MRI Systems III: Gradients

M219 - Principles and Applications of MRI

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1/29/2024

Course Overview

- 2024 course schedule
  - https://mrrl.ucla.edu/pages/m219_2024
- Assignments
  - Homework #1 is due today
  - Homework #2 is out
- TA office hours, Weds 4-6pm
- Office hours, Fridays 10-12pm

Bloch Equations - Lab Frame

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

- Precession
  - Magnitude of M unchanged
  - Phase (rotation) of M changes due to B
- Relaxation
  - T_1 changes are slow O(100ms)
  - T_2 changes are fast O(10ms)
  - Magnitude of M can be ZERO

Free Precession in the Rotating Frame

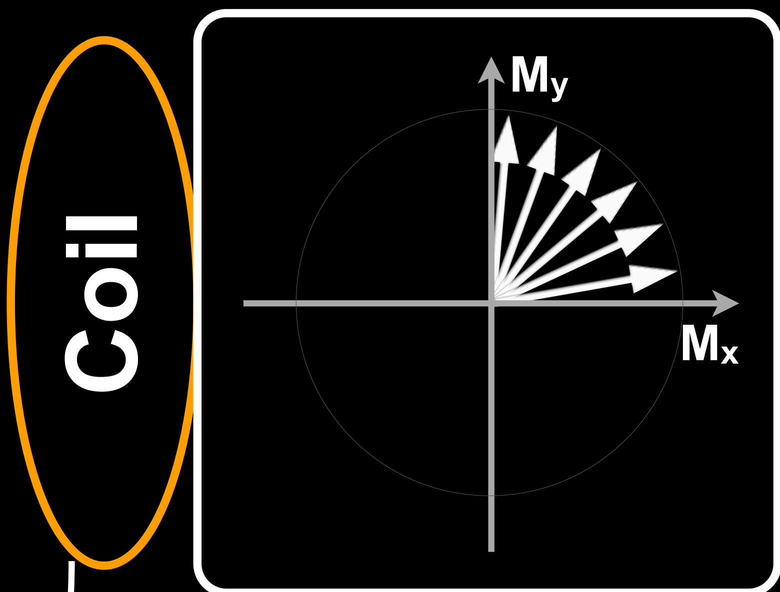
$$\frac{\partial \vec{M}_{rot}}{\partial t} = -\underbrace{\frac{M_{x'}\vec{i}' + M_{y'}\vec{j}'}{T_2}}_{\text{Transverse Relaxation}} - \underbrace{\frac{(M_{z'} - M_0)\vec{k}'}{T_1}}_{\text{Longitudinal Relaxation}}$$

- **No precession**
- **T_1 and T_2 Relaxation**
- **Drop the diffusion term**
- **System or first order, linear, separable ODEs!**

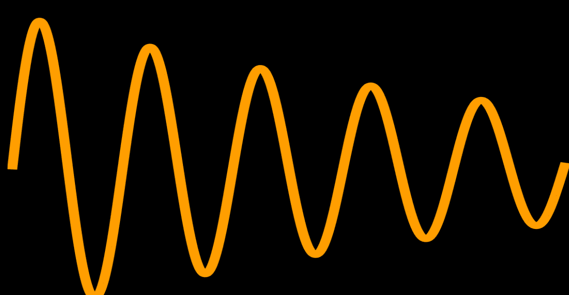
The precessional term drops out in the rotating frame.

T_2 versus T_2*

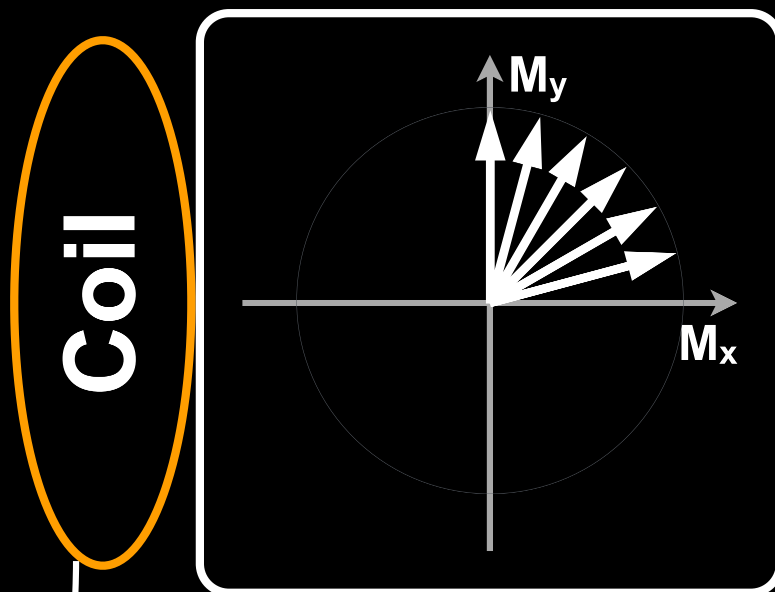
T_2 Decay



Signal loss from spin-spin interaction.



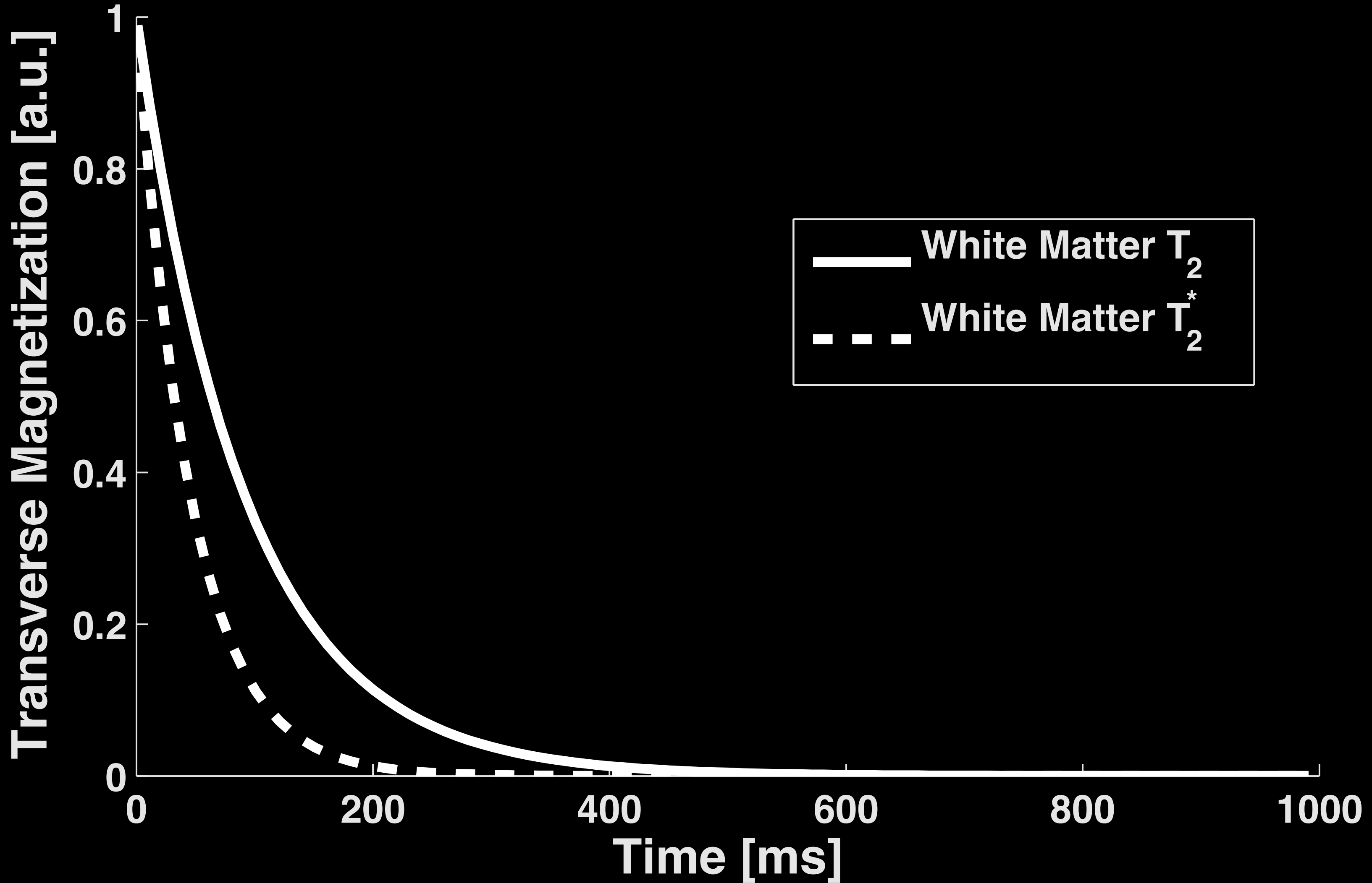
T_2^* Decay



Signal loss from spin-spin interaction and off-resonance dephasing and T_2*.

T_2* is signal loss from spin dephasing and T_2

T2*<T2 (always!)



