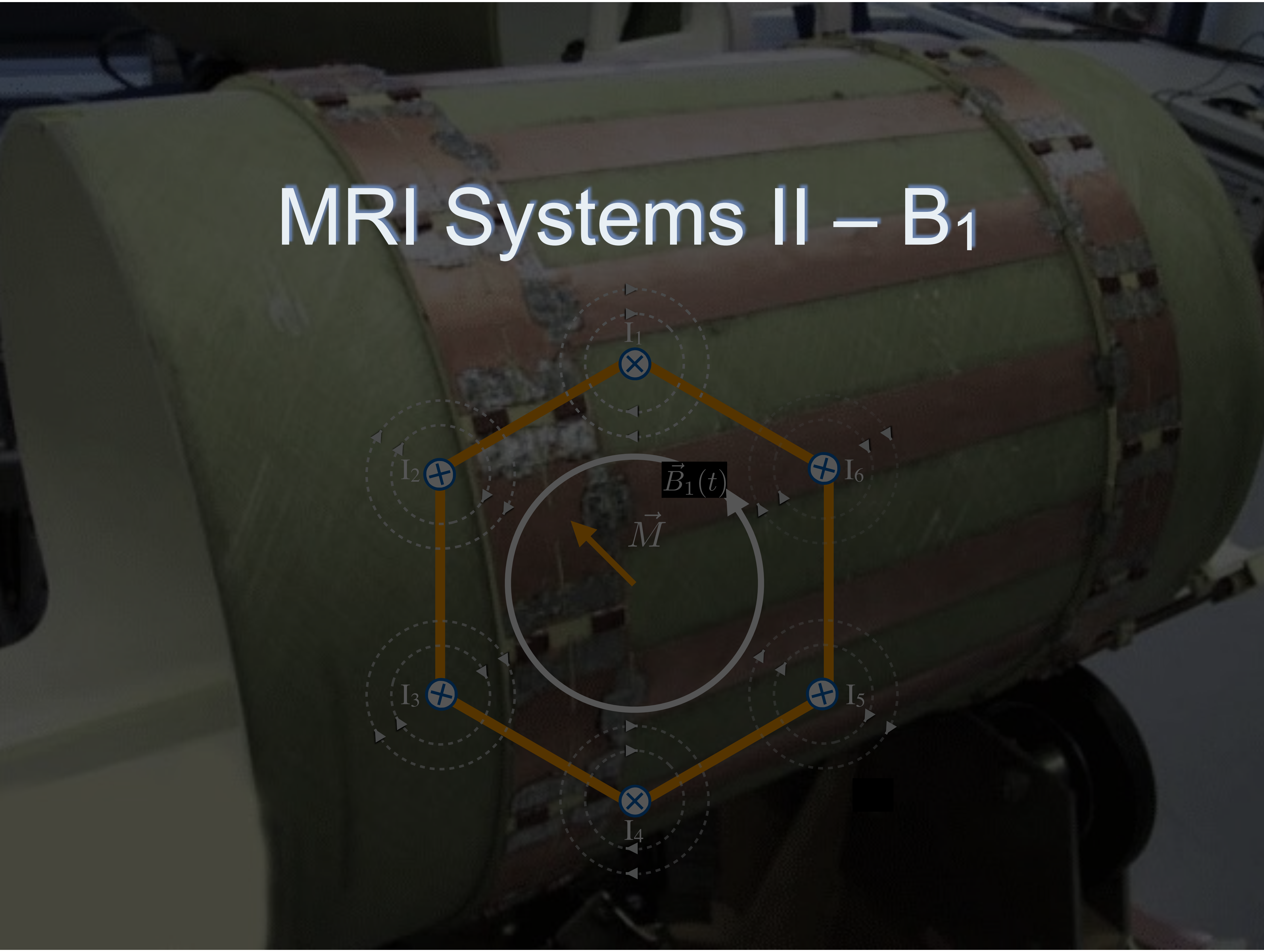
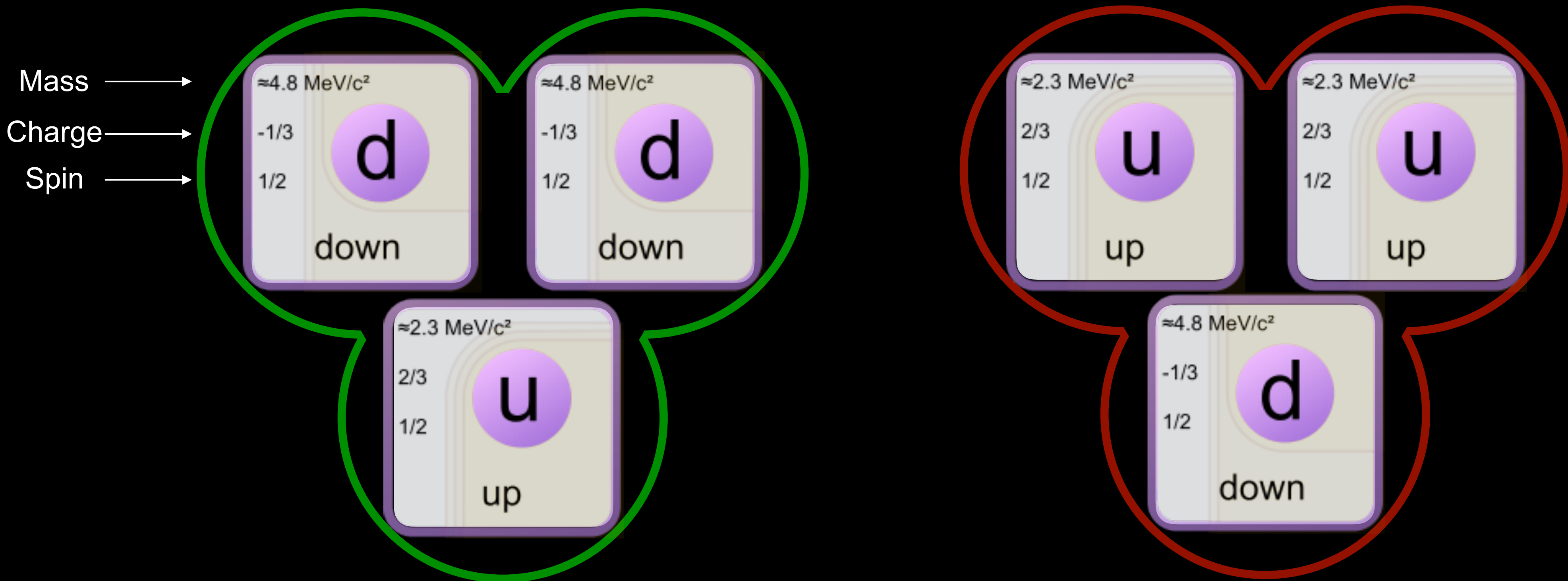
MRI Systems II – B_1



Spin+Charge⇒Magnetic Moment?

Neutron **Proton**



Charge=0
Spin=1/2

Charge=+e
Spin=1/2

What about the neutron? It has no charge, but it has spin!

Lecture #2 Learning Objectives

- Explain three B_0 principles and the importance of Zeeman splitting.
- Describe the importance of spin, charge, and mass to NMR.
- Define the equation of motion for an ensemble of spins.
- Differentiate free and forced precession in the laboratory and rotating frames.
- Learn to solve for the bulk magnetization dynamics under specific conditions.

Lecture 2 - Summary

$$\vec{\tau} = \vec{\mu} \times \vec{B} \quad \vec{S} = \vec{r} \times \vec{p}$$

$$\vec{\tau} = \frac{d\vec{S}}{dt} \quad \vec{\mu} = \gamma \vec{S}$$

$$\frac{d\vec{\mu}}{dt} = \vec{\mu} \times \gamma \vec{B}$$

Equation of Motion for a Magnetic Dipole

$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n$$

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

Equation of Motion for the bulk magnetization.

$$\vec{B}_0 = B_0 \vec{k}$$

$$\frac{d\vec{M}}{dt} = \vec{M} \times \gamma \left(\vec{B}_0 \right) = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ M_x & M_y & M_z \\ 0 & 0 & \gamma B_0 \end{vmatrix}$$

$$M_x(t) = M_x^0 \cos(\gamma B_0 t) + M_y^0 \sin(\gamma B_0 t)$$
$$M_y(t) = -M_x^0 \sin(\gamma B_0 t) + M_y^0 \cos(\gamma B_0 t)$$
$$M_z(t) = M_z^0$$

How do we perturb the equilibrium?

Lecture 2 - Summary

- Free Precession in the Laboratory Frame
- **Forced Precession in the Laboratory Frame**
  - Coordinate system anchored to scanner

- **Free Precession in the Rotating Frame**
- **Forced Precession in the Rotating Frame**
  - Coordinate system anchored to spin system

- **...all without relaxation.**
  - a) Relaxation time constants are “really” long
  - b) Time scale of event is $<<$ relaxation time constant

Dipoles to Images

$\vec{\mu}$	Magnetic Moment	
$\downarrow$		B_0
$\vec{M}$	Bulk Magnetization	
$\downarrow$		B_1
$\vec{M}_{xy}(t)$	Transverse Magnetization	
$\downarrow$		$G_{Encoding}$
$\vec{M}_{xy}(\vec{r},t)$	Spatially Encoded Magnetization	
$\downarrow$		Coil
$V(t)$	Received Voltage	
$\downarrow$		PSD
$S(t)$	Complex Signal	
$\downarrow$		$G_{Decoding}$
$S\left(\vec{k}\right)$	k-space signal	
$\downarrow$		Reconstruction
$I(\vec{r})$	Image	

MRI Systems II – B_1

Lecture #3 Learning Objectives

- Distinguish spin, precession, and nutation.
- Appreciate that any B-field acts on the the spin system.
- Understand the advantage of a circularly polarized RF B-field.
- Differentiate the lab and rotating frames.
- Define the equation of motion in the lab and rotating frames.
- Know how to compute the flip angle from the B1-envelope function.
- Understand how to apply the RF hard pulse matrix operator.

B_1 Field - RF Pulse

- B_1 is a
  - radiofrequency (RF)
    - 42.58MHz/T (63MHz at 1.5T)
  - short duration pulse (~0.1 to 5ms)
  - small amplitude
    - <30 μT
  - circularly polarized
    - rotates at Larmor frequency
  - magnetic field
  - perpendicular to B_0

RF Birdcage Coil

MRI Hardware

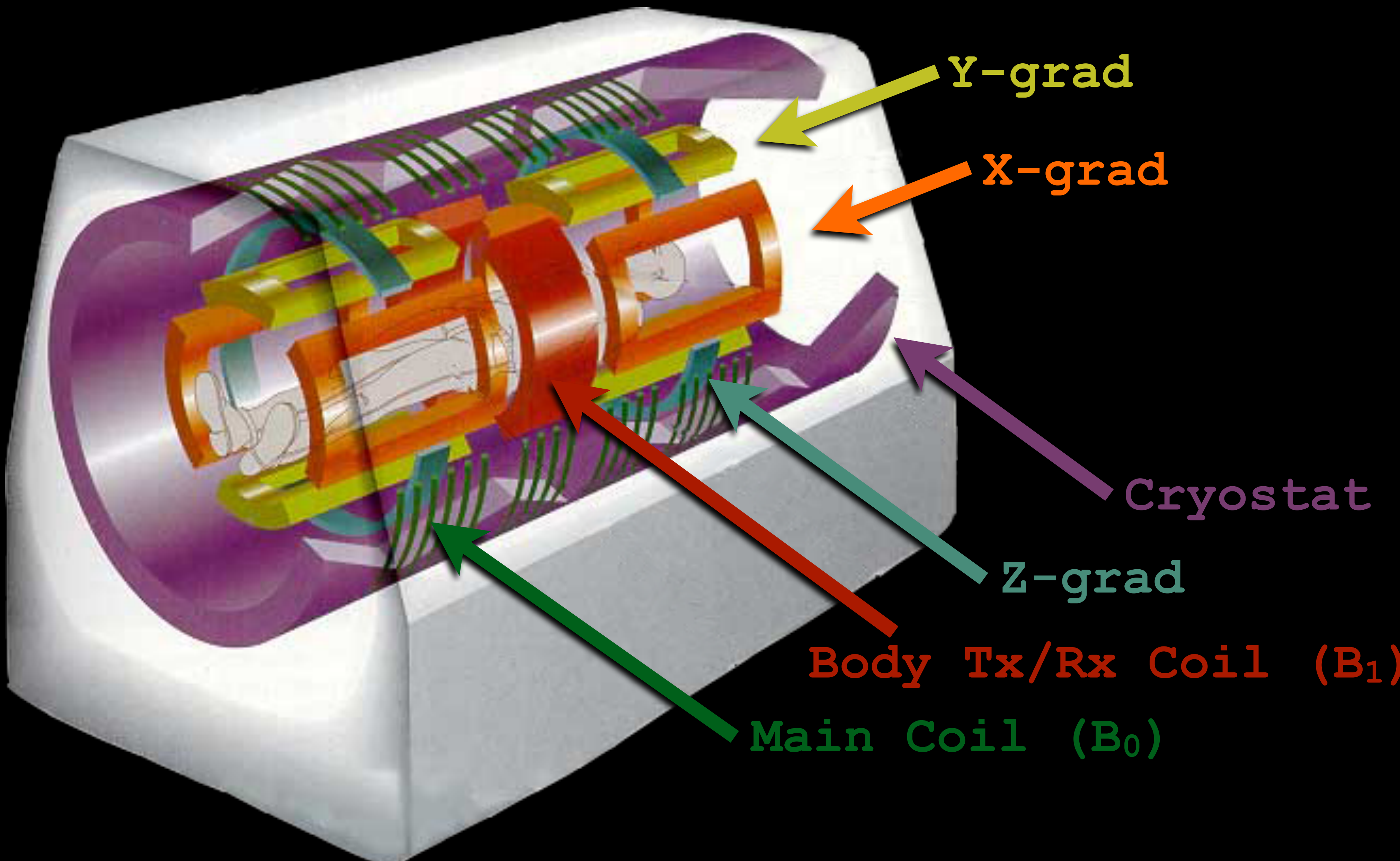
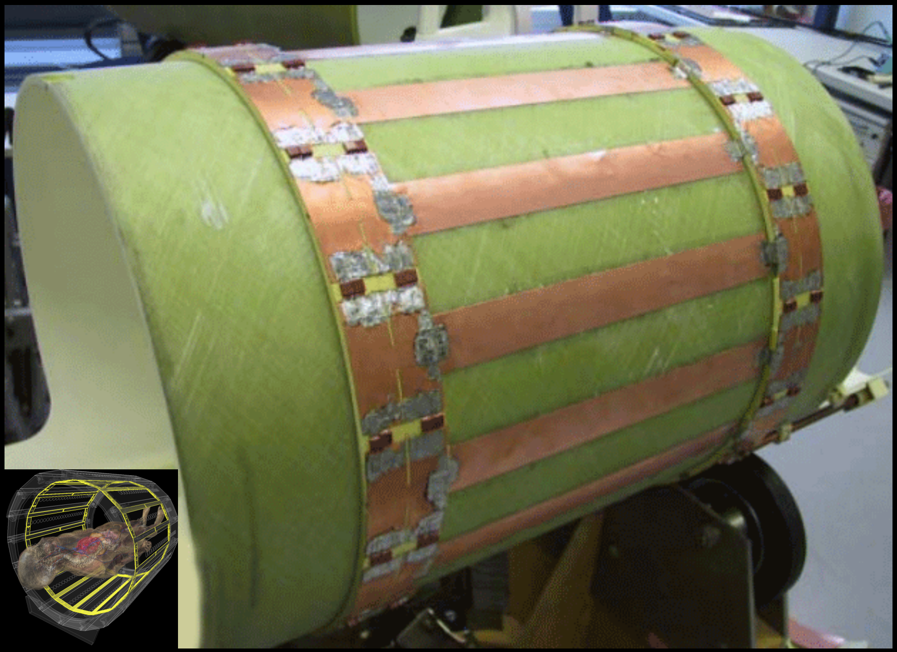


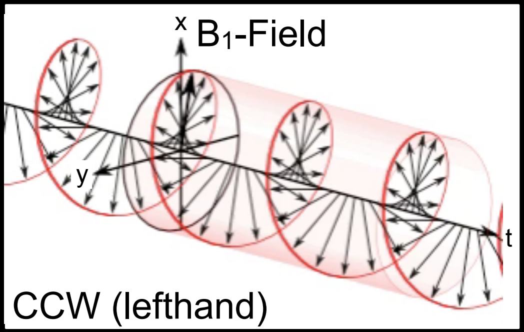
Image Adapted From: http://www.ee.duke.edu/~jshorey

