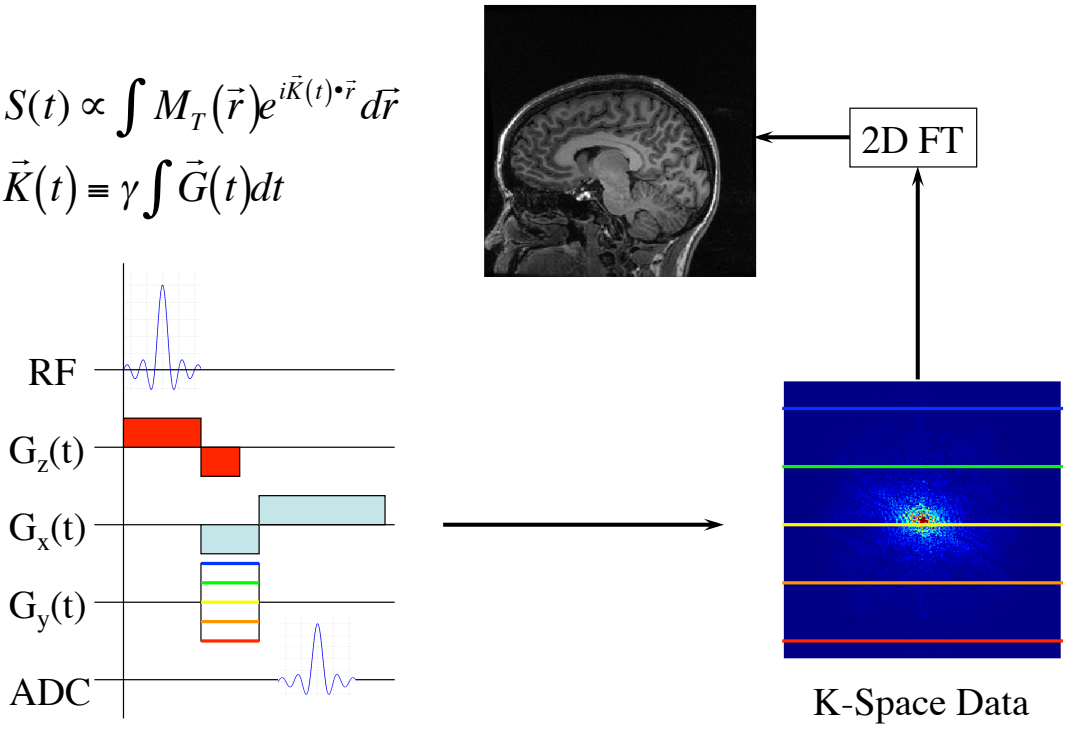
An NMR Experiment



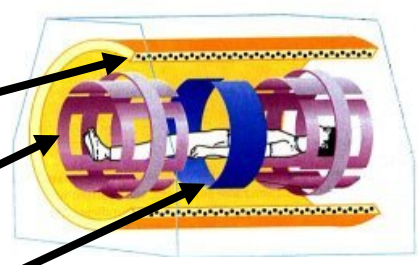
Basic 2D Imaging Pulse Sequence

$$S(t) \propto \int M_T(\vec{r}) e^{i\vec{K}(t)\bullet\vec{r}} d\vec{r}$$

$$\vec{K}(t) \equiv \gamma \int \vec{G}(t) dt$$



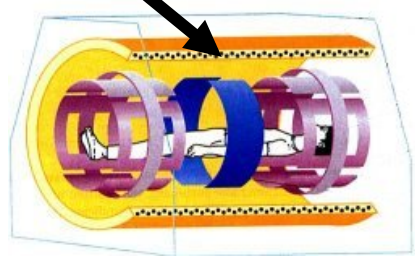
Hardware Overview



<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)

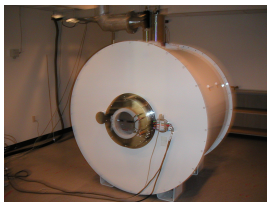
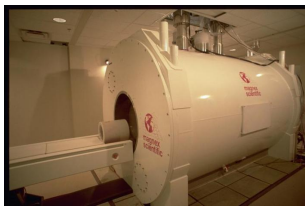


How do we decide on B_0?

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

$$M_0 \propto \Delta E$$

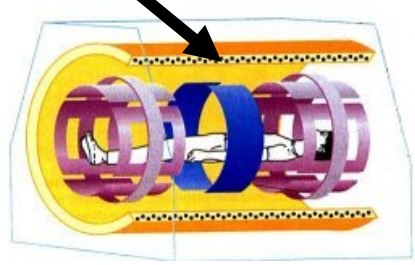
$\therefore$ **Bigger** is better! … except …


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 $1m^3$:

$$E = \frac{1}{2(1.25\times10^{-6})}9 = 3.6MJ$$

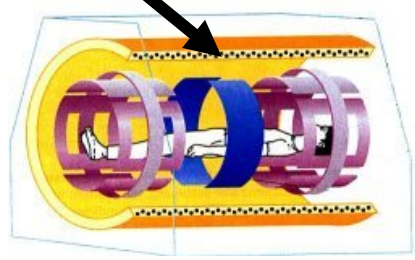
= dropping a 1000Kg car from 360m high

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

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

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

Main Field (B_0)

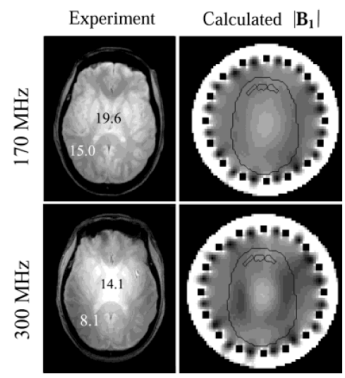


Wavelength (λ) of RF:

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

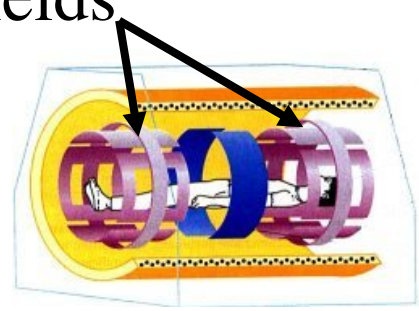
In Brain:
12cm @ 300MHz (7T)[1]

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



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

How big do gradient fields need to be?

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

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

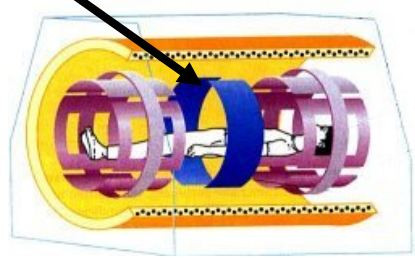
- To fill $1m^3$ with 5G/cm gradients in 0.2ms requires:

$$P = \frac{E}{T} = \frac{1/2\mu_0 \int B^2 dV}{T} \approx \frac{1/2\mu_0 (B_{RMS}(5G/cm))^2 (1m^3)}{0.2ms} \approx 500KW$$

→ 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



How big do RF fields need to be?

•Shortest soft tissue $T_2^* \sim 1ms$

•To flip spins by 90° (0.25 rotations) in 0.2ms:

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

- 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.

Prescan

Adjustments:

1. Center Frequency
2. Transmit Gain
3. Receive Gains
4. Shim