Transverse Magnetization [a.u.]
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
Time [ms]
White Matter T2
White Matter T2*

Forced Precession in the Rot. Frame with Relaxation

$$\frac{\partial \vec{M}_{rot}}{\partial t} = \gamma \vec{M}_{rot} \times \vec{B}_{eff} - \frac{M_{x'}\vec{i}' + M_{y'}\vec{j}'}{T_2} - \frac{(M_{z'} - M_0)\vec{k}'}{T_1}$$

$$\vec{B}_{eff} = B_1^e(t)\hat{\vec{i}}'$$

- **B1 induced nutation**
- **T_1 and T_2 Relaxation**
- **Drop the diffusion term**
- **System or first order, linear, coupled PDEs!**
- **When does this equation apply?**

The precessional term ***does not*** drop out in the rotating frame.

Types of RF Pulses

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

Gradient Fields & Spins

Gradients

Gradients are a special kind of inhomogeneous field whose z-component varies linearly along a specific direction called the gradient direction.

$$(\overrightarrow{G} \cdot \vec{r})\ \hat{k} = (G_x \cdot x + G_y \cdot y + G_z \cdot z)\ \hat{k}$$

$$\overrightarrow{B}(\vec{r}, t) = (B_0 + \underbrace{\overrightarrow{G}(t) \cdot \vec{r}})\ \hat{k}$$

$$B_G(\vec{r}, t)$$

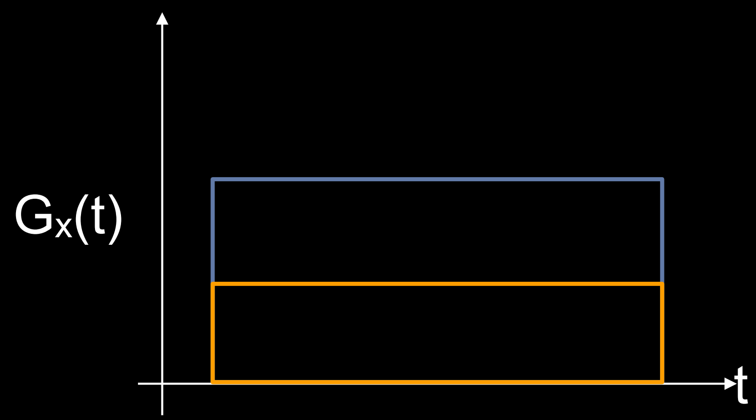
- Each gradient coil can be activated independently and simultaneously

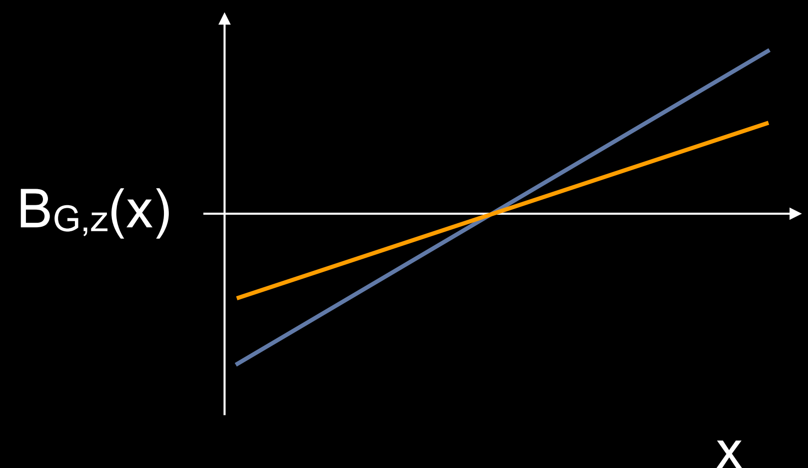
Gradient Induced B-Fields

$$B_G(x) = G_x x$$ x-gradient

$$B_G(y) = G_y y$$ y-gradient

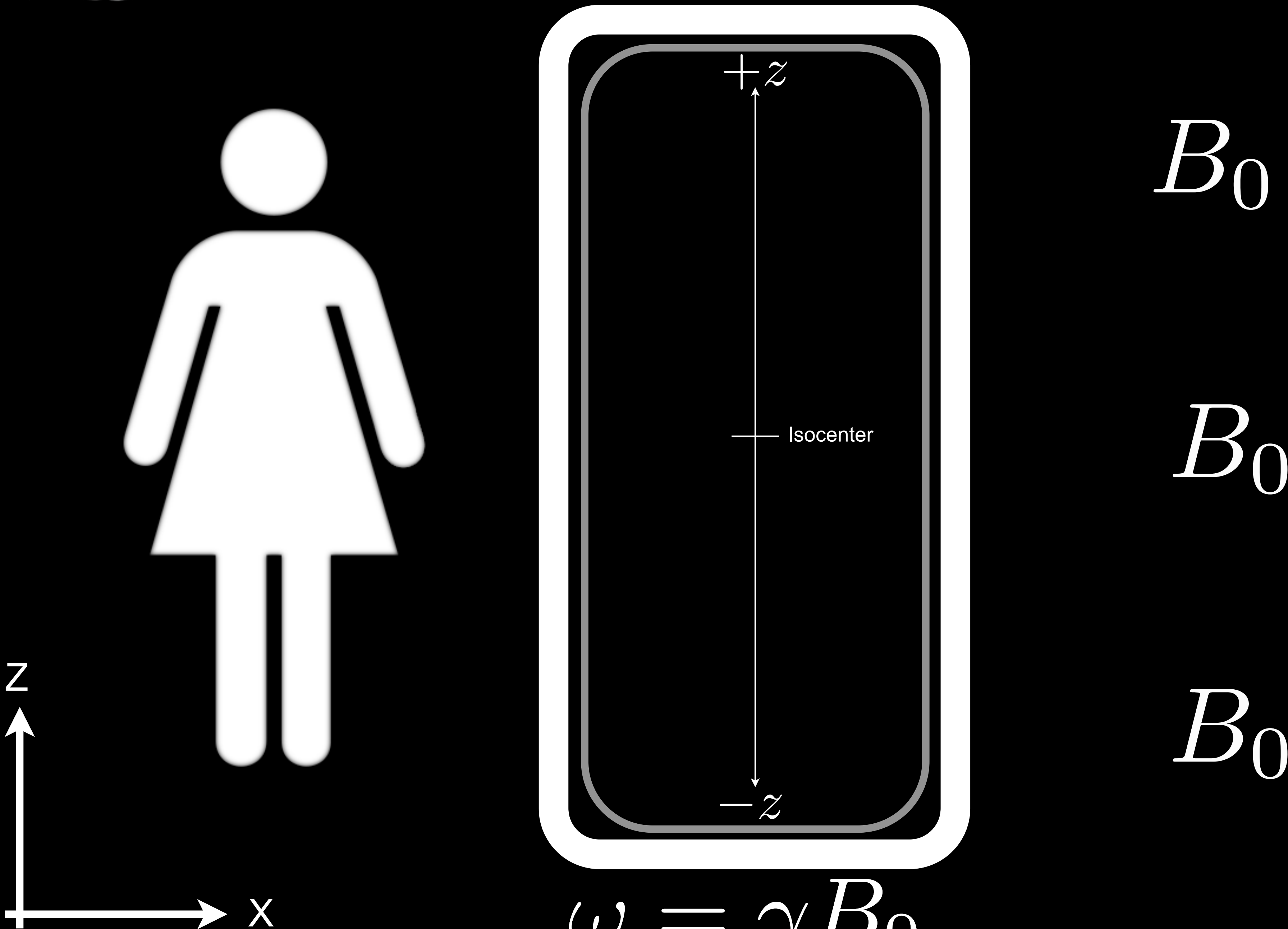
$$B_G(z) = G_z z$$ z-gradient



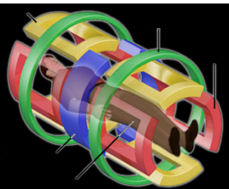


The magnetic field at a position depends on the magnitude of the applied gradient.