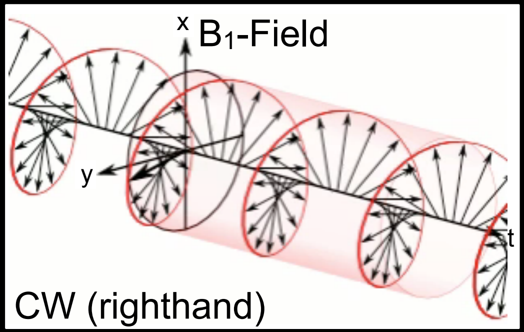
RF Birdcage Coil

- **Most common design**
- **Highly efficient**
  - Nearly all of the fields produced contribute to imaging
- **Very uniform field**
  - Especially radially
  - Decays axially
  - Uniform sphere if L≈D
- **Generates a "quadrature" field**
  - Circular polarization

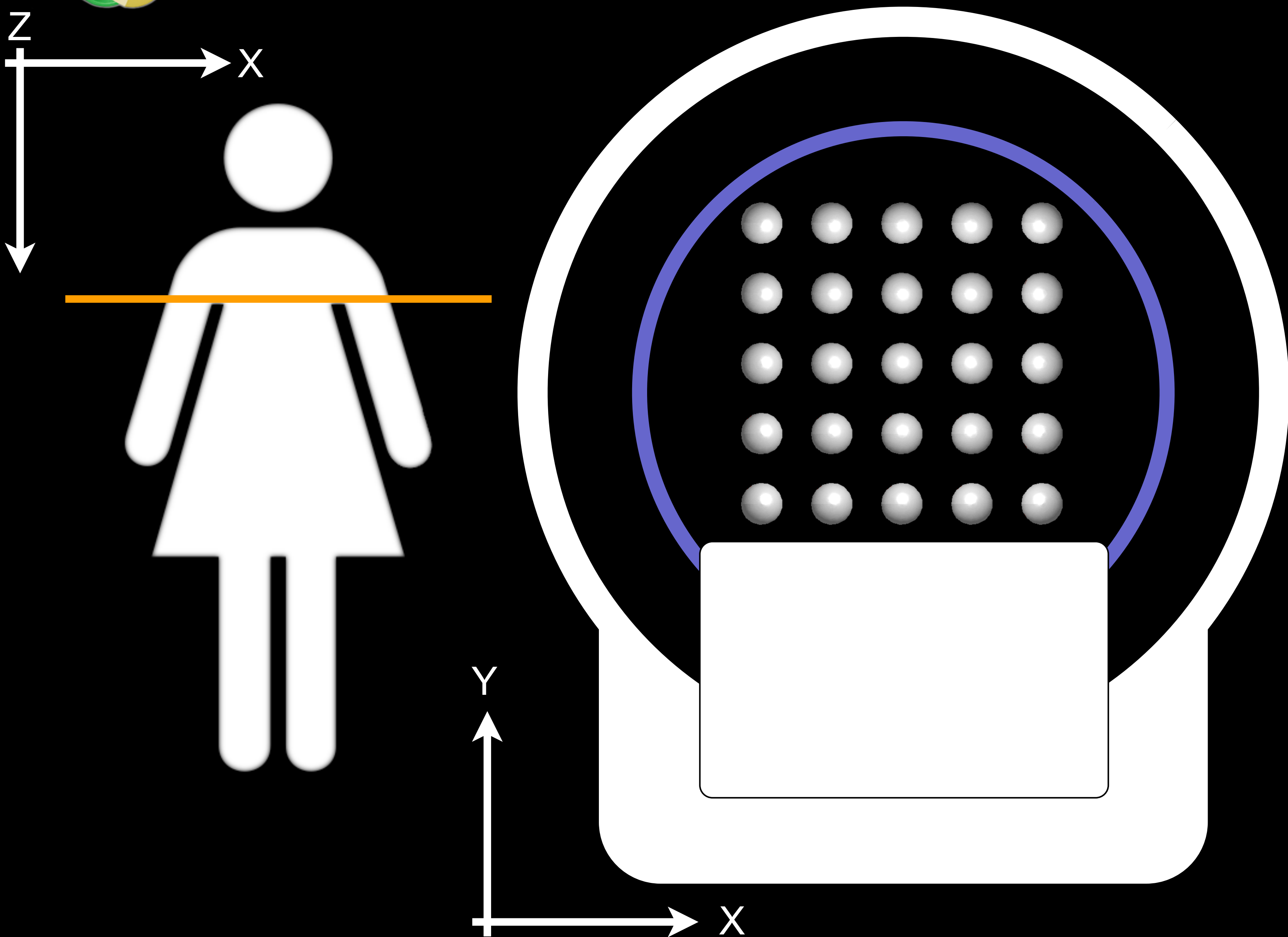
Body Tx/Rx Coil (B_1)





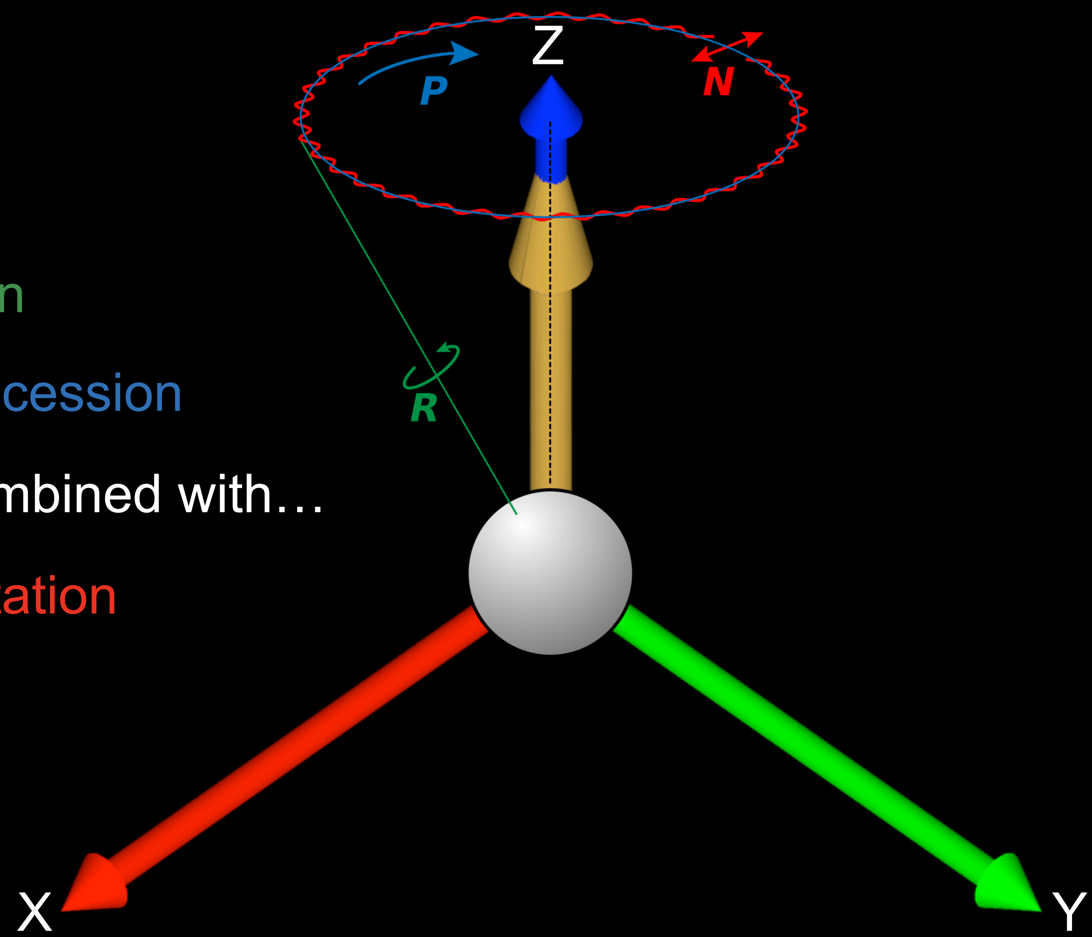


RF Excitation - Lab Frame



RF pulses can generate transverse magnetization (M_{xy}).

RF Excitation - Lab Flame



^{1}H has intrinsic Spin

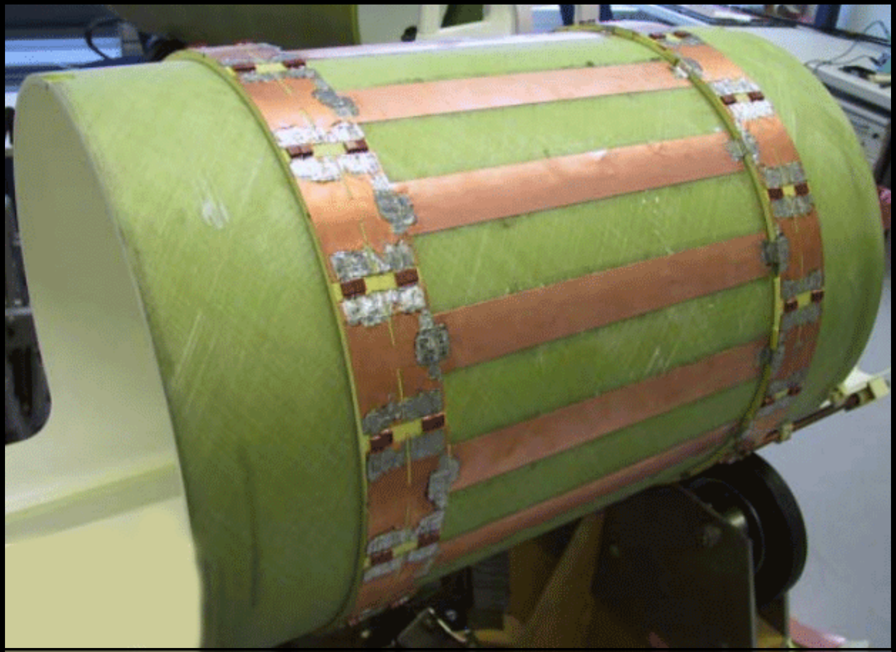
$\omega_0 = \gamma B_0$ Precession

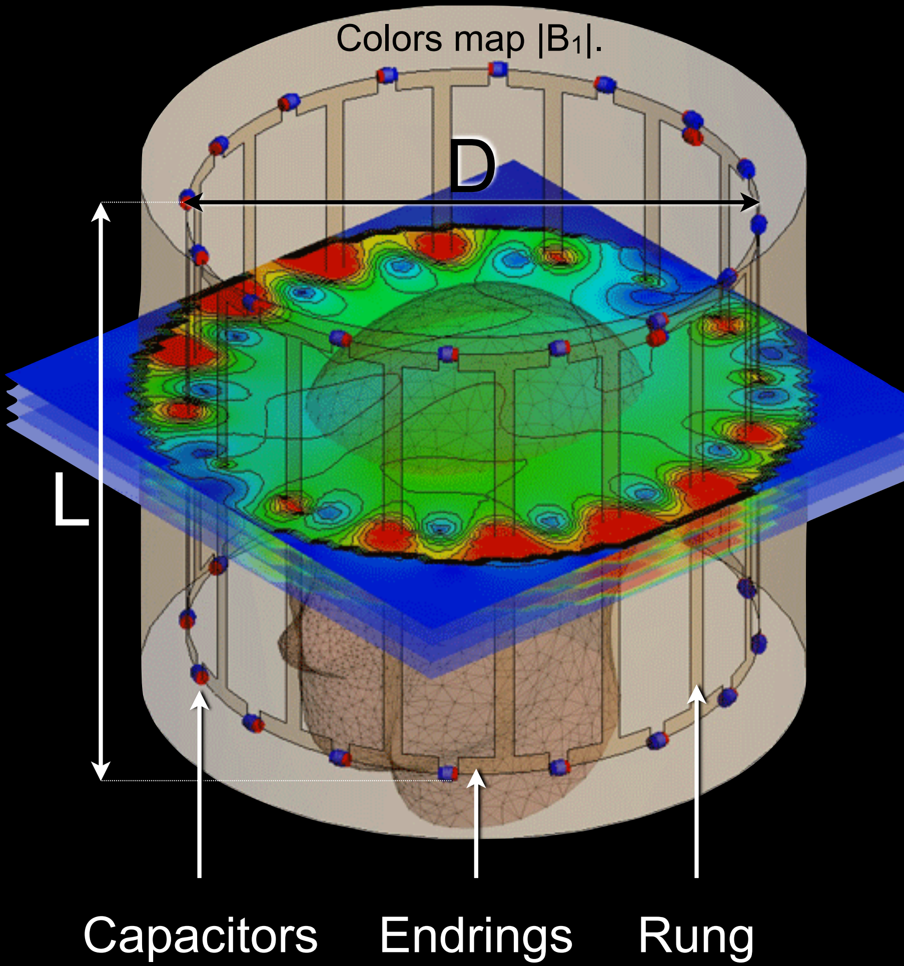
Combined with…

$\omega_1 = \gamma B_1$ Nutation

B_0 causes precession about z-axis. B_1 causes precession **nutation**.

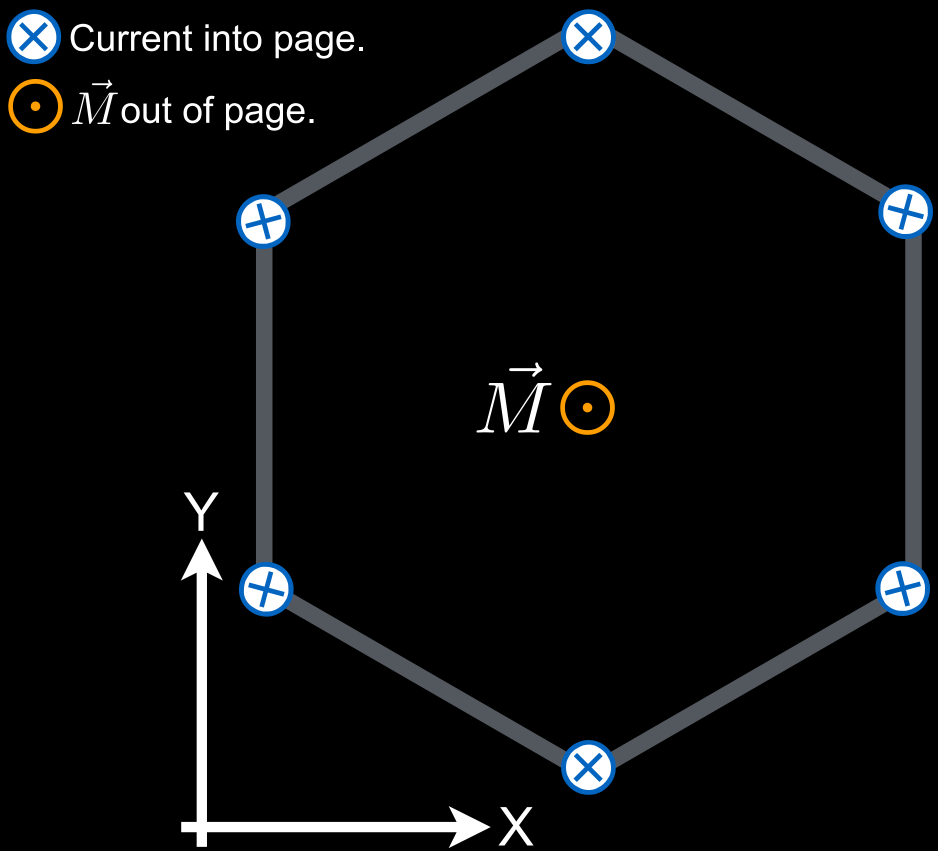
RF Birdcage Coil

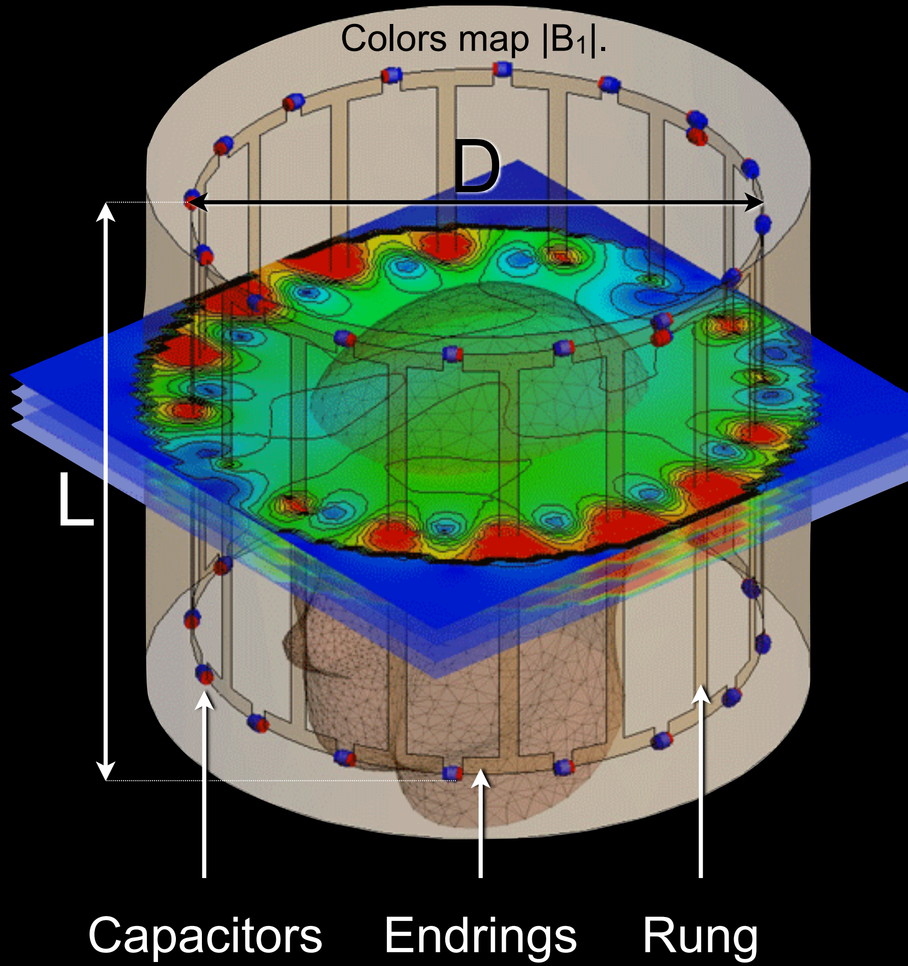




Birdcage coils are used to generate **low SAR** [W/kg] **circularly polarized** RF B_1-fields.

RF Birdcage Coil



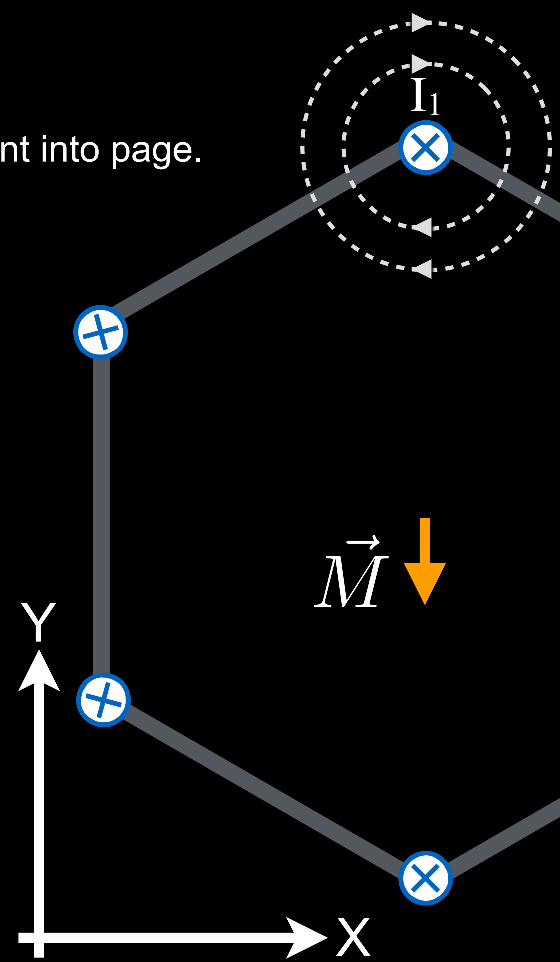


In the absence of any applied RF the bulk magnetization is oriented along the z-axis.

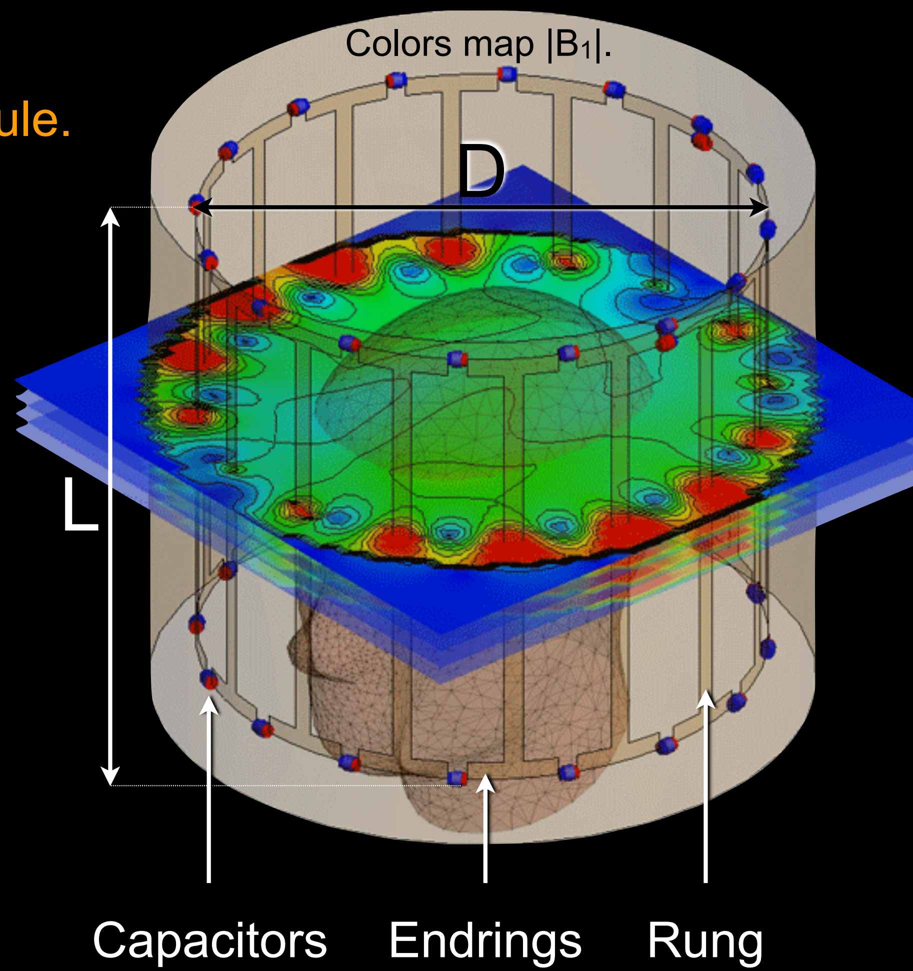
RF Birdcage Coil

⊗ Current into page.

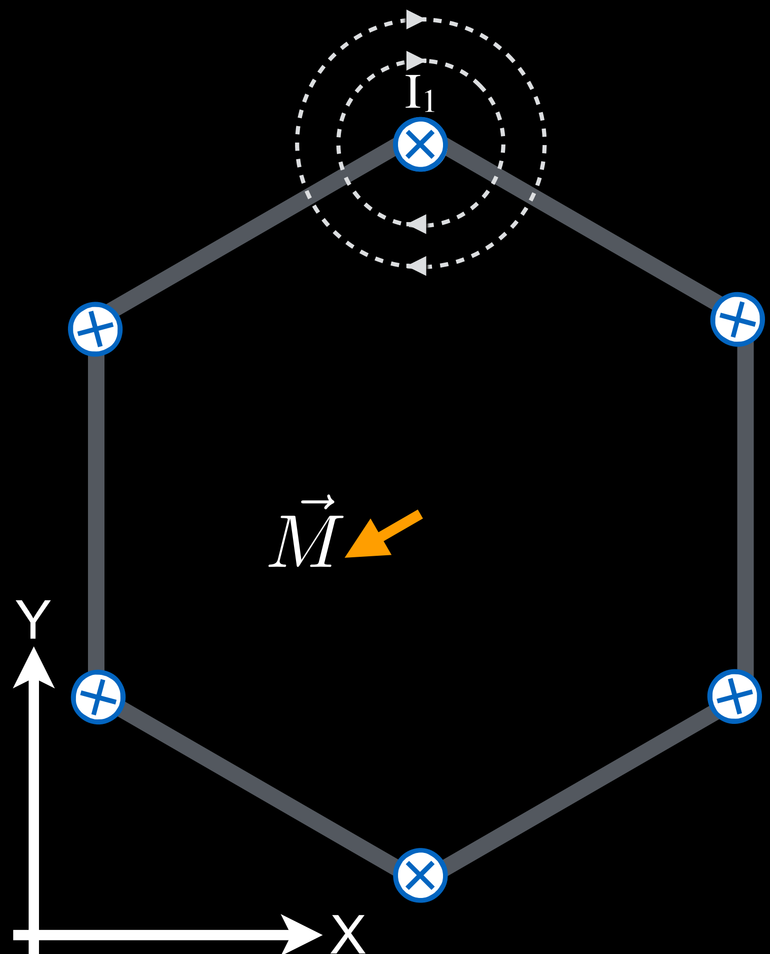
Direction of B_1-field follows ***right hand*** rule.



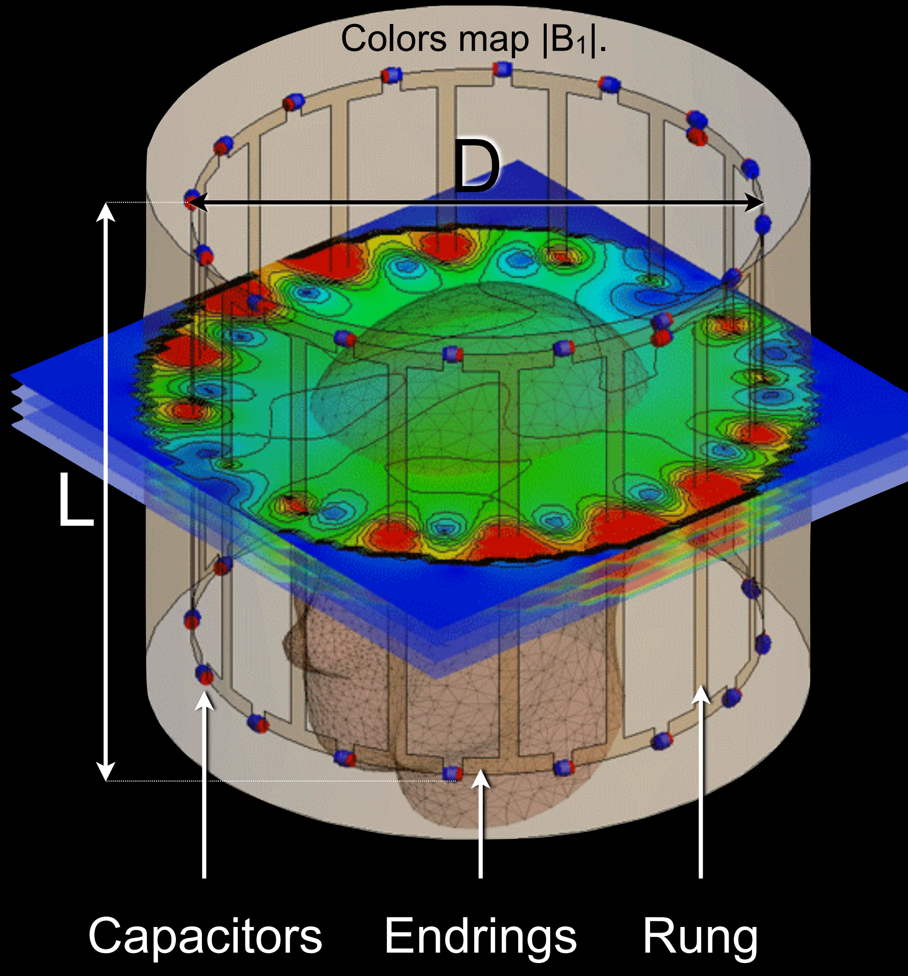
A current (I_1) induces a ***left-handed*** nutation about the B_1-field.



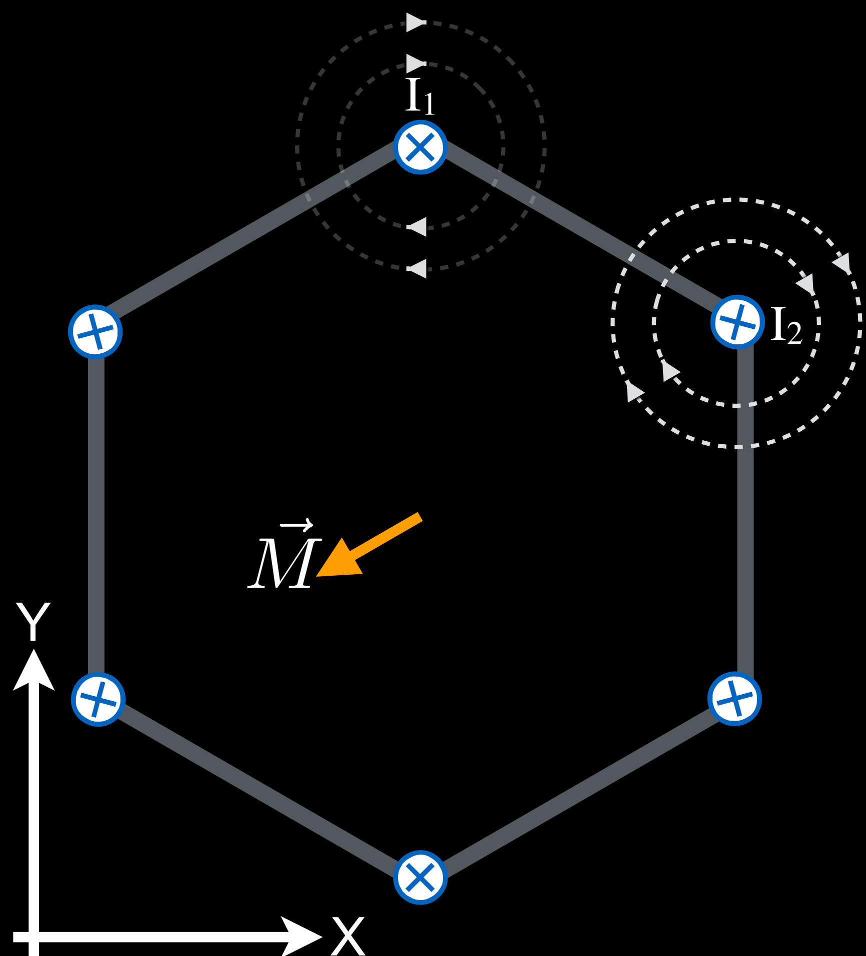
RF Birdcage Coil



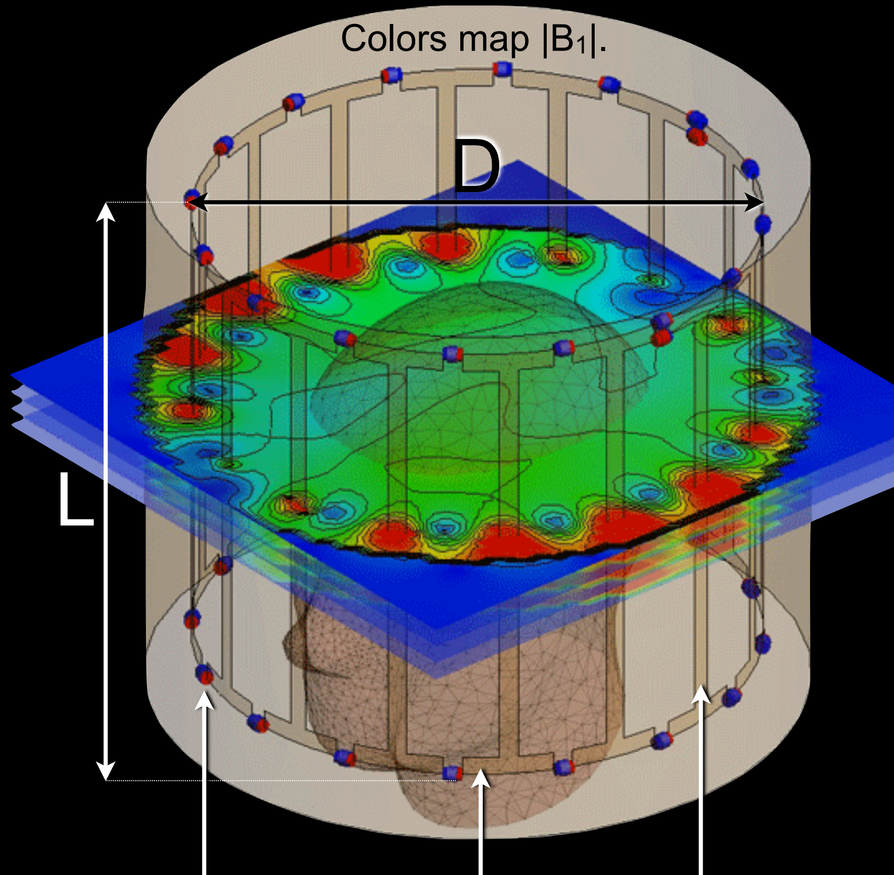
Precession from B_0 advances the spin clockwise (***left hand rule***).