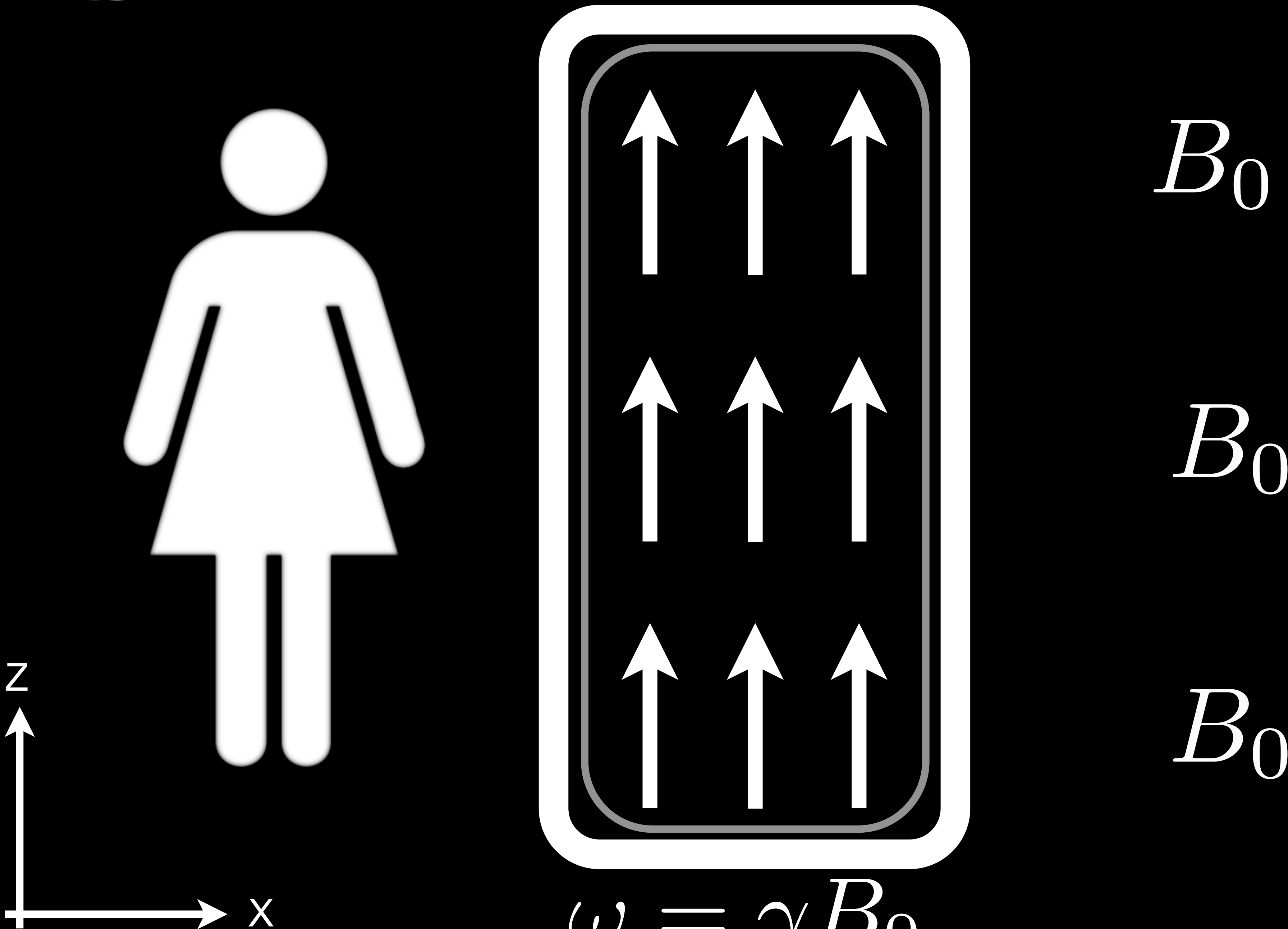
No Gradients Turned On



$$\omega = \gamma B_0$$



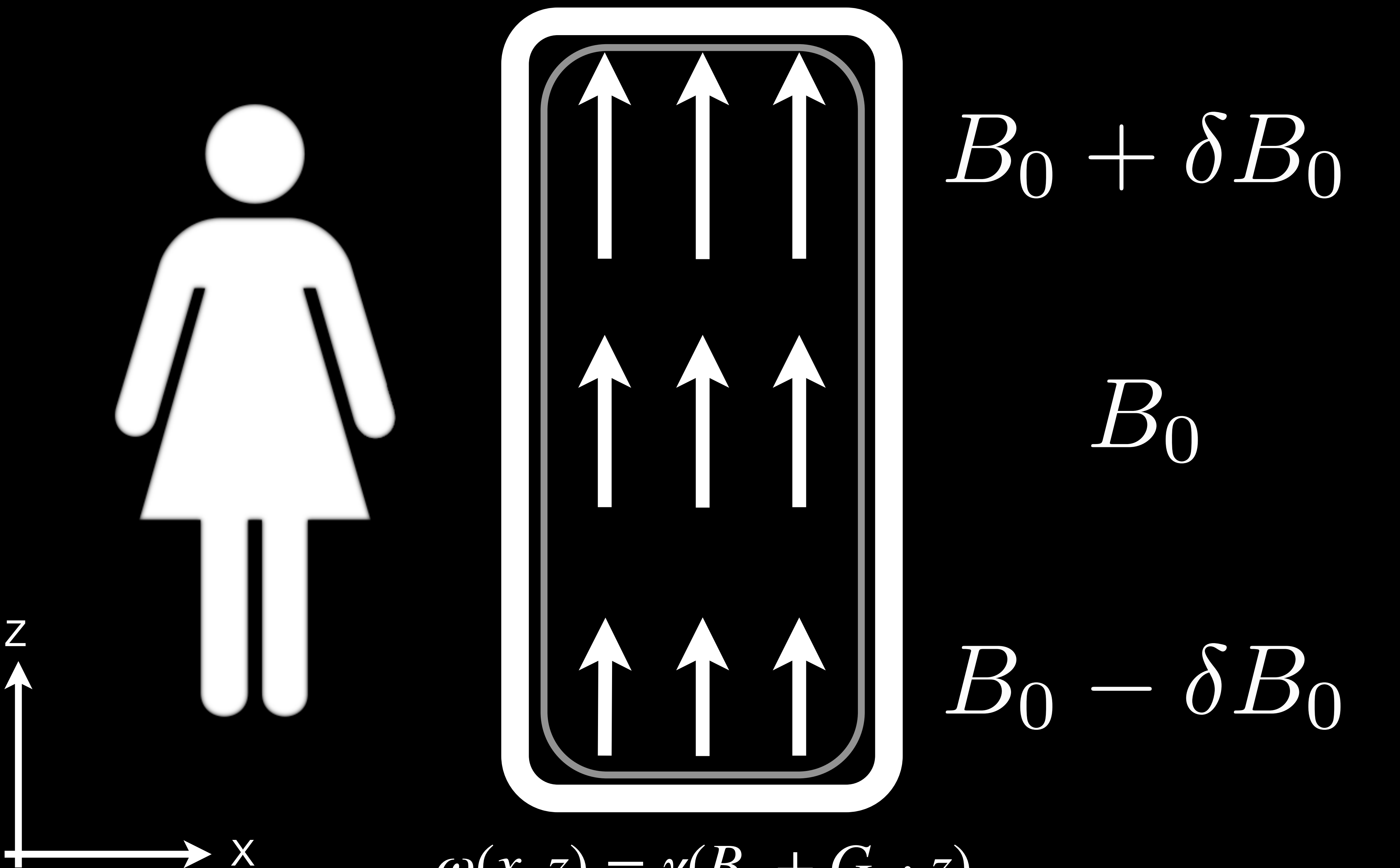
No Gradients Turned On



$$\omega = \gamma B_0$$

Length of arrow indicates strength of local field.

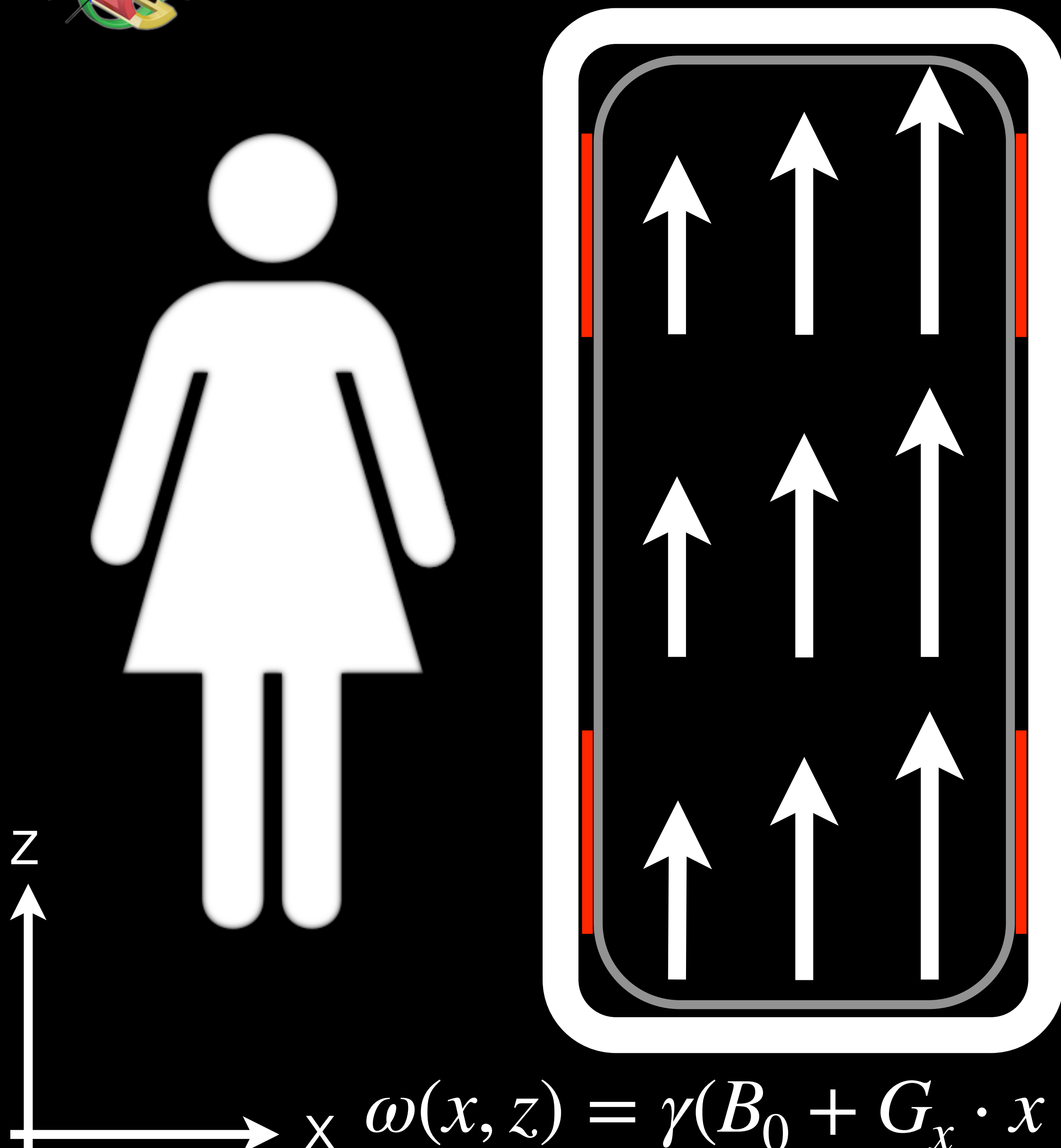
Z-Gradients



$$\omega(x, z) = \gamma(B_0 + G_z \cdot z)$$

What coordinate frame are we in?

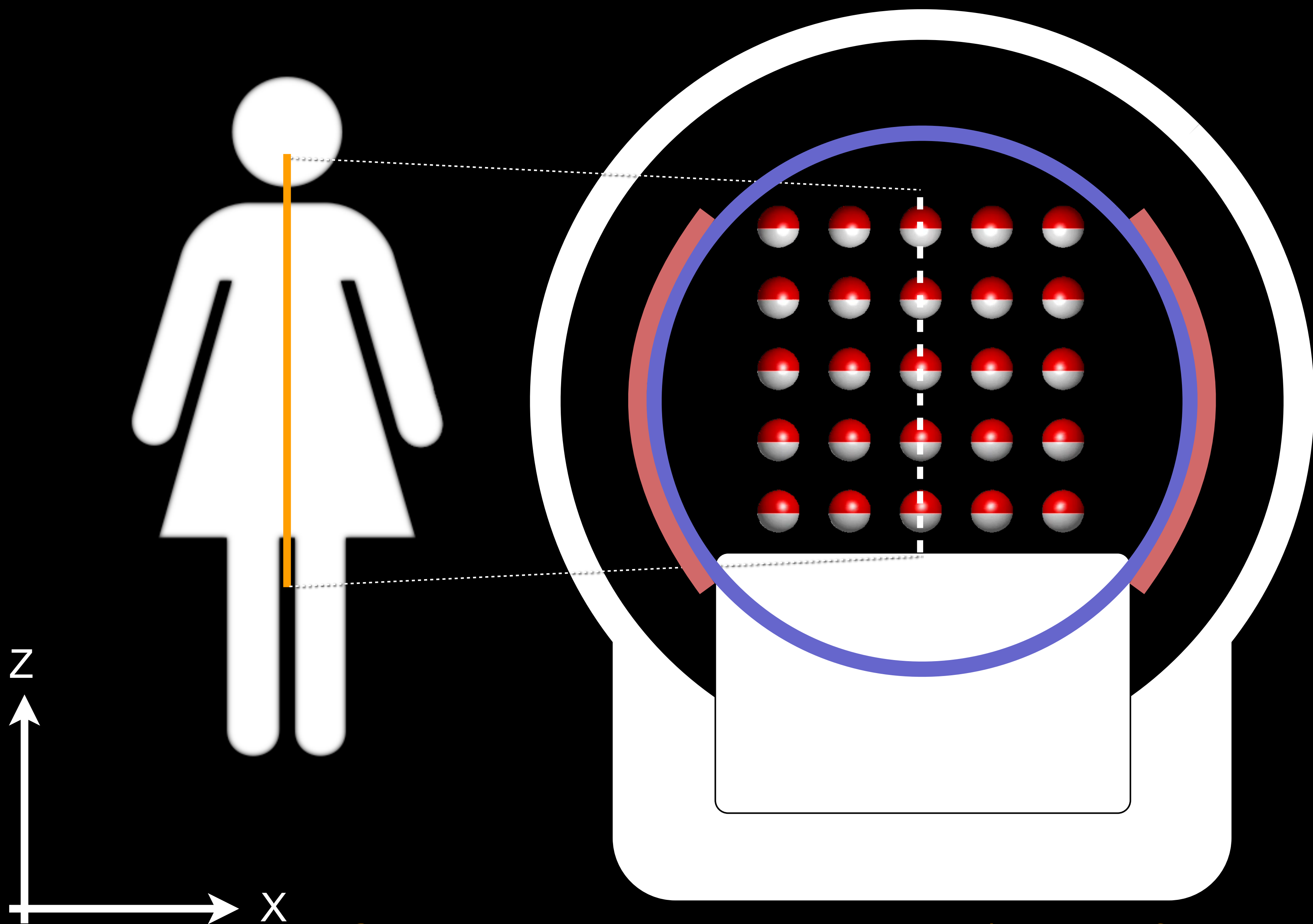
X-Gradients



$$\omega(x,z) = \gamma(B_0 + G_x \cdot x + G_z \cdot z)$$

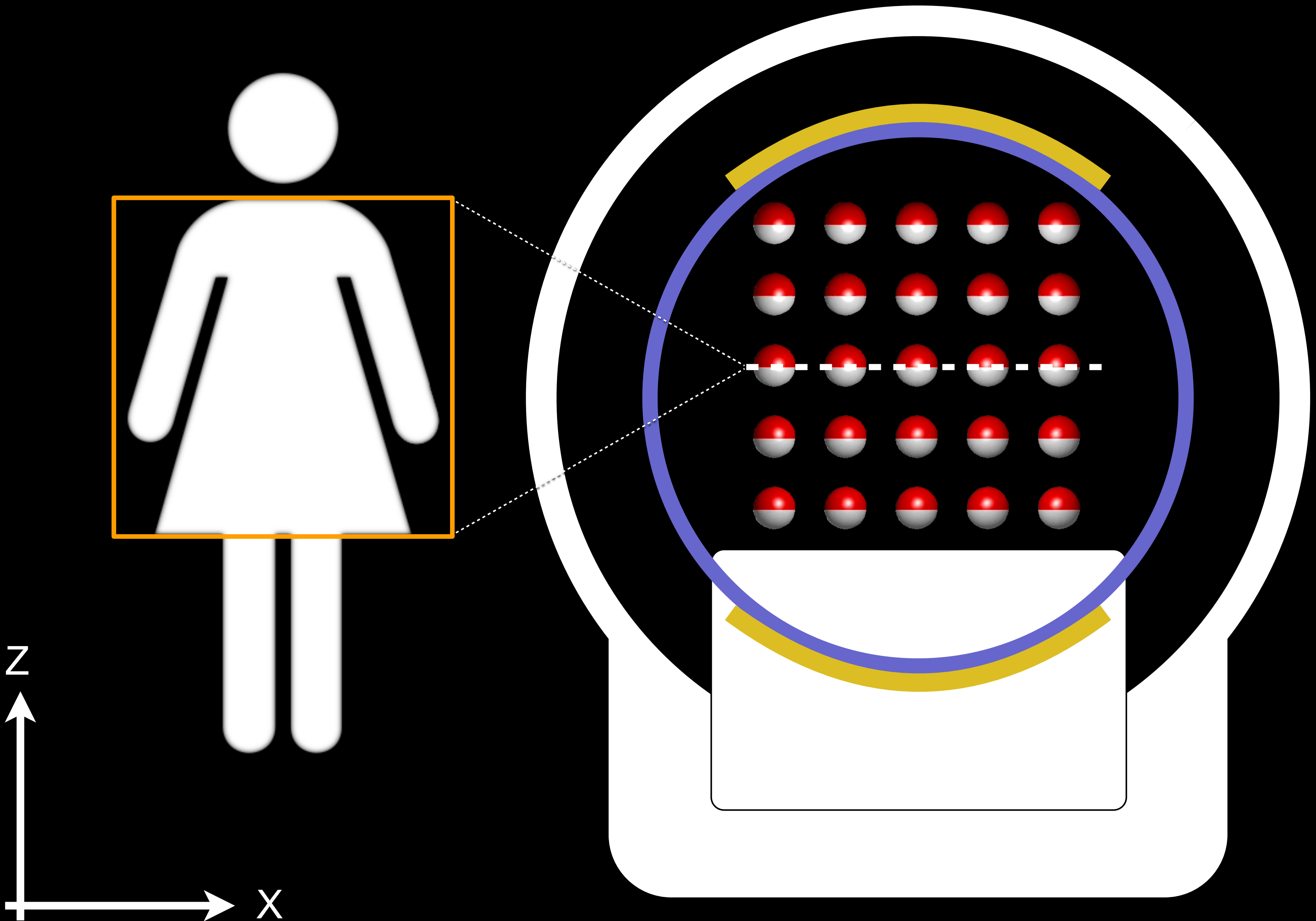
$B_0 - \delta B_0$ B_0 $B_0 + \delta B_0$