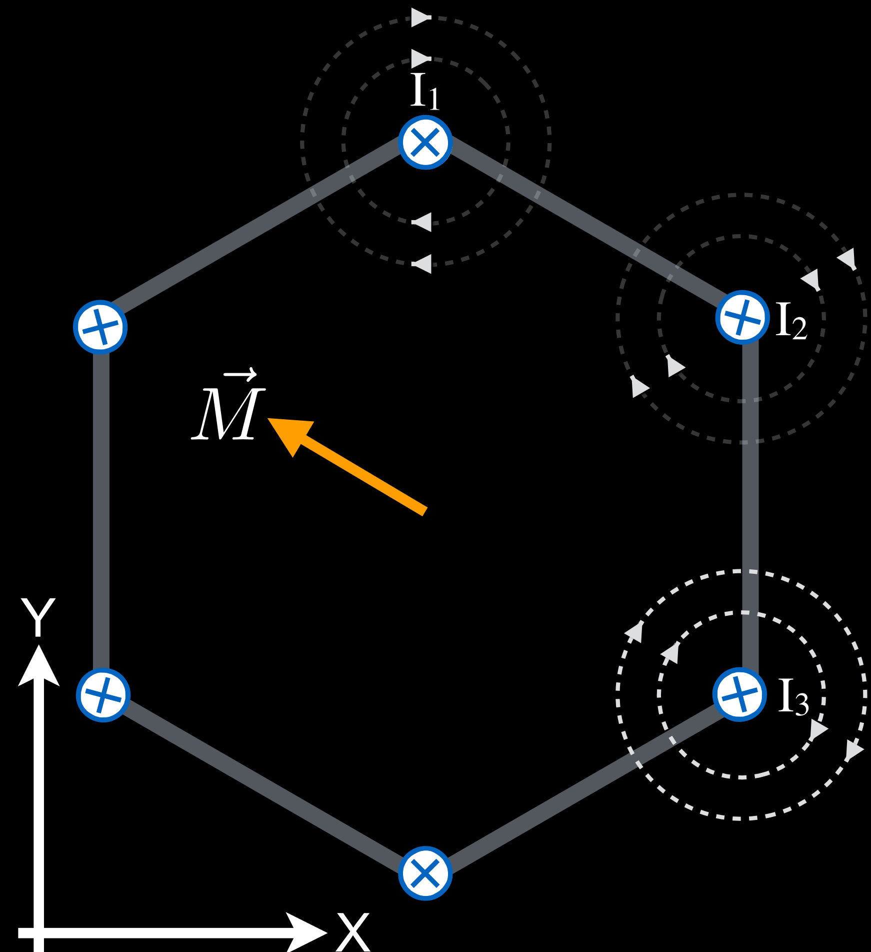
RF Birdcage Coil

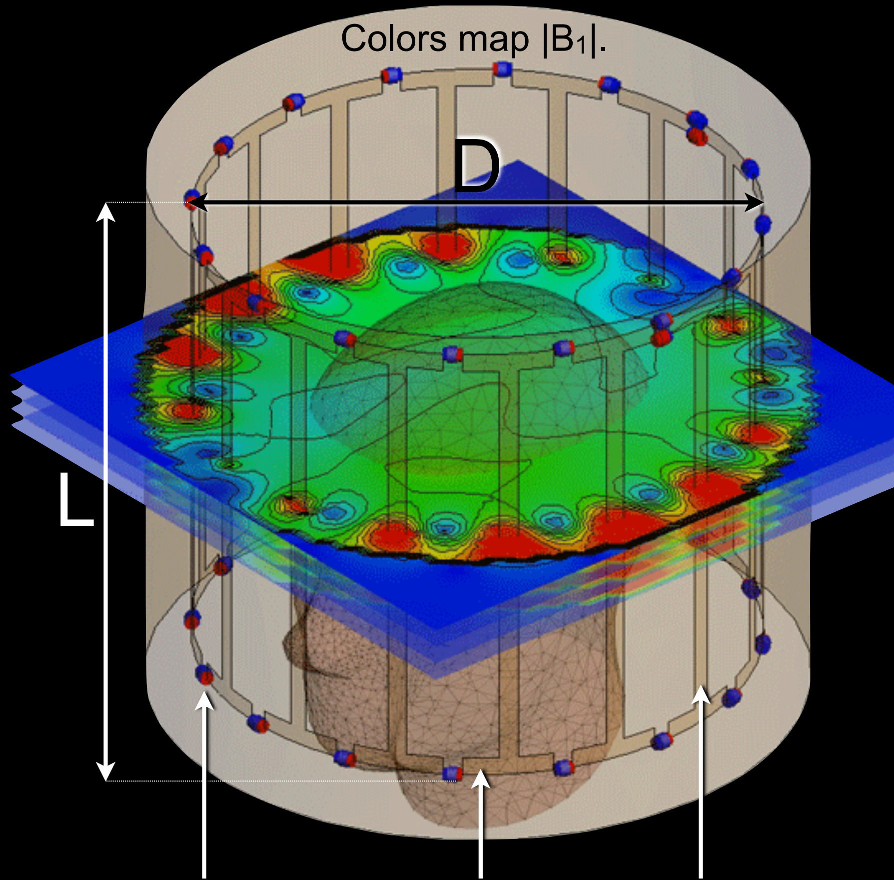


B_1 nutation from I_2 generates more M_{xy}.



RF Birdcage Coil

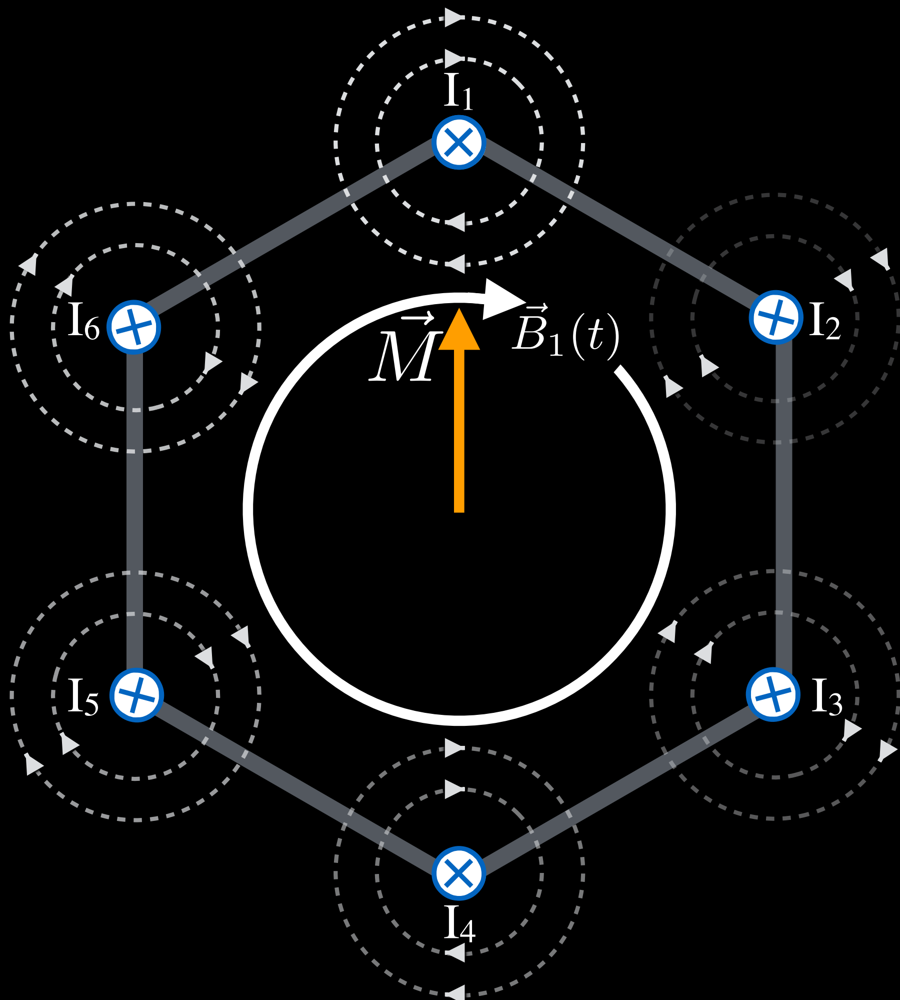


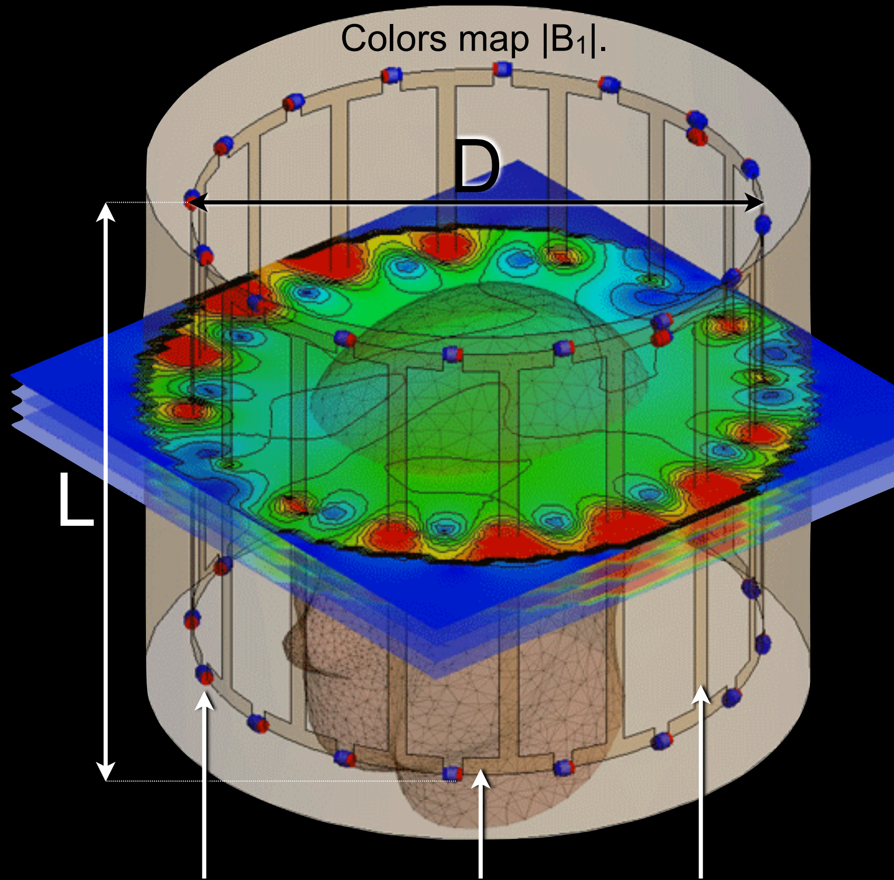


$$I_n(t) = I_0 \sin\left(\omega_{RF} t - \frac{2\pi(n-1)}{N_{Rungs}}\right)$$

Current in the n^{th} rung.
Creates a CW B_1-field.

RF Birdcage Coil





$$I_n(t) = I_0 \sin\left(\omega_{RF} t - \frac{2\pi(n-1)}{N_{Rungs}}\right)$$

Current in the n^{th} rung.
Creates a CW B_1-field.

Consider reading Chp. 16.3 in Haacke.

B_1 Inhomogeneity

B_1 Inhomogeneity: Imperfect B_1 amplitude as a function of spatial position.

Sources:

- Hardware imperfections.
- Conductivity & permittivity of subject/object [1].
- Wavelength effects.

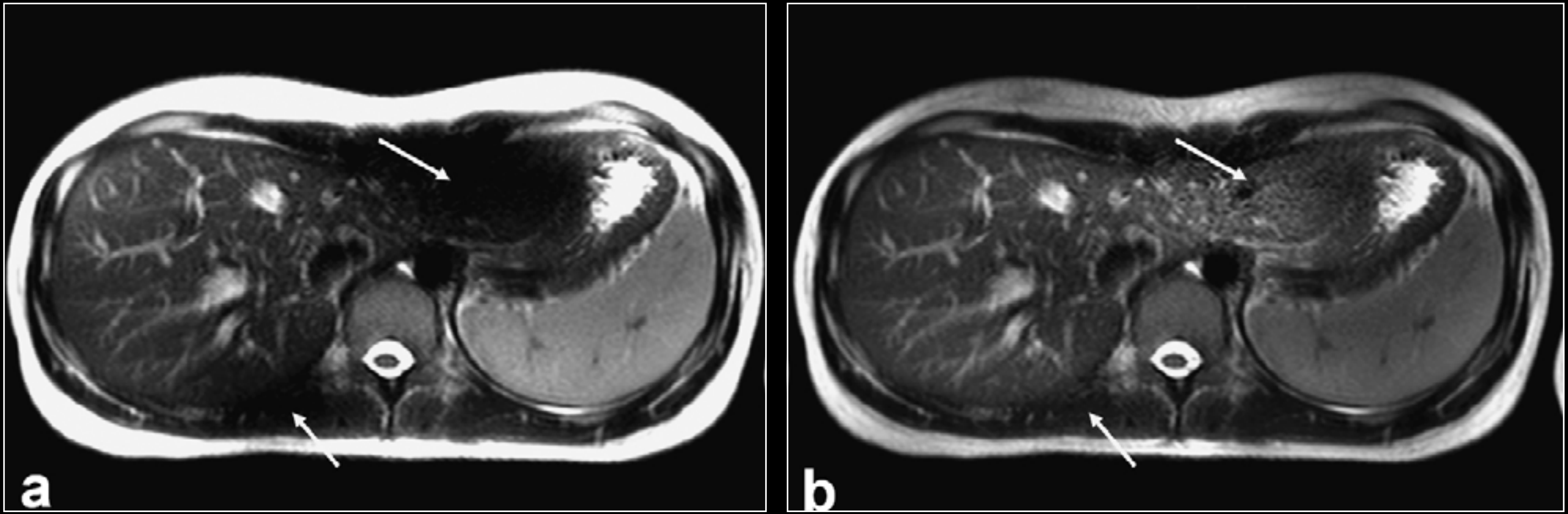
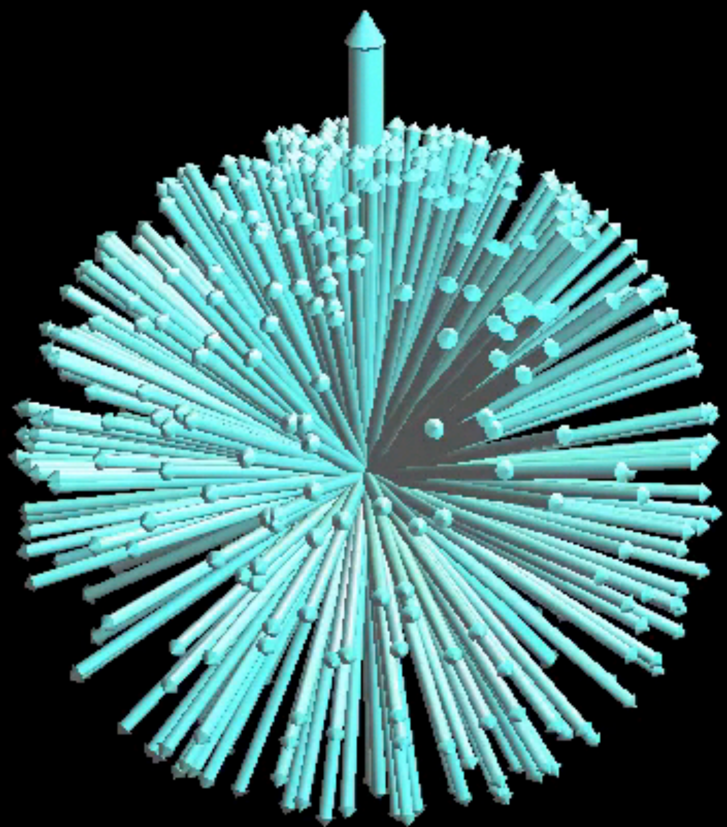


Fig. 5. Signal loss due to ***inhomogeneous flip-angle distribution*** at 3T. (a) Wavelength effects result in reduced signal intensity in the abdomen (arrows). (b) This effect can in some cases be reduced by manually increasing the RF-transmitter amplitude (here by 50%) and by applying image post-processing filters to obtain more uniform image intensities. Images courtesy of W. Horger, Siemens Medical Solutions, Germany [2]

[1] Franklin KM *et al*. Improvement in B1-inhomogeneity artifacts in the abdomen at 3T MR imaging using a RF cushion. JMRI. 2008;27(6):1443-7.
[2] Artifacts in 3-T MRI: Physical background and reduction strategies, Dietrich O. *et al*. *European J. of Radiology*, v65, Issue 1, Jan 2008, p29–35

Resonance

Ensemble of Precessing Spins



"The equilibrium magnetization is stationary, so even though the individual spins are precessing, there is no net emission of radio waves in equilibrium."

David Geffen School of Medicine

Hanson, L. G. (2008). "Is Quantum Mechanics Necessary for Understanding Magnetic Resonance?" Concepts in Magnetic Resonance Part A 32(A): 329-340.