Spins and X-Gradients



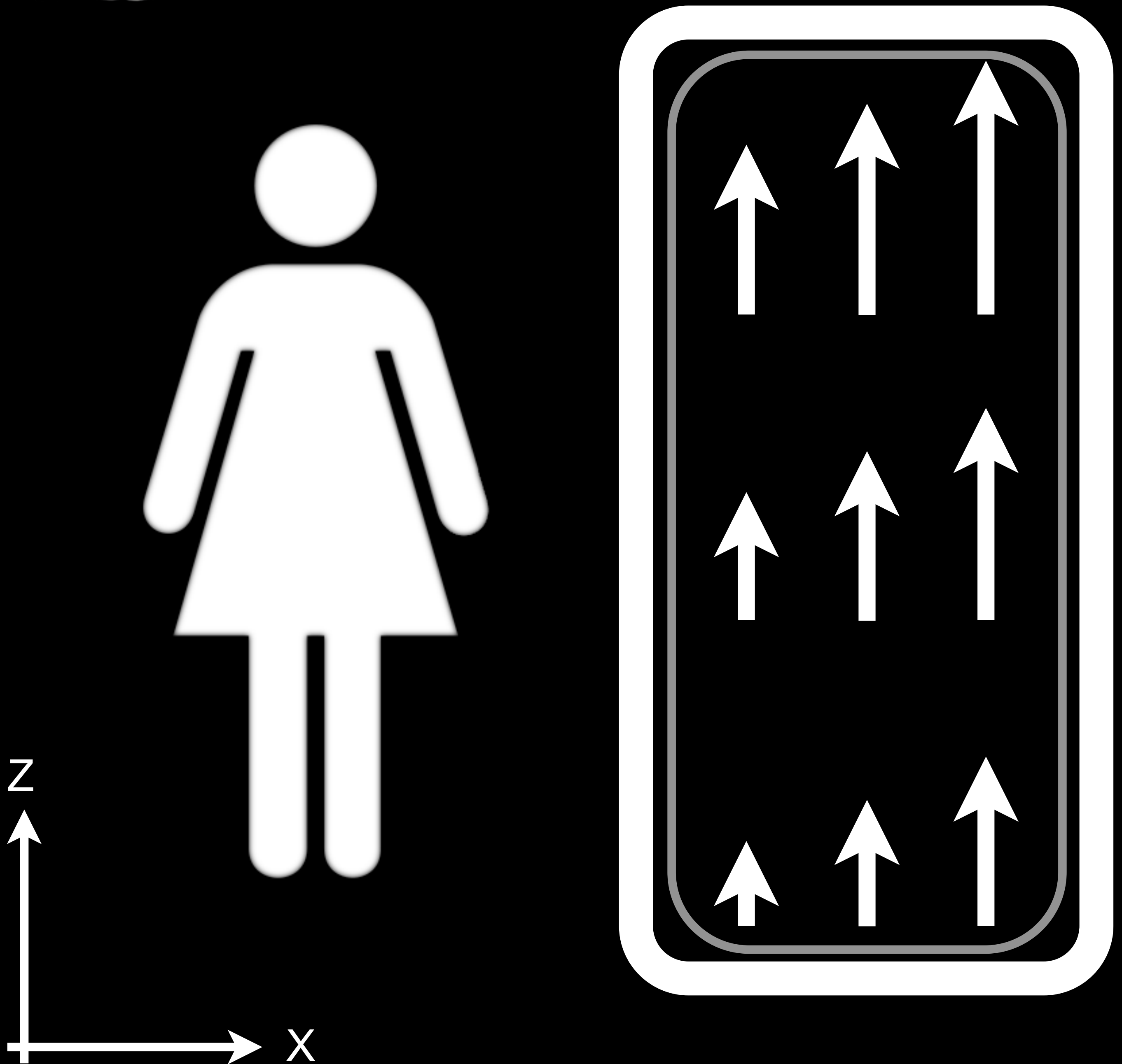
Gradients give rise to isochromats (planes of common frequency).

Spins and Y-Gradients

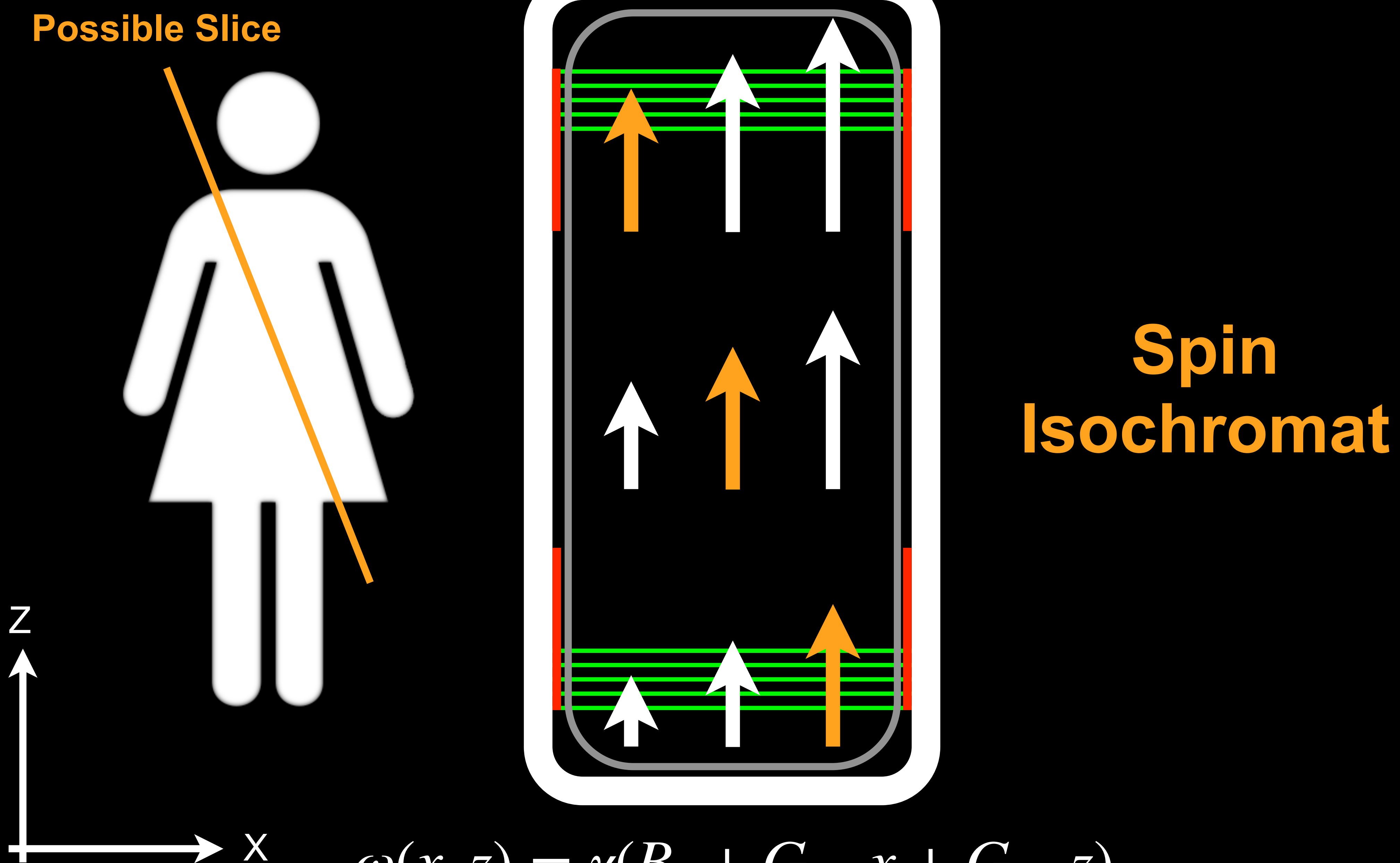


Gradients add/subtract to B_0 along a specific direction.

How do we do this?

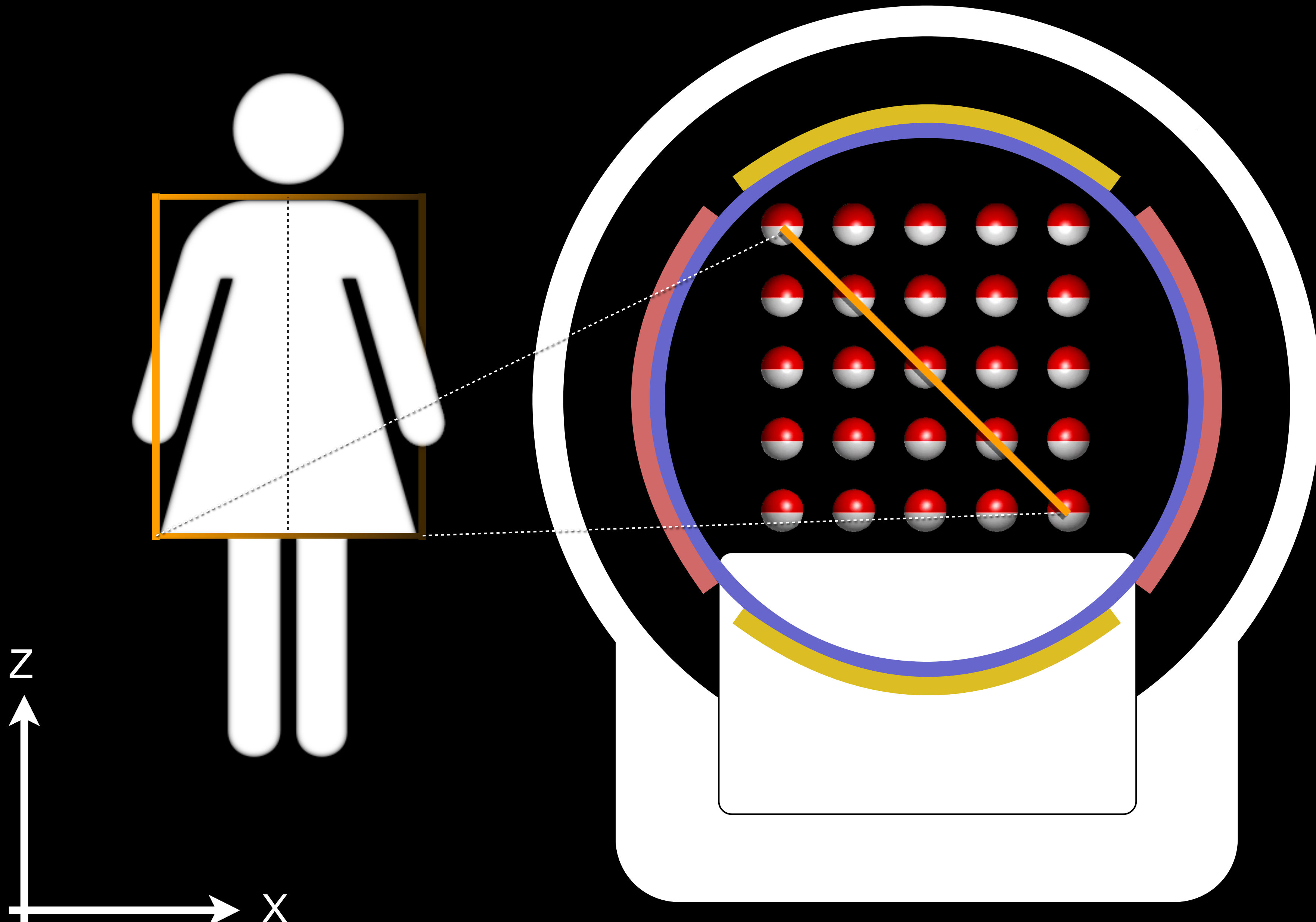


X+Z-Gradients



$$\omega(x, z) = \gamma(B_0 + G_x \cdot x + G_z \cdot z)$$

Spins and X- & Y-Gradients



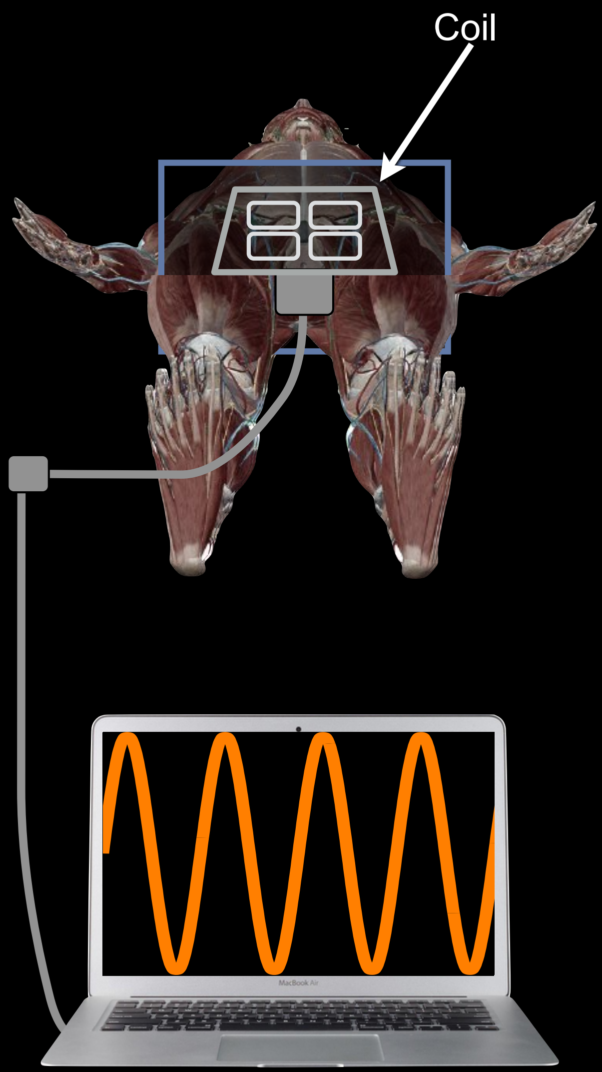
David Geffen School of Medicine

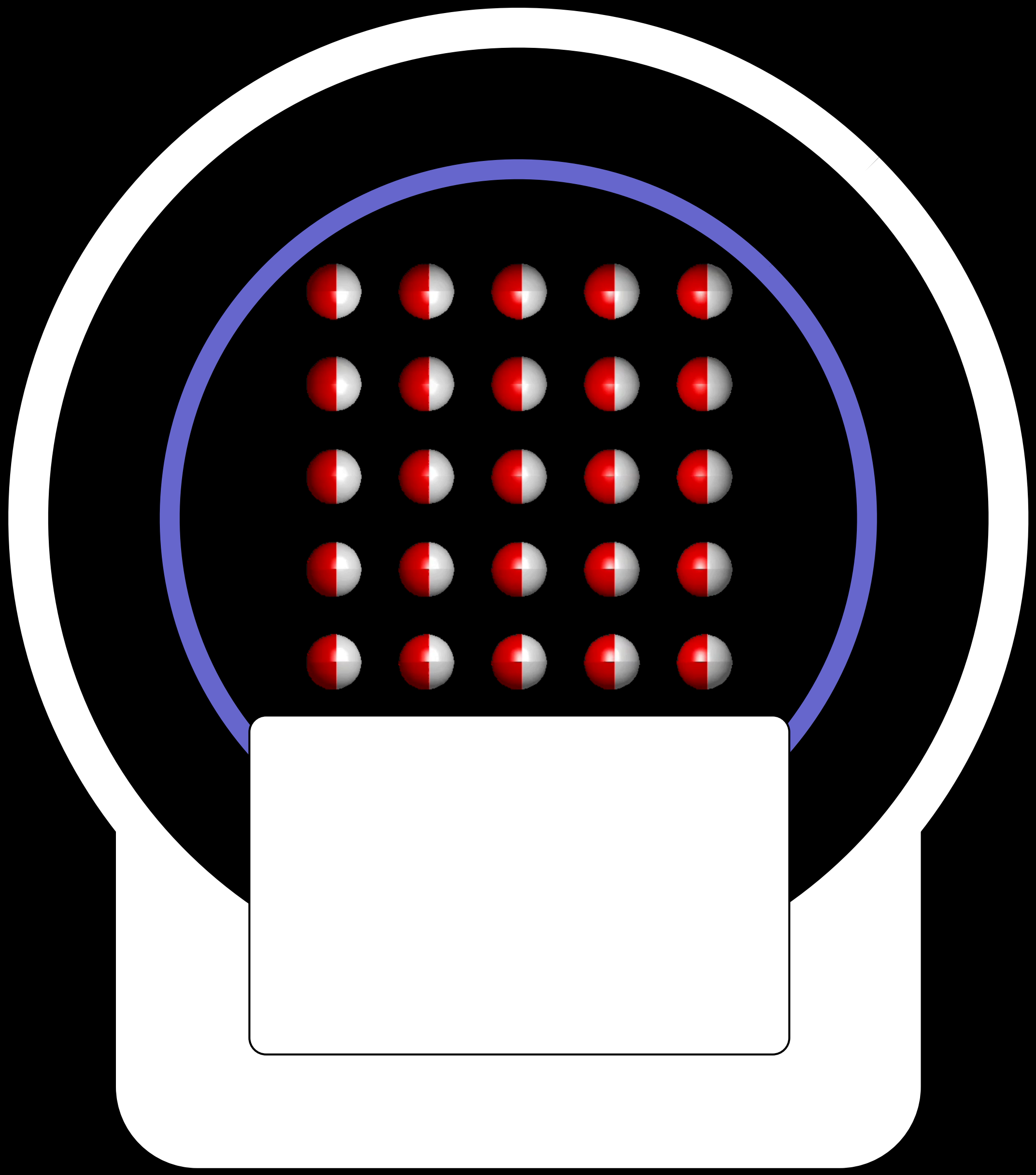
Simultaneous gradients create an arbitrary isochromat plane.

UCLA Radiology

How do we measure M_{xy}?