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Resonance

- Quantum Physics
  - Electromagnetic radiation of frequency ω_{RF} carries energy that induces a coherent transition of spins from $N_\uparrow$ to $N_\downarrow$.
- Classical Physics
  - $\vec{B}_1(t)$rotates in the same manner as the precessing spins.
  - Coherently “pushes” on bulk magnetization.

Resonance Condition (Quantum)

$$\Delta E = E_{\downarrow} - E_{\uparrow} = \hbar\gamma B_0$$

Zeeman Splitting

$$E_{RF} = \hbar\omega_{RF}$$

Planck's Law

$$\hbar\gamma B_0 = \hbar\omega_{RF}$$

$$\omega_{RF} = \gamma B_0 = \omega_0$$

Resonance Condition

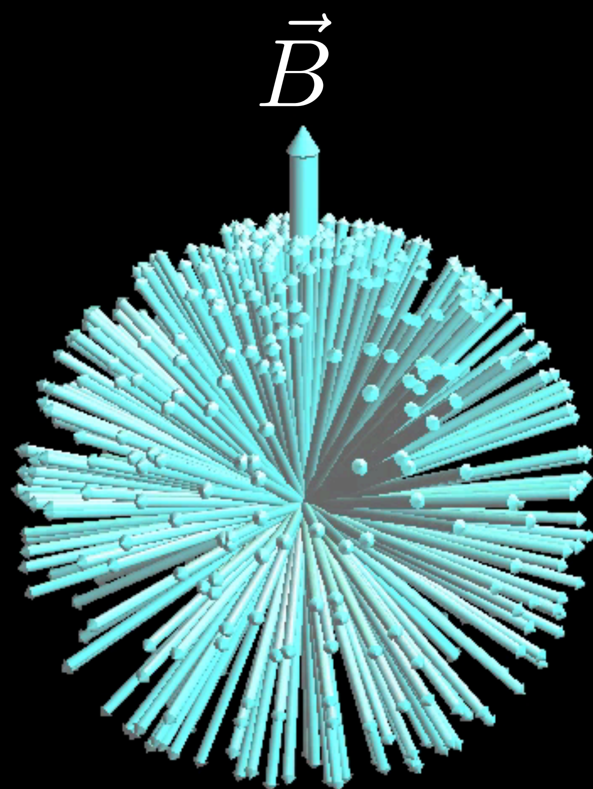
Resonance requires that the frequency of the RF energy (ω_{RF}) match the frequency of precession (ω_0).

Resonance Condition (Classical)

"Establishment of a phase coherence among these 'randomly' precessing spins in a magnetized spin system is referred to as *resonance*."

– Liang & Lauterbur p.69

$$N_{\uparrow} \approx N_{total} \times (1 + 2.25 \times 10^{-6})$$



$$N_{\downarrow} \approx N_{total} \times (1 - 2.25 \times 10^{-6})$$

SAR, Polarization, and B_1 Safety

SAR Limitations

- **Specific Absorption Rate**
  - Measure of the rate of energy absorption during exposure to a RF electromagnetic field
  - Measured in units of [W/kg]
- High-field (>1.5T) imaging with high flip angles (>45-90°) can be challenging.

$$\mathrm{SAR} \propto \omega_0^2 B_1^2 \propto B_0^2 \alpha^2$$

SAR Limits

Limit	Whole-Body Average	Head Average	Head, Trunk Local SAR	Extremities Local
IEC (6-minute average)				
Normal (all patients)	2 W/kg (0.5°C)	3.2 W/kg	10 W/kg	20 W/kg
First level (supervised)	4 W/kg (1°C)	3.2 W/kg	10 W/kg	20 W/kg
Second level (IRB approval)	4 W/kg (>1°C)	>3.2 W/kg	>10 W/kg	>20 W/kg
Localized heating limit	39°C in 10 g	38°C in 10 g		40°C in 10 g
FDA	4 W/kg for 15 min	3 W/kg for 10 min	8 W/kg in 1g for 10 min	12 W/kg in 1g for 5 min

Bottomley PA. Turning up the heat on MRI. J Am Coll Radiol 2008;5(7):853-855.

Basic RF Pulse - Linear Polarized

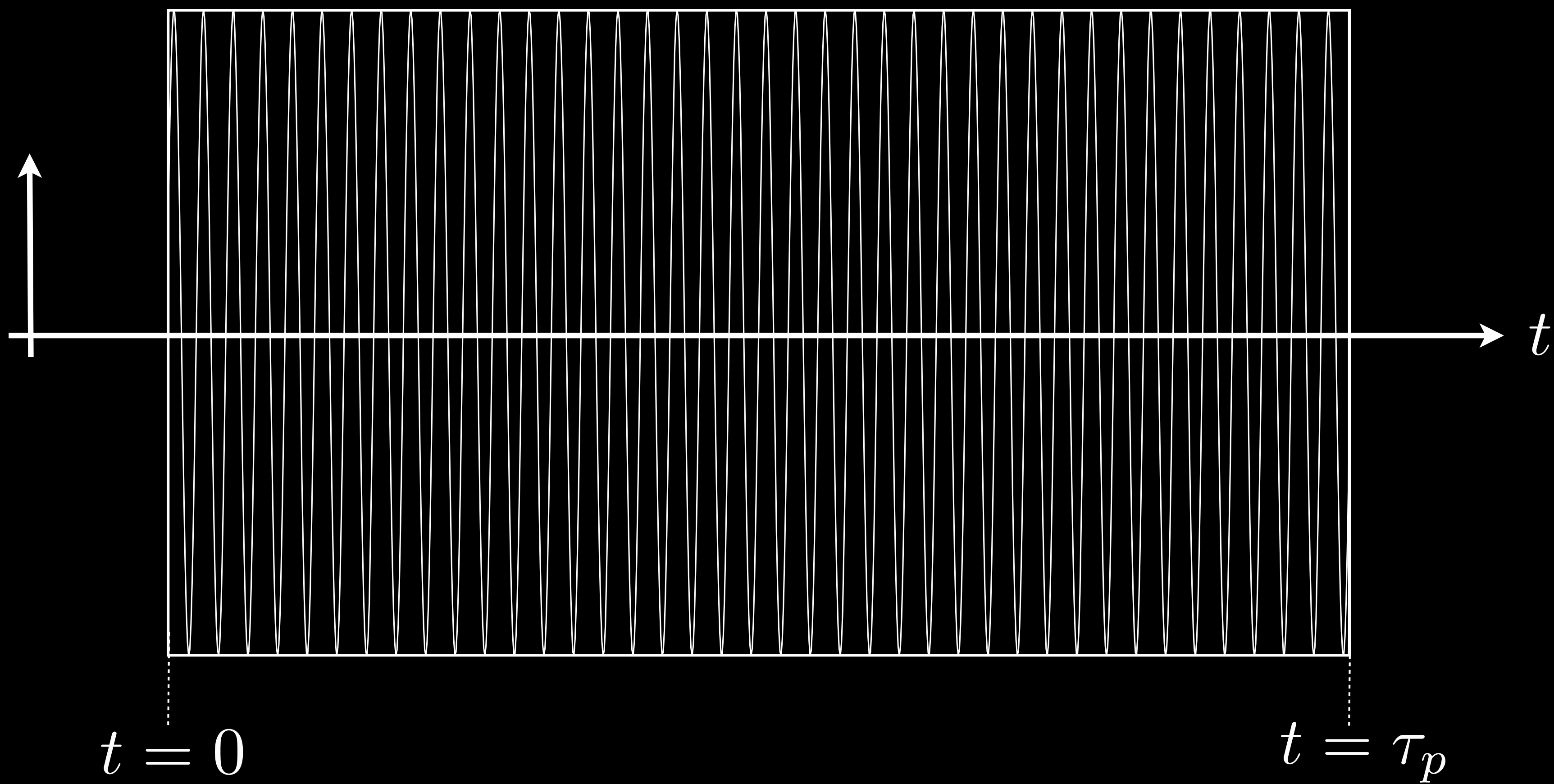
$$\vec{B}_1(t) = 2B_1^e(t)\cos(\omega_{RF}t + \theta)\vec{i}$$

$B_1^e(t)$	**pulse envelope function**
ω_{RF}	**excitation carrier frequency**
θ	**initial phase angle**
$\vec{i}$	**linearly polarized**

B_1 is perpendicular to B_0.

Rect Envelope Function

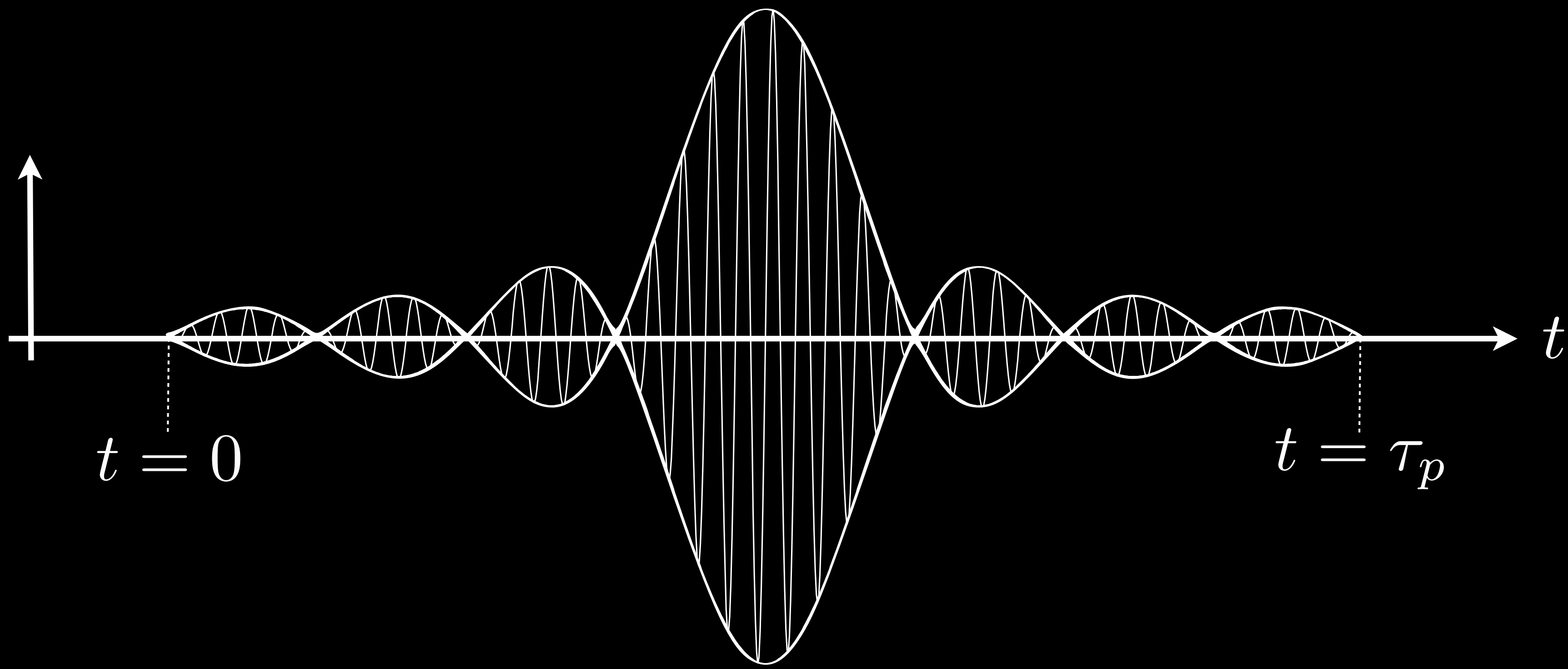
$$B_1^e(t) = B_1 \sqcap\left(\frac{t-\tau_p/2}{\tau_p}\right) = \begin{cases} B_1, & 0 \le t \le \tau_p \\ 0, & otherwise \end{cases}$$



RECT functions are used to excite a “single” frequency.

Sinc Envelope Function

$$B_1^e(t) = \begin{cases} B_1 \mathrm{sinc}\left[\pi f_\omega \left(t - \tau_p/2\right)\right], & 0 \le t \le \tau_p \\ 0, & otherwise \end{cases}$$



SINC functions are used to excite a narrow band of frequencies.

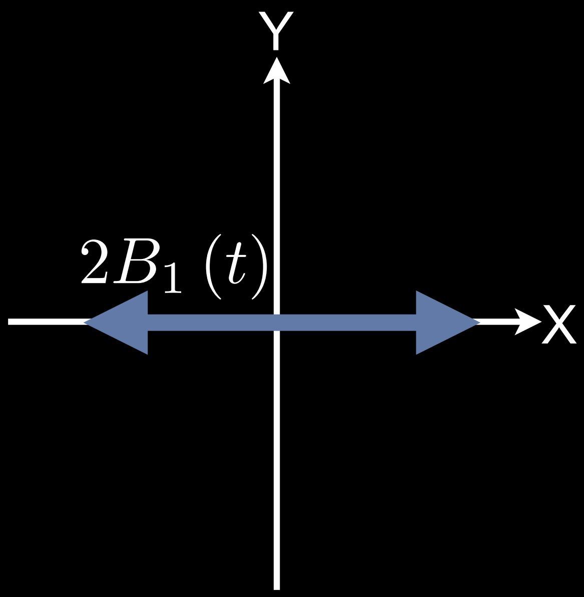
Circular vs. Linear Polarization

- Linear Polarization
  - Simple, cheap
  - Higher RF power
- Circular Polarization
  - Generated with a quadrature RF transmitter coil
    - More complex & more expensive
  - Reduced RF power deposition

Linearly Polarized Fields

Linear Polarization

$$2B_1^e(t)\cos(\omega_{RF}t)\,\hat{i}$$

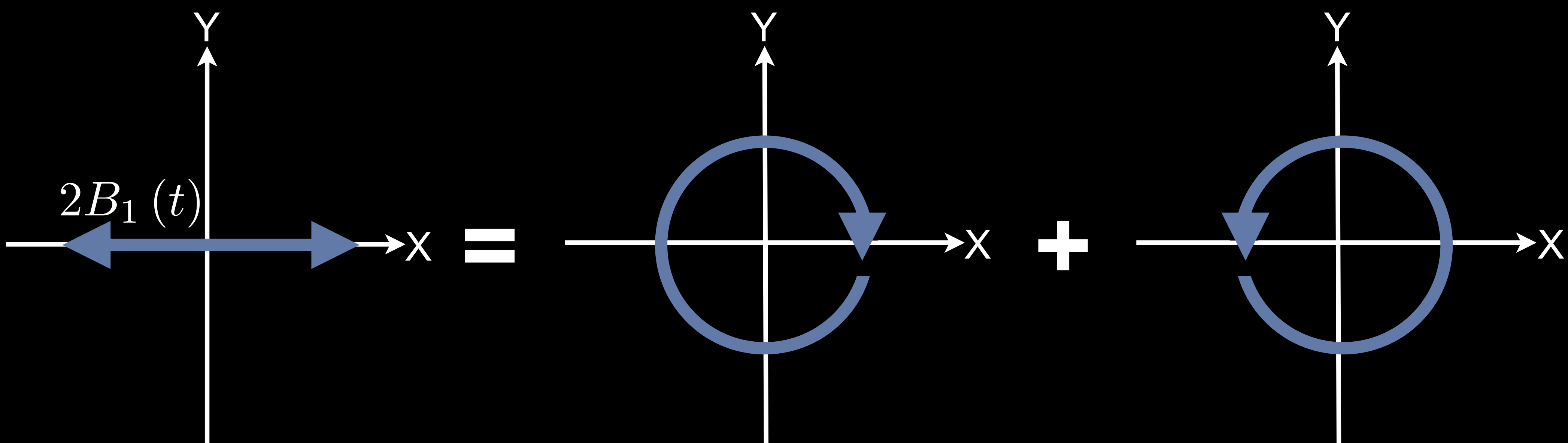


Arrow indicates direction of B-field.

Circularly Polarized Fields

Linear Polarization — CW Circular Polarization — CCW Circular Polarization

$$2B_1^e(t)\cos(\omega_{RF}t)\,\hat{i} = B_1^e(t)\left[\cos(\omega_{RF}t)\,\hat{i} - \sin(\omega_{RF}t)\,\hat{j}\right] + B_1^e(t)\left[\cos(\omega_{RF}t)\,\hat{i} + \sin(\omega_{RF}t)\,\hat{j}\right]$$



On-Resonance
Excitation+Heating

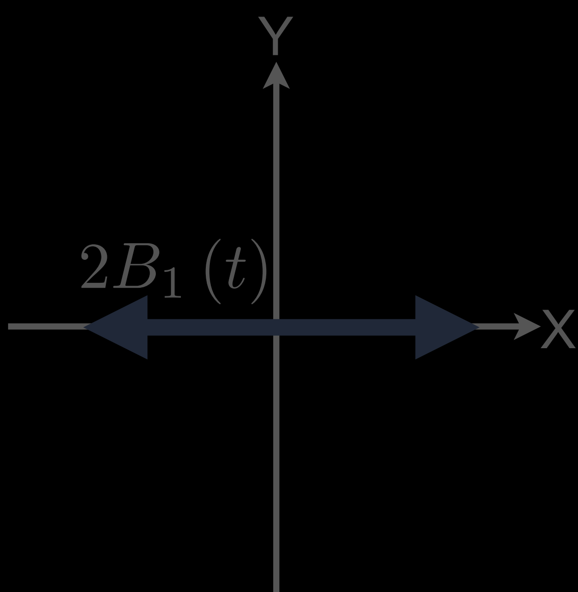
Very Off-Resonance
Heating

Arrow indicates direction of B-field.