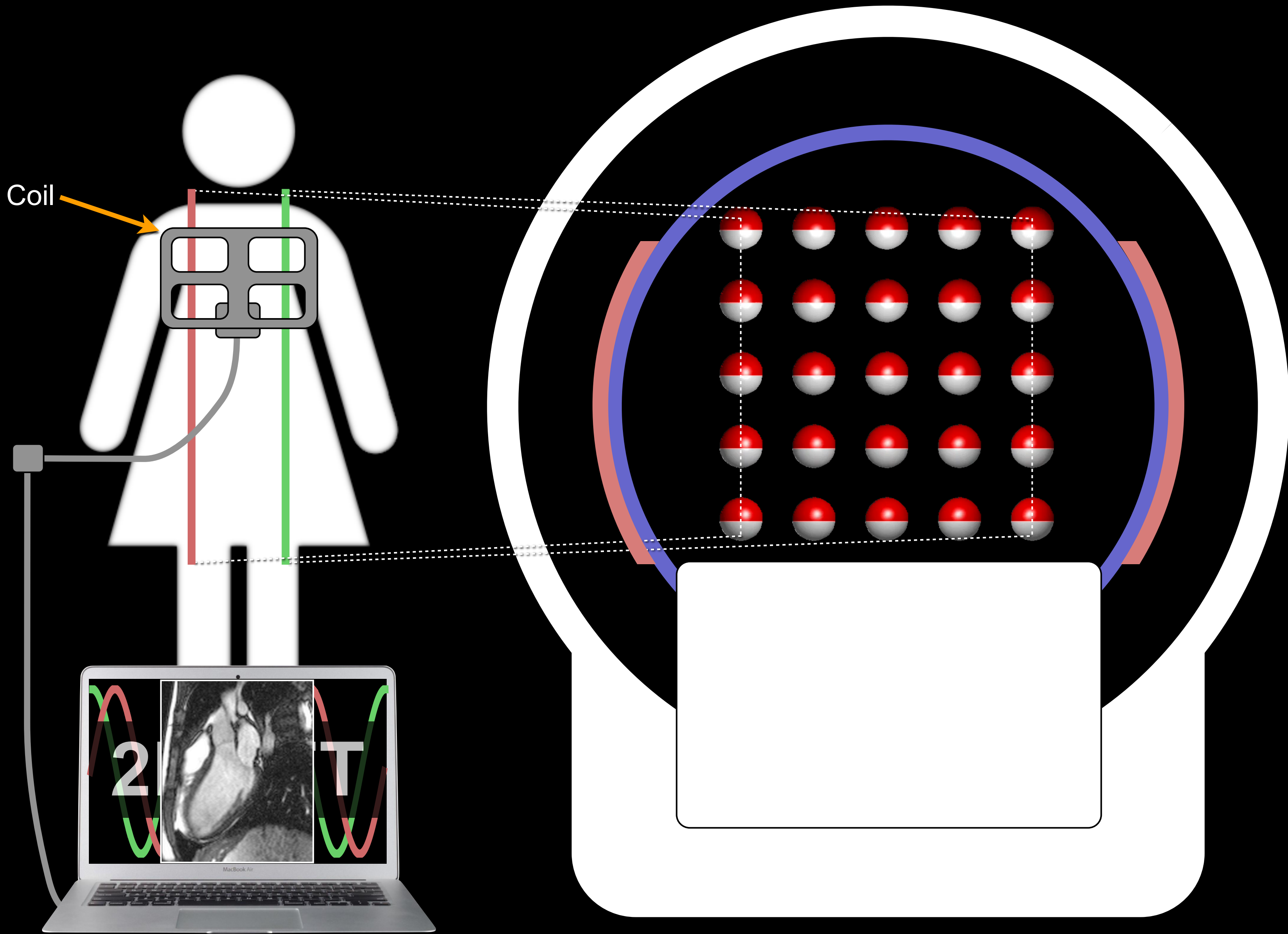
Faraday's Law of Induction





Precessing spins *induce* a current in a nearby coil.

Faraday's Law of Induction



The trick is to encode spatial information and image contrast in the echo.

Basic Detection Principles

Magnetic Flux Through The Coil – *Reciprocity*

$$\Phi\left(t\right)=\int_{object}\vec{B}_r\left(\vec{r}\right)\cdot\vec{M}\left(\vec{r},t\right)d\vec{r}$$

Magnetic Flux

Coil Sensitivity

Bulk Magnetization

Eqn. 5.38

What happens if the coil has poor sensitivity?

What happens if the coil's sensitivity is perpendicular to the bulk magnetization? How would that happen?

Basic Detection Principles

We get here

$$S(t) = \int_{\text{object}} M_{xy}(\mathbf{r}, 0) e^{-i\gamma \Delta B(\mathbf{r}) t} d\mathbf{r}$$

From Here

$$V(t) = -\frac{\partial \Phi(t)}{\partial t} = -\frac{\partial}{\partial t} \int_{object} \vec{B}(\vec{r}) \cdot \vec{M}(\vec{r}, t)\, d\vec{r}$$

with 25 pages of Math!

Basic Detection Principles

$$S(t) = \int_{\text{object}} M_{xy}(\mathbf{r},0)e^{-i\gamma\Delta B(\mathbf{r})t}d\mathbf{r}$$

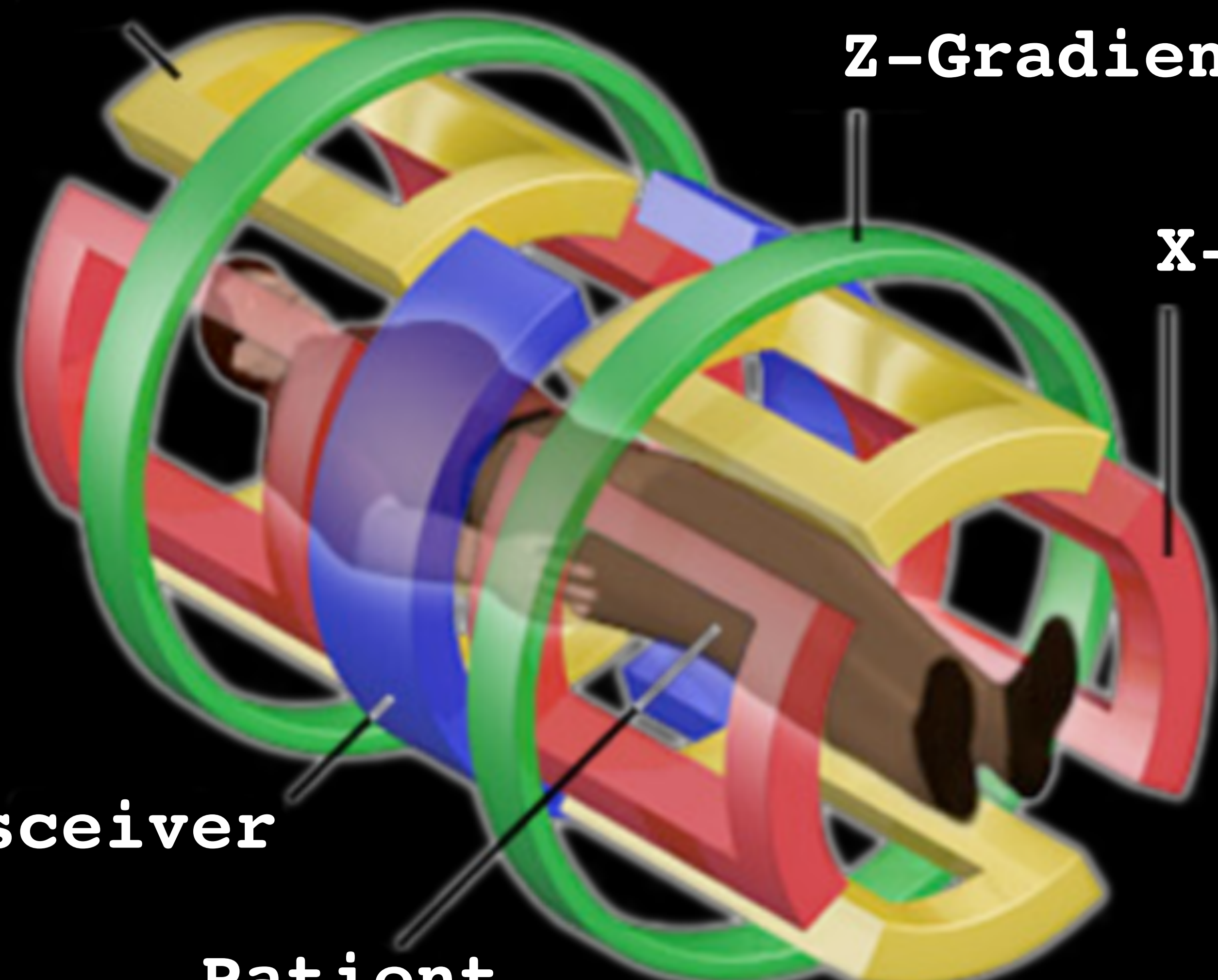
Observations

Detected signal is the vector sum of all transverse magnetizations in the "rotating frame" within the imaging volume.