Circularly Polarized Fields

Linear Polarization | CW Circular Polarization | CCW Circular Polarization

$$2B_1^e(t)\cos(\omega_{RF}t)\,\hat{i} = B_1^e(t)\left[\cos(\omega_{RF}t)\,\hat{i} - \sin(\omega_{RF}t)\,\hat{j}\right] + B_1^e(t)\left[\cos(\omega_{RF}t)\,\hat{i} + \sin(\omega_{RF}t)\,\hat{j}\right]$$



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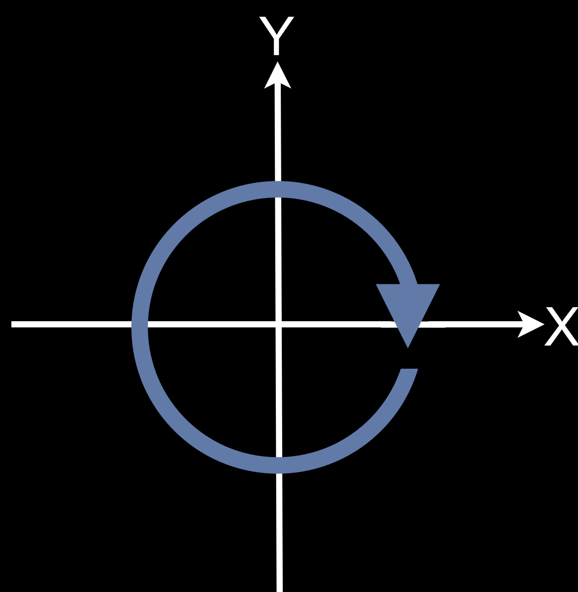

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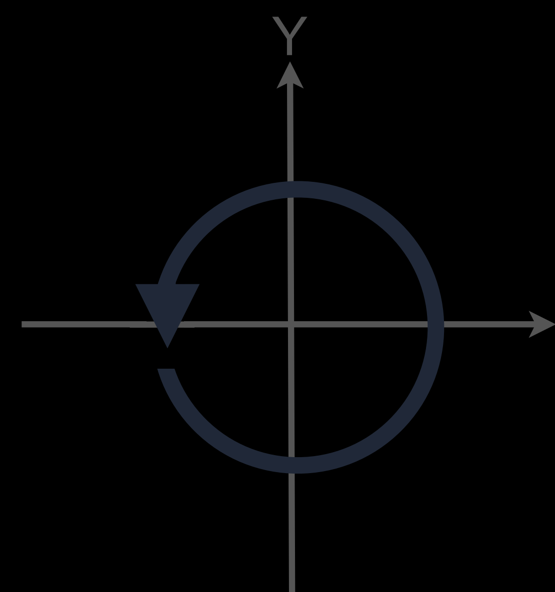


On-Resonance
Excitation+Heating

Very Off-Resonance
Heating

First Generation MRI Systems Used Linear Polarization

Modern MRI Systems Only Use CW Circular Polarization

Modern MRI Systems Don't Apply The CCW Field

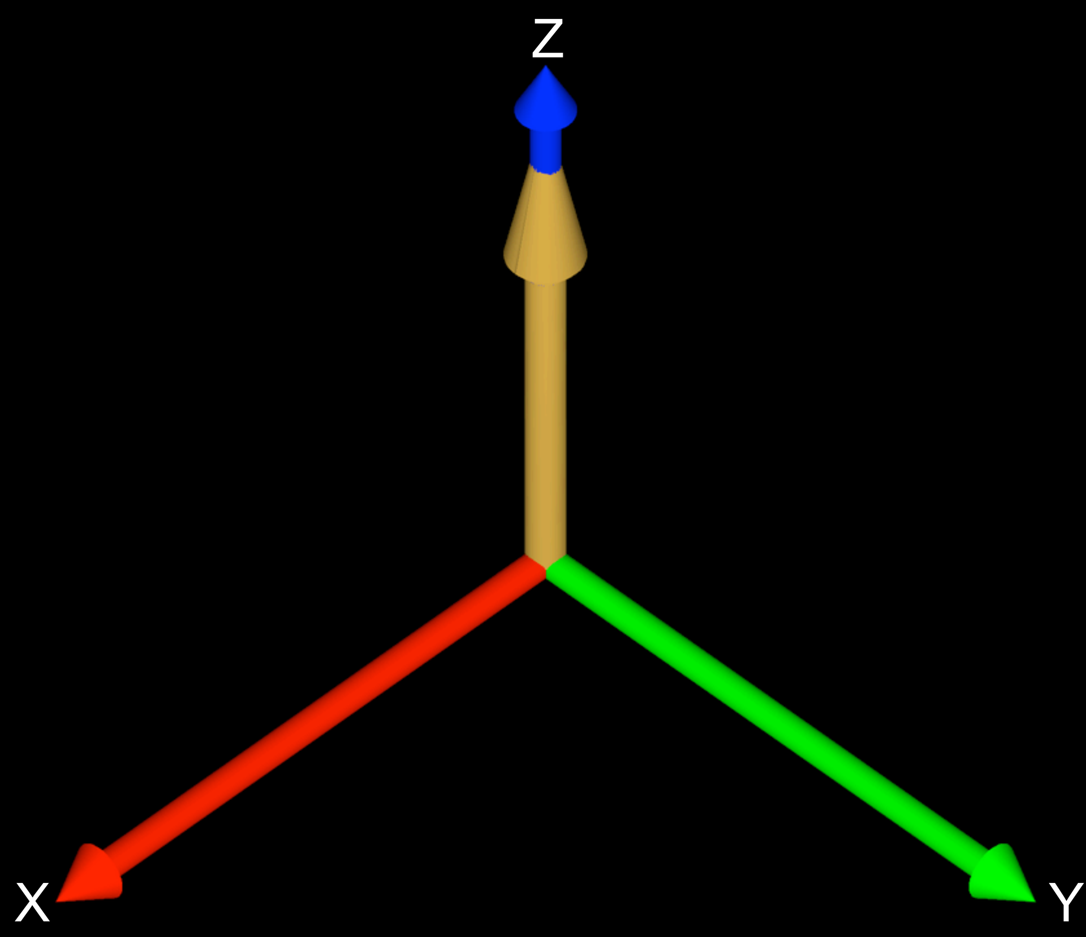
Arrow indicates direction of B-field.

Forced Precession in the Laboratory Frame without Relaxation

Four Special Cases…

- Free Precession in the Laboratory Frame
- **Forced Precession in the Laboratory Frame**
  - Coordinate system anchored to scanner
- Free Precession in the Rotating Frame
- Forced Precession in the Rotating Frame
  - Coordinate system anchored to spin system
- ...all without relaxation.
  - a) Relaxation time constants are “really” long
  - b) Time scale of event is << relaxation time constant

Forced Precession - Lab Frame



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Forced Precession in the Laboratory Frame without Relaxation

$$\frac{d\vec{M}}{dt} = \vec{M} \times \gamma\left(\vec{B}_0 + \vec{B}_1\right) = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ M_x & M_y & M_z \\ \gamma B^e_{1,x}(t) & \gamma B^e_{1,y}(t) & \gamma B_0 \end{vmatrix}$$

$$\Downarrow$$

$$\left.\begin{aligned} \frac{dM_x}{dt} &= \gamma B_0 M_y - \gamma B^e_{1,y}(t) M_z \\ \frac{dM_y}{dt} &= -\gamma B_0 M_x + \gamma B^e_{1,x}(t) M_z \\ \frac{dM_z}{dt} &= \gamma B^e_{1,y}(t) M_x - \gamma B^e_{1,x}(t) M_y \end{aligned}\right\}$$ Complex Coupling

$$\Downarrow$$

Forced Precession in the Laboratory Frame without Relaxation

$$\frac{dM_x}{dt} = \gamma B_0 M_y - \gamma B^e_{1,y}(t) M_z$$

$$\frac{dM_y}{dt} = -\gamma B_0 M_x + \gamma B^e_{1,x}(t) M_z$$

$$\frac{dM_z}{dt} = \gamma B^e_{1,y}(t) M_x - \gamma B^e_{1,x}(t) M_y$$

Complex Coupling

$$\Downarrow$$

$$B_1(t) = B^e_1(t)\left[\cos(\omega_{RF} t + \theta)\hat{i} - \sin(\omega_{RF} t + \theta)\hat{j}\right]$$

Forced Precession in the Laboratory Frame without Relaxation

$$\left.\begin{aligned} \frac{dM_x}{dt} &= \gamma B_0 M_y - \gamma B_{1,y}^e(t) M_z \\ \frac{dM_y}{dt} &= -\gamma B_0 M_x + \gamma B_{1,x}^e(t) M_z \\ \frac{dM_z}{dt} &= \gamma B_{1,y}^e(t) M_x - \gamma B_{1,x}^e(t) M_y \end{aligned}\right\}$$

Complex Coupling

$$\Downarrow$$

$$B_1(t) = B_1^e(t)\left[\cos(\omega_{RF} t + \theta)\,\hat{i} - \sin(\omega_{RF} t + \theta)\,\hat{j}\right]$$

$$\Downarrow$$

$$\frac{dM_x}{dt} = \gamma B_0 M_y + \gamma B_1^e(t)\sin(\omega_{RF} t + \theta) M_z$$

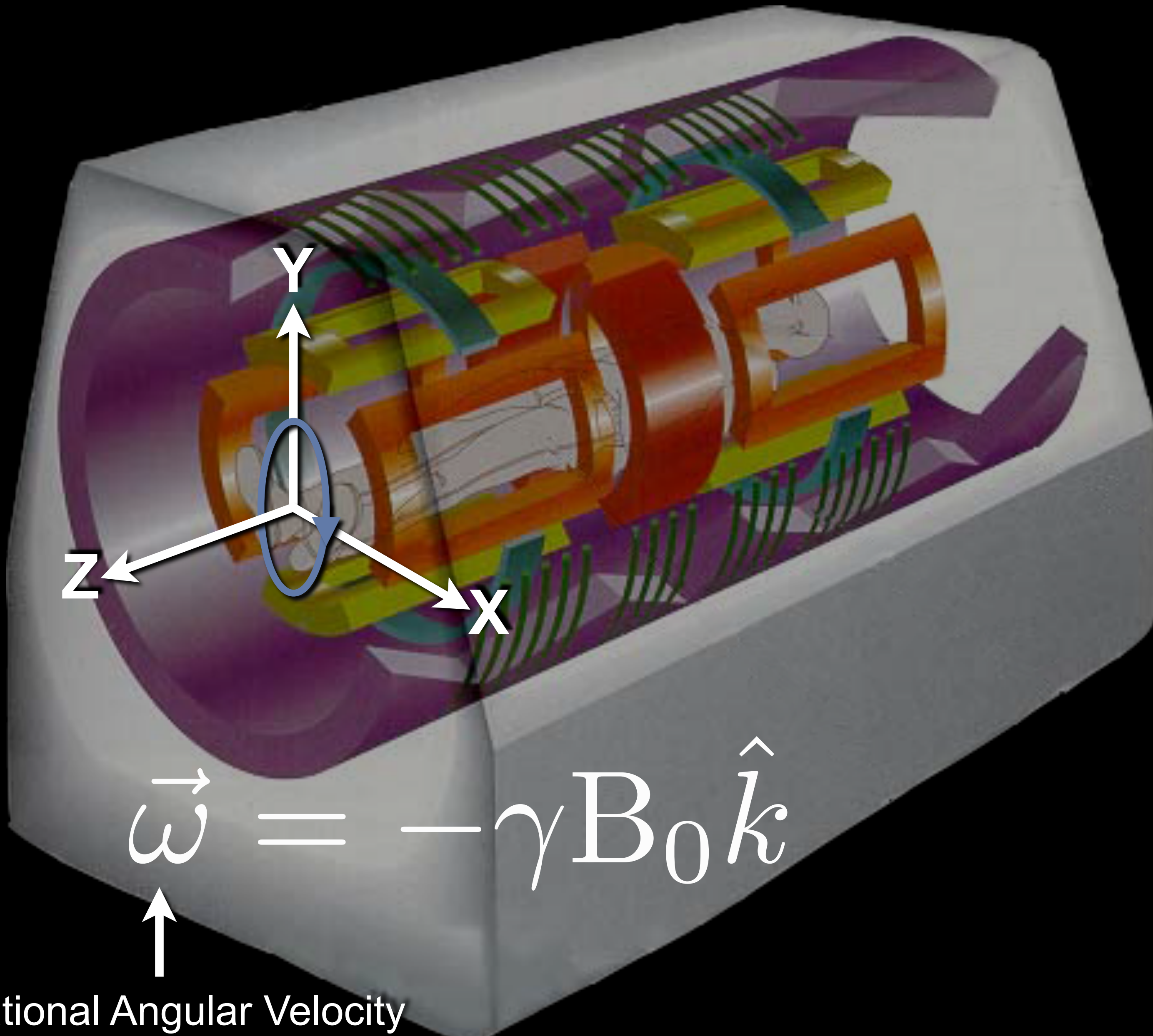
$$\frac{dM_y}{dt} = -\gamma B_0 M_x + \gamma B_1^e(t)\cos(\omega_{RF} t + \theta) M_z$$

$$\frac{dM_z}{dt} = -\gamma B_1^e(t)\sin(\omega_{RF} t + \theta) M_x - \gamma B_1^e(t)\cos(\omega_{RF} t + \theta) M_y$$

This is a relatively complicated set of coupled ODEs!

Rotating Coordinate Frame

Laboratory Coordinates

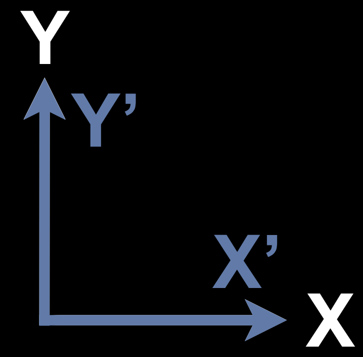


$$\vec{\omega} = -\gamma B_0 \hat{k}$$

Rotational Angular Velocity

Rotating Frame Coordinates

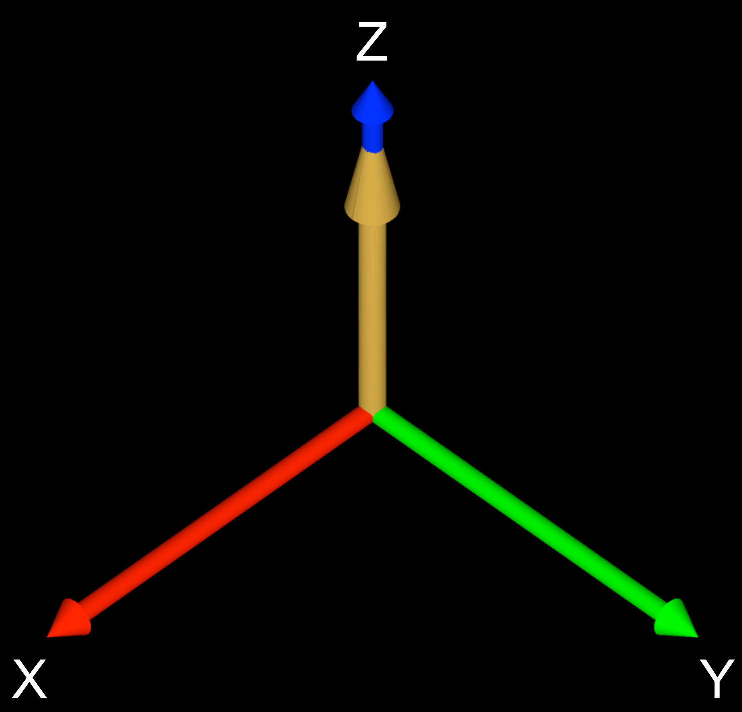
- Simplifies the mathematics of MRI
- If the rotational frequency of the rotating frame (x'-y') is matched to the bulk magnetization's precessional frequency, then rotational motion of the bulk magnetization is "removed" or demodulated.
- The rotating frame's transverse (x'y') plane rotates clockwise (left-handed) at frequency ω.



Lab vs. Rotating Frame

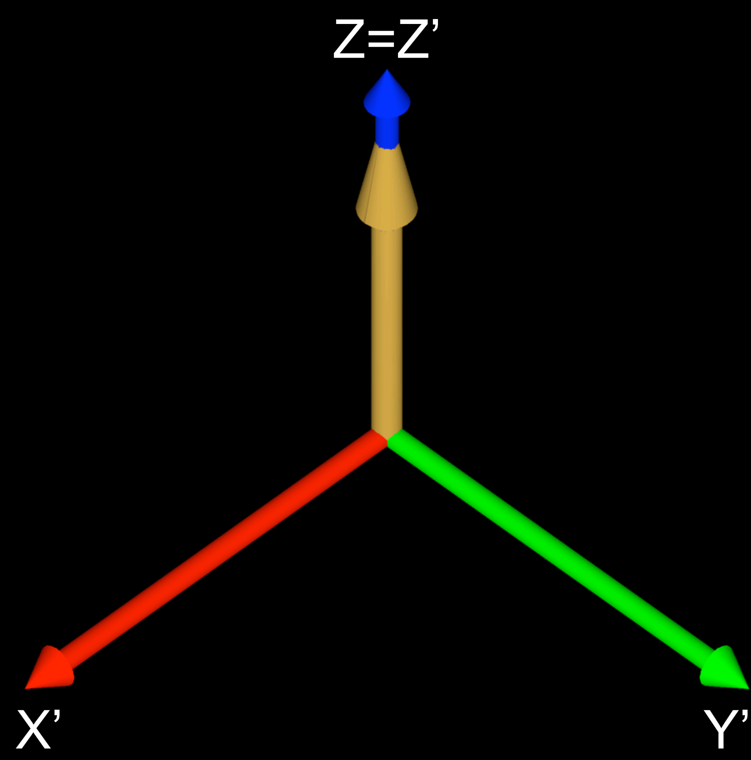
- **The rotating frame simplifies the mathematics and permits more intuitive understanding.**

Laboratory Frame



Spins Precess

Rotating Frame



Observer Precesses

Note: Both coordinate frames share the same z-axis.

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Relationship Between Lab and Rotating Frames

Rotating Frame

$$\hat{i}' \equiv \cos(\omega t)\,\hat{i} - \sin(\omega t)\,\hat{j}$$
$$\hat{j}' \equiv \sin(\omega t)\,\hat{i} + \cos(\omega t)\,\hat{j}$$
$$\hat{k}' \equiv \hat{k}$$

Laboratory Frame

$$\hat{i} \equiv \cos(\omega t)\,\hat{i}' + \sin(\omega t)\,\hat{j}'$$
$$\hat{j} \equiv -\sin(\omega t)\,\hat{i}' + \cos(\omega t)\,\hat{j}'$$
$$\hat{k} \equiv \hat{k}'$$

Note: Both coordinate frames share the same z-axis.

$$\vec{M}_{rot} \equiv \begin{bmatrix} M_{x'} \\ M_{y'} \\ M_{z'} \end{bmatrix}$$

Bulk magnetization components in the rotating frame.

$$\vec{B}_{rot} \equiv \begin{bmatrix} B_{x'} \\ B_{y'} \\ B_{z'} \end{bmatrix}$$

Applied B-field components in the rotating frame.

$$B_{z'} \equiv B_z$$
$$M_{z'} \equiv M_z$$

Note: B-field and bulk magnetization z-components are equivalent in the two frames.

Equation of Motion

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

Equation of motion for an ensemble of spins (isochromats).
[Laboratory Frame]

$$\frac{d\vec{M}_{rot}}{dt} = \vec{M}_{rot} \times \gamma \left(\frac{\vec{\omega}_{rot}}{\gamma} + \vec{B}_{rot} \right)$$

Equation of motion for an ensemble of spins (isochromats).
[Rotating Frame]

$$\vec{B}_{eff} \equiv \frac{\vec{\omega}_{rot}}{\gamma} + \vec{B}_{rot}$$

Effective B-field that *M* experiences in the rotating frame.

Fictitious field that demodulates the apparent effect of B_0.

Applied B-field in the rotating frame.

$$\frac{d\vec{M}_{rot}}{dt} = \vec{M}_{rot} \times \gamma \vec{B}_{eff}$$

Four Special Cases…

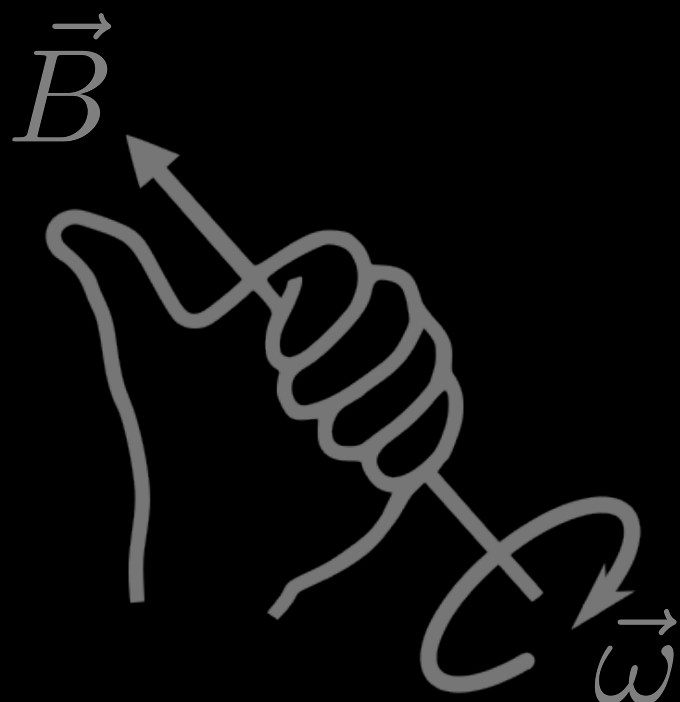
- **Free Precession in the Laboratory Frame**
- **Forced Precession in the Laboratory Frame**
  - Coordinate system anchored to scanner
- **Free Precession in the Rotating Frame**
- **Forced Precession in the Rotating Frame**
  - Coordinate system anchored to spin system
- **...all without relaxation.**
  - a) Relaxation time constants are “really” long
  - b) Time scale of event is << relaxation time constant

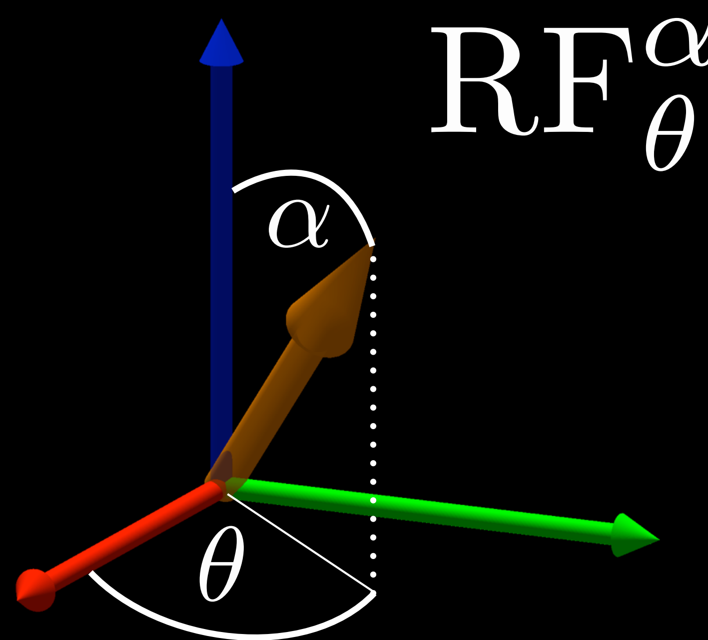
To The Board…

Mathematics of Hard RF Pulses

Parameters & Rules for RF Pulses

- **RF pulses have a "flip angle" (α)**
  - RF fields induce **left-hand** rotations
    - All B-fields do this for positive γ
- **RF pulses have a "phase" (θ)**
  - Phase of 0° is about the x-axis
  - Phase of 90° is about the y-axis

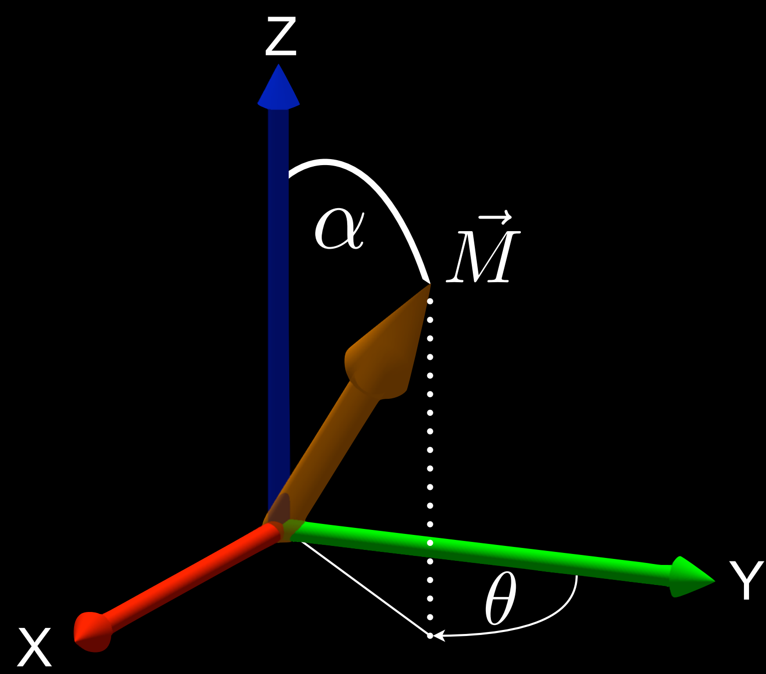




RF Flip Angle

Flip Angle

- **"Amount of rotation of the bulk magnetization vector produced by an RF pulse, with respect to the direction of the static magnetic field."**
  - Liang & Lauterbur, p. 374



$$\omega_1 = \gamma B_1$$

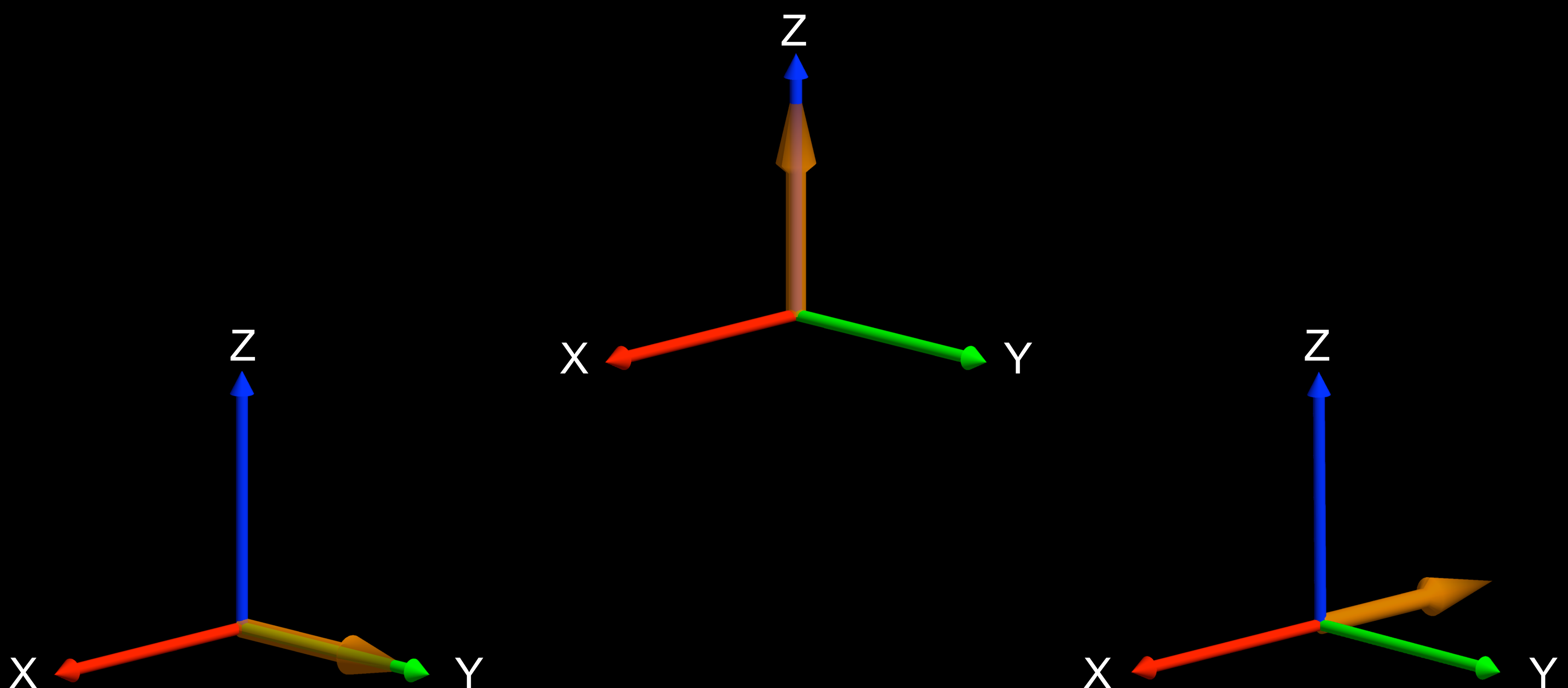
B-fields induce precession!

Rules for RF Pulses

$$\mathbf{RF}_{\theta}^{\alpha}$$

α → Flip Angle

θ → Phase



$\mathbf{RF}_{0^\circ}^{90^\circ}$ $\mathbf{RF}_{90^\circ}^{90^\circ}$

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B-fields induce left-handed nutation!

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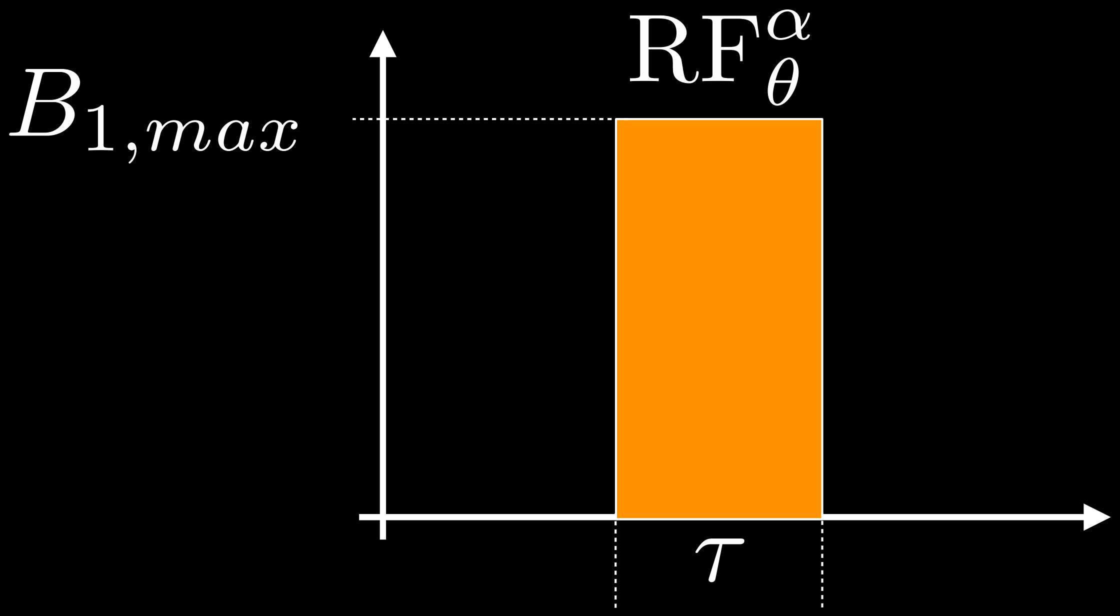
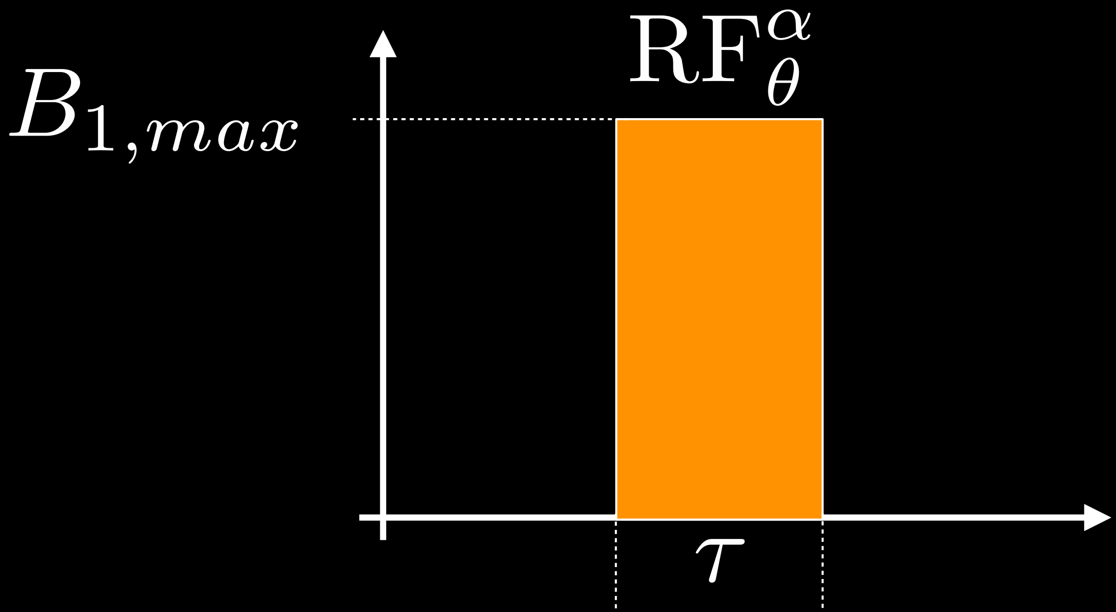
How to determine α?