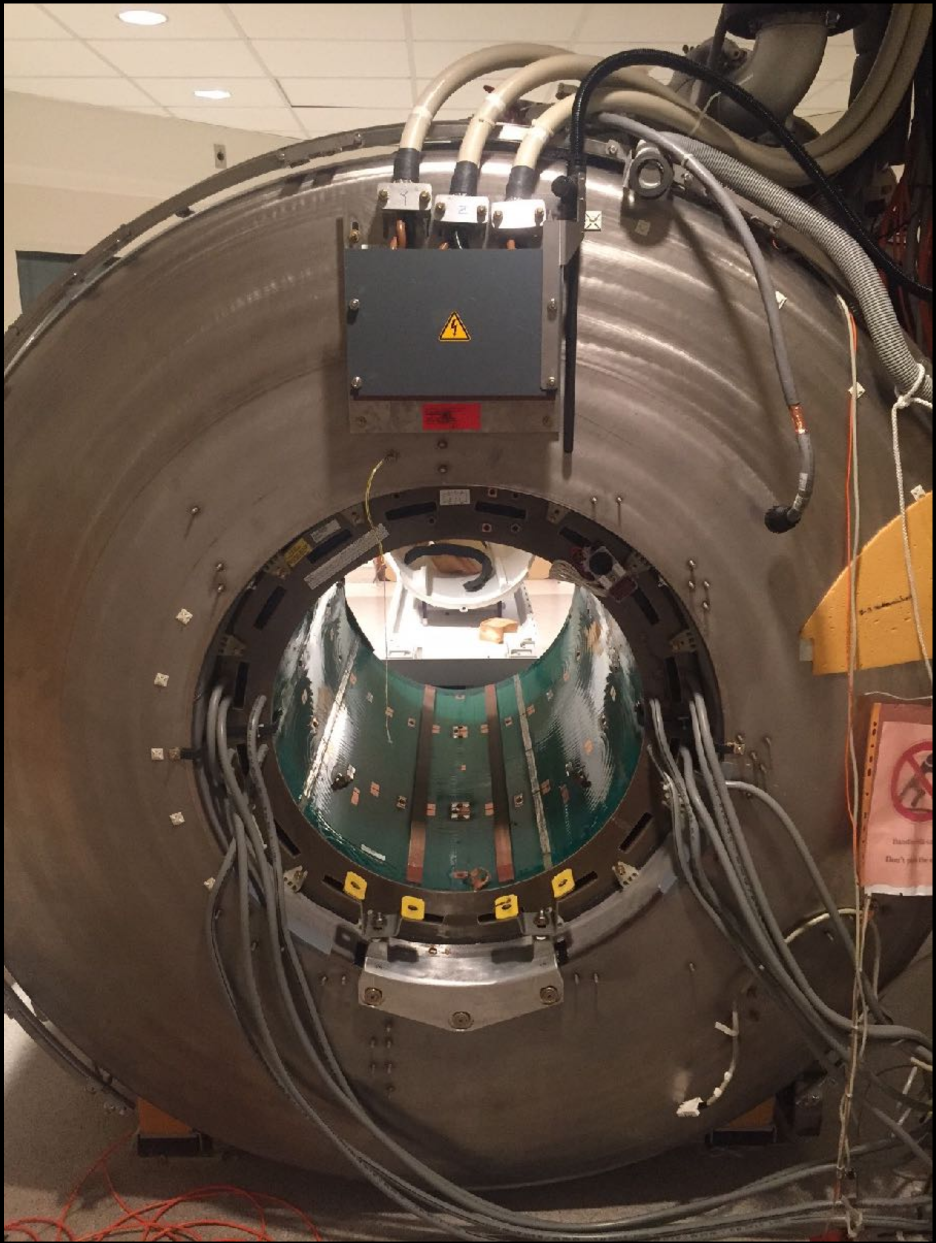
The Larmor frequency precession (Lab frame rotation) is necessary for detection, although only the baseband signal matters for imaging

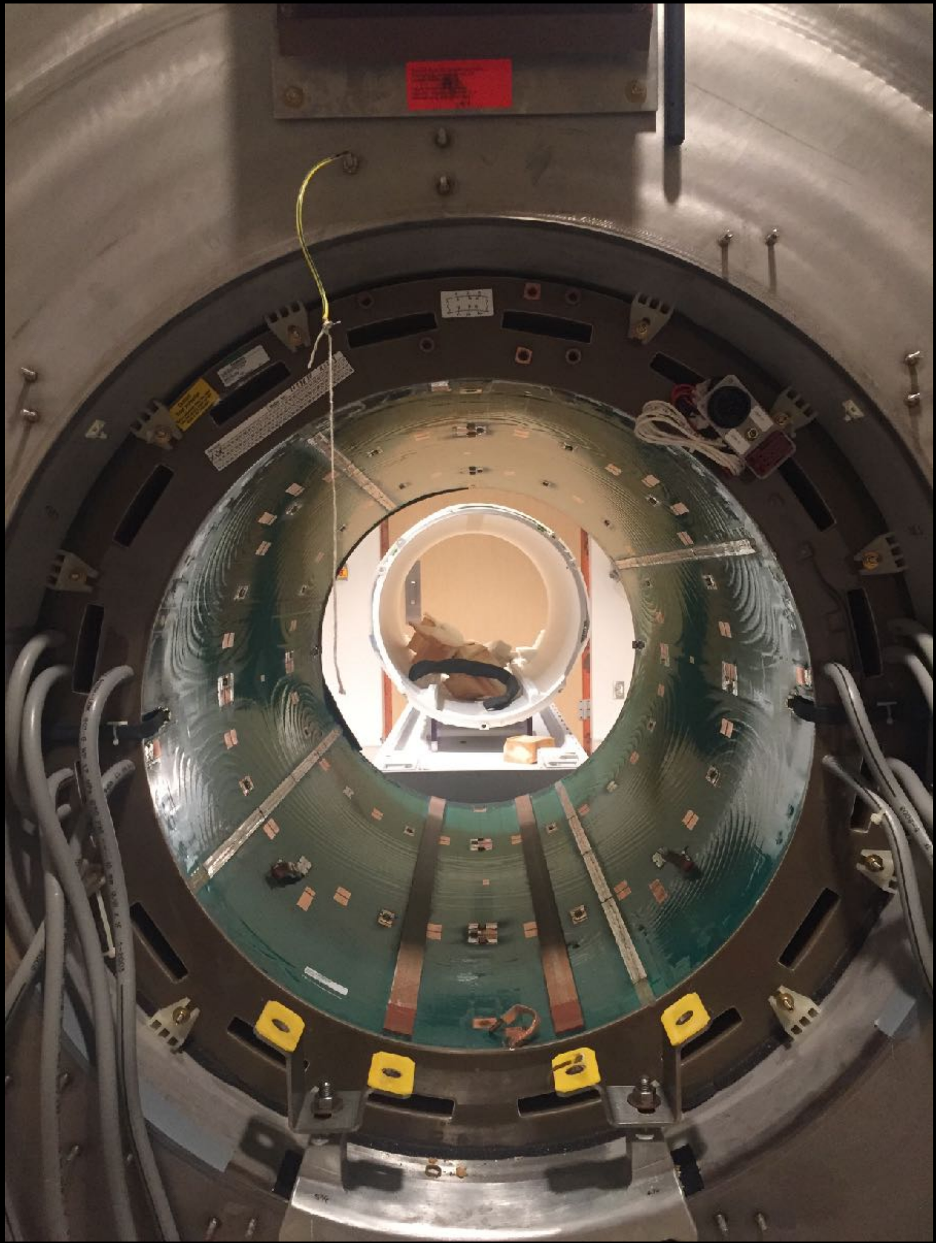
To the Board

Gradient Hardware



Gradient Hardware





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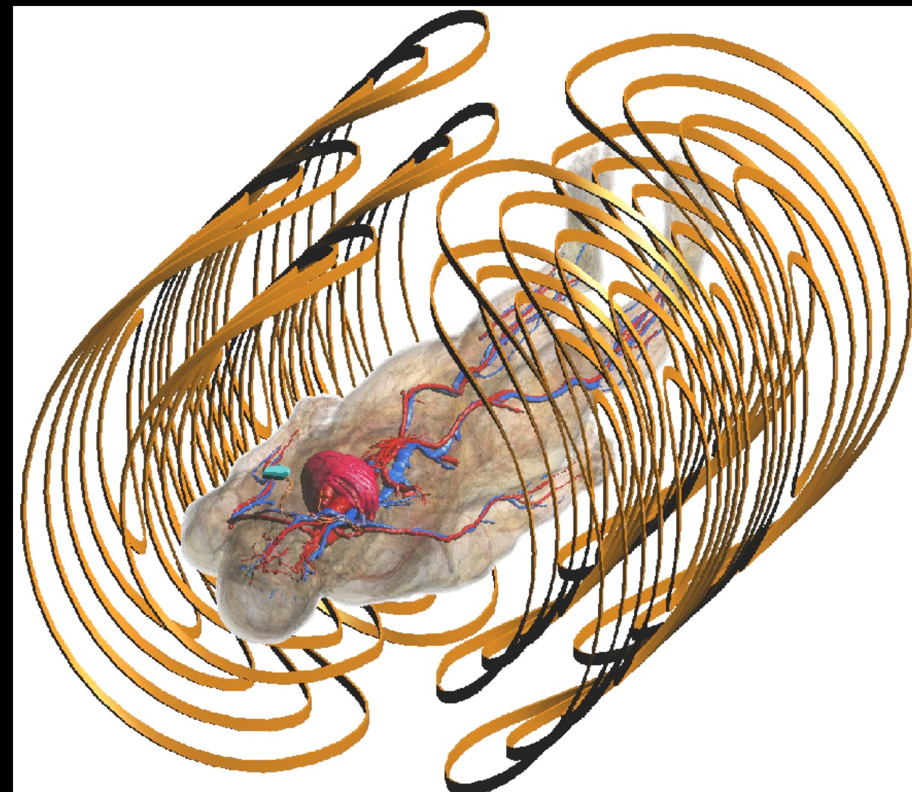

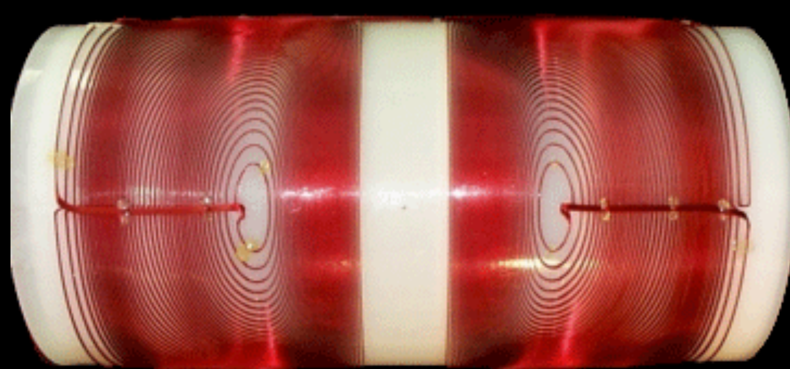

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