$$\alpha = \gamma \int_0^{\tau_p} B_1^e\,(t)\,dt$$

Rules: 1) Specify α
2) Use $B_{1,max}$ if we can
3) Shortest duration pulse

How to determine α?



$$\alpha = \gamma \int_0^{\tau_p} B_1^e(t)\, dt$$

$$\tau = \frac{\alpha}{\gamma B_{1,max}} = \frac{\pi/2}{2\pi \cdot 42.57Hz/\mu T \cdot 60\mu T} = 0.098ms$$

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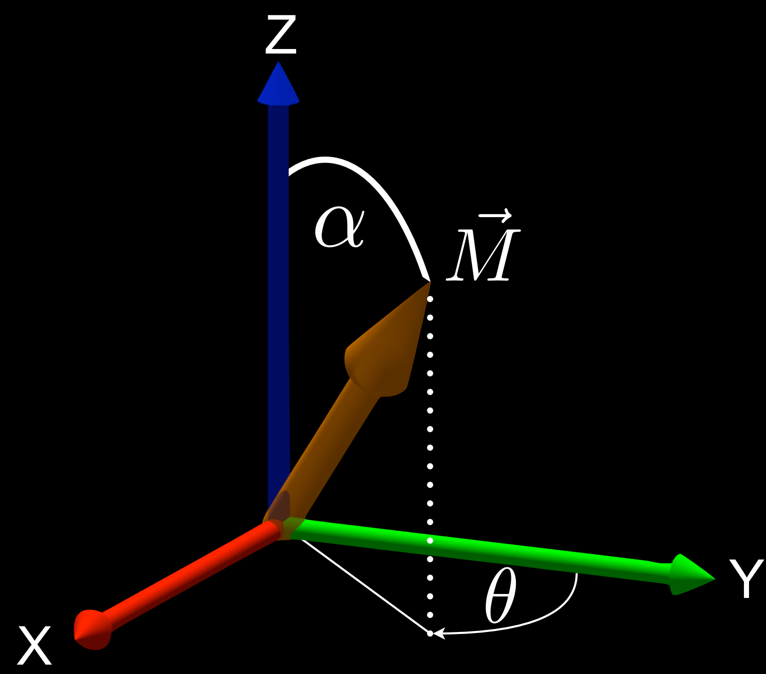
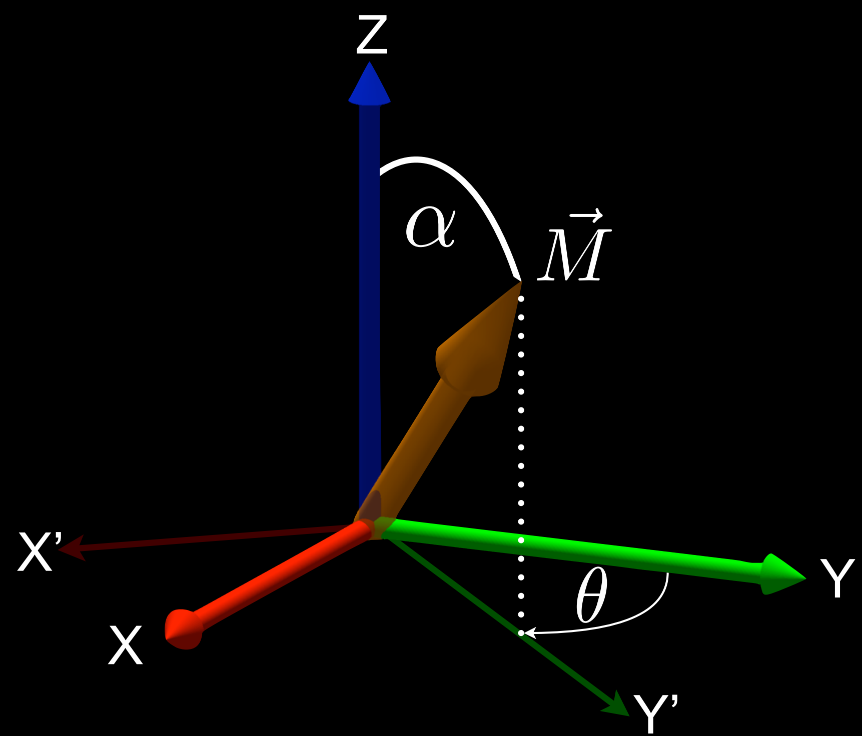
RF Phase

Bulk Magnetization in the Lab Frame



How do we mathematically account for α and θ?

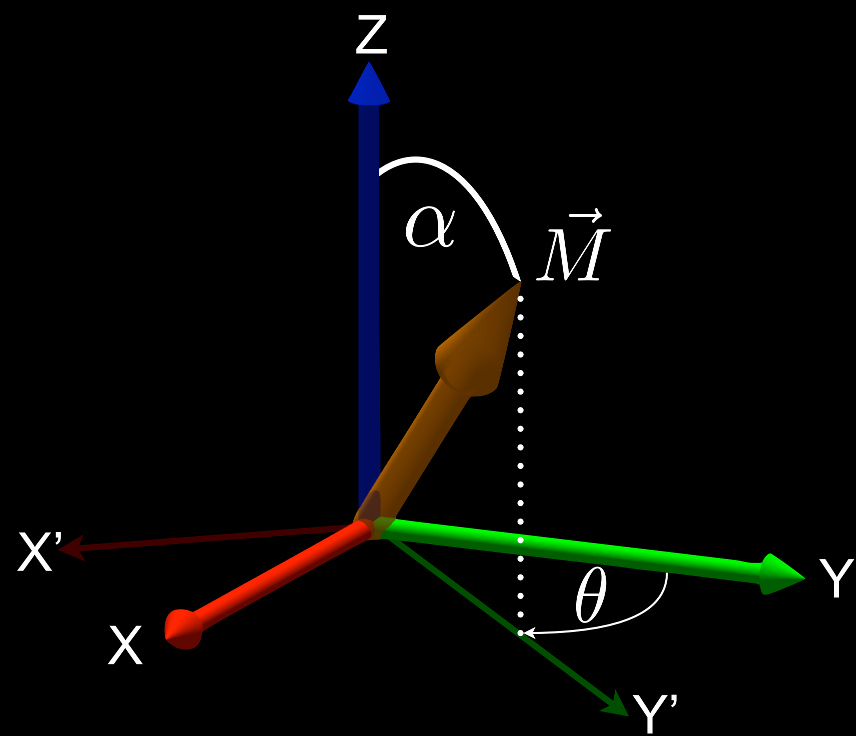
Change of Basis (θ)



$$\mathbf{R}_Z(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotate into a coordinate system where ***M*** falls along the y'-axis.

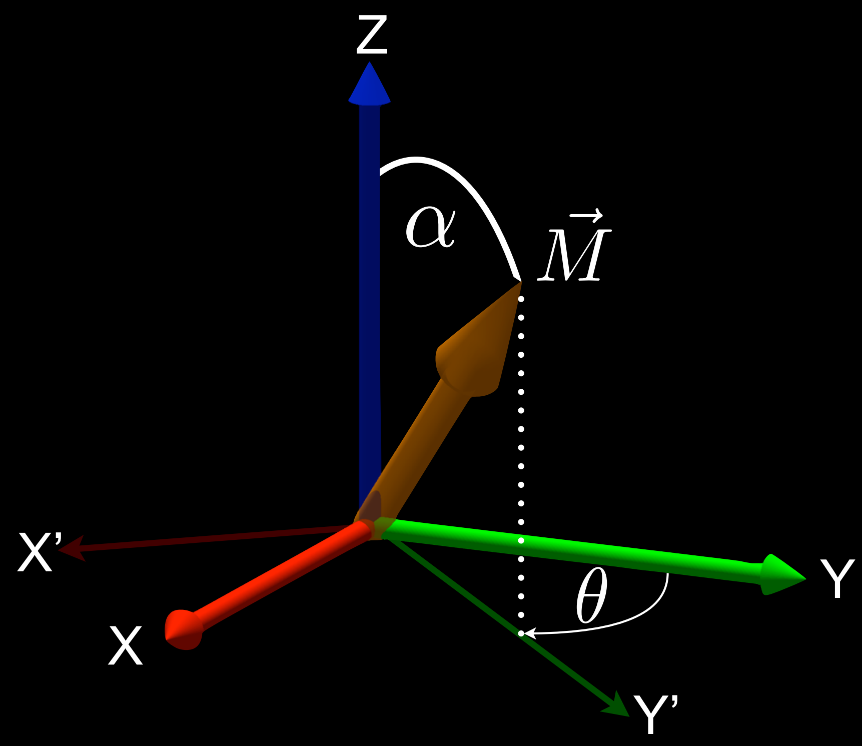
Rotation by Alpha



$$\mathbf{R}_{X'}(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix}$$

Rotate ***M*** by α about x'-axis.

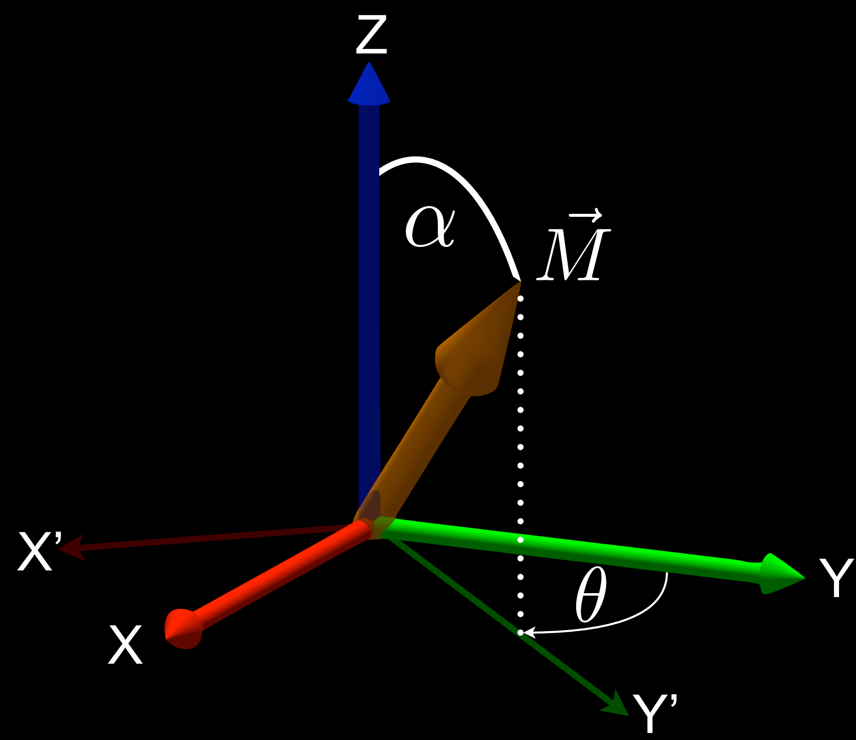
Change of Basis (-θ)



$$\mathbf{R}_Z(-\theta) = \begin{bmatrix} \cos(-\theta) & \sin(-\theta) & 0 \\ -\sin(-\theta) & \cos(-\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotate back to the lab frame's x-axis and y-axis.

RF Pulse Operator



$$\mathbf{R}_\theta^\alpha = \mathbf{R}_Z(-\theta)\,\mathbf{R}_X(\alpha)\,\mathbf{R}_Z(\theta)$$

$$= \begin{bmatrix} c^2\theta + s^2\theta c\alpha & c\theta s\theta - c\theta s\theta c\alpha & -s\theta s\alpha \\ c\theta s\theta - c\theta s\theta c\alpha & s^2\theta + c^2\theta c\alpha & c\theta s\alpha \\ s\theta s\alpha & -c\theta s\alpha & c\alpha \end{bmatrix}$$

This is the composite matrix operator for a hard RF pulse.

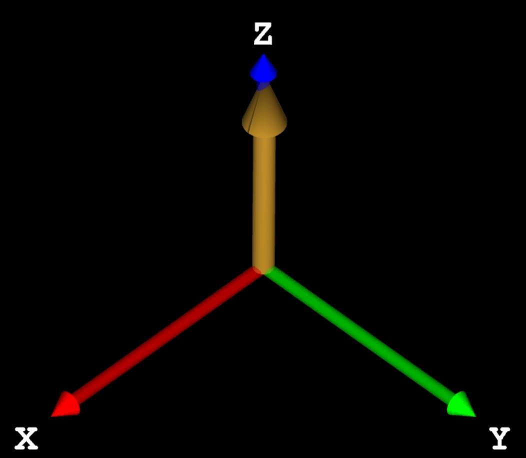
Types of RF Pulses

Types of RF Pulses

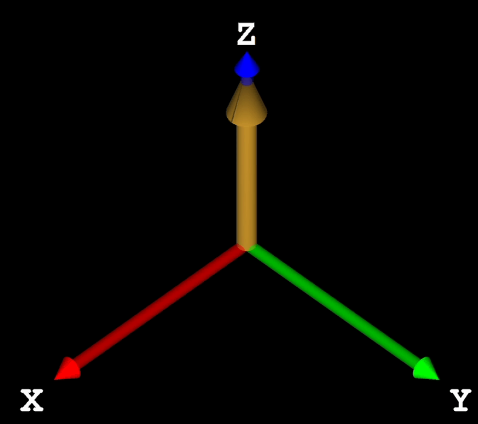
- **Excitation Pulses**
- **Inversion Pulses**
- **Refocusing Pulses**
- **Saturation Pulses**
- **Spectrally Selective Pulses**
- **Spectral-spatial Pulses**
- **Adiabatic Pulses**

Excitation Pulses

- **Tip M_z into the transverse plane**
- **Typically 200µs to 5ms**
- **Non-uniform across slice thickness**
  - Imperfect slice profile
- **Non-uniform within slice**
  - Termed B_1 inhomogeneity
  - Non-uniform signal intensity across FOV



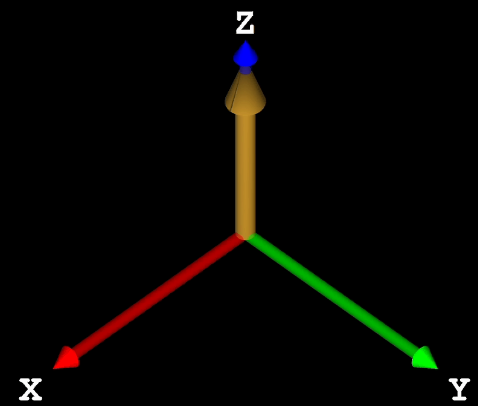
90° Excitation Pulse



Small Flip Angle Pulse

Inversion Pulses

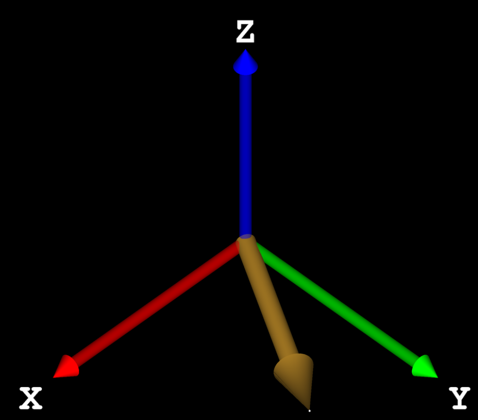
- **Typically, 180° RF Pulse**
  - non-180° that still results in $-M_Z$
- **Invert M_Z to $-M_Z$**
  - Ideally produces no M_{XY}
- **Hard Pulse**
  - Constant RF amplitude
  - Typically non-selective
- **Soft (Amplitude Modulated) Pulse**
  - **Frequency/spatially/spectrally selective**
- **Typically followed by a crusher gradient**



180° Inversion Pulse

Refocusing Pulses

- **Typically, 180° RF Pulse**
  - Provides optimally refocused M_{XY}
  - Largest spin echo signal
- **Refocus spin dephasing due to**
  - imaging gradients
  - local magnetic field inhomogeneity
  - magnetic susceptibility variation
  - chemical shift
- **Typically followed by a crusher gradient**



180° Refocusing Pulse

Thanks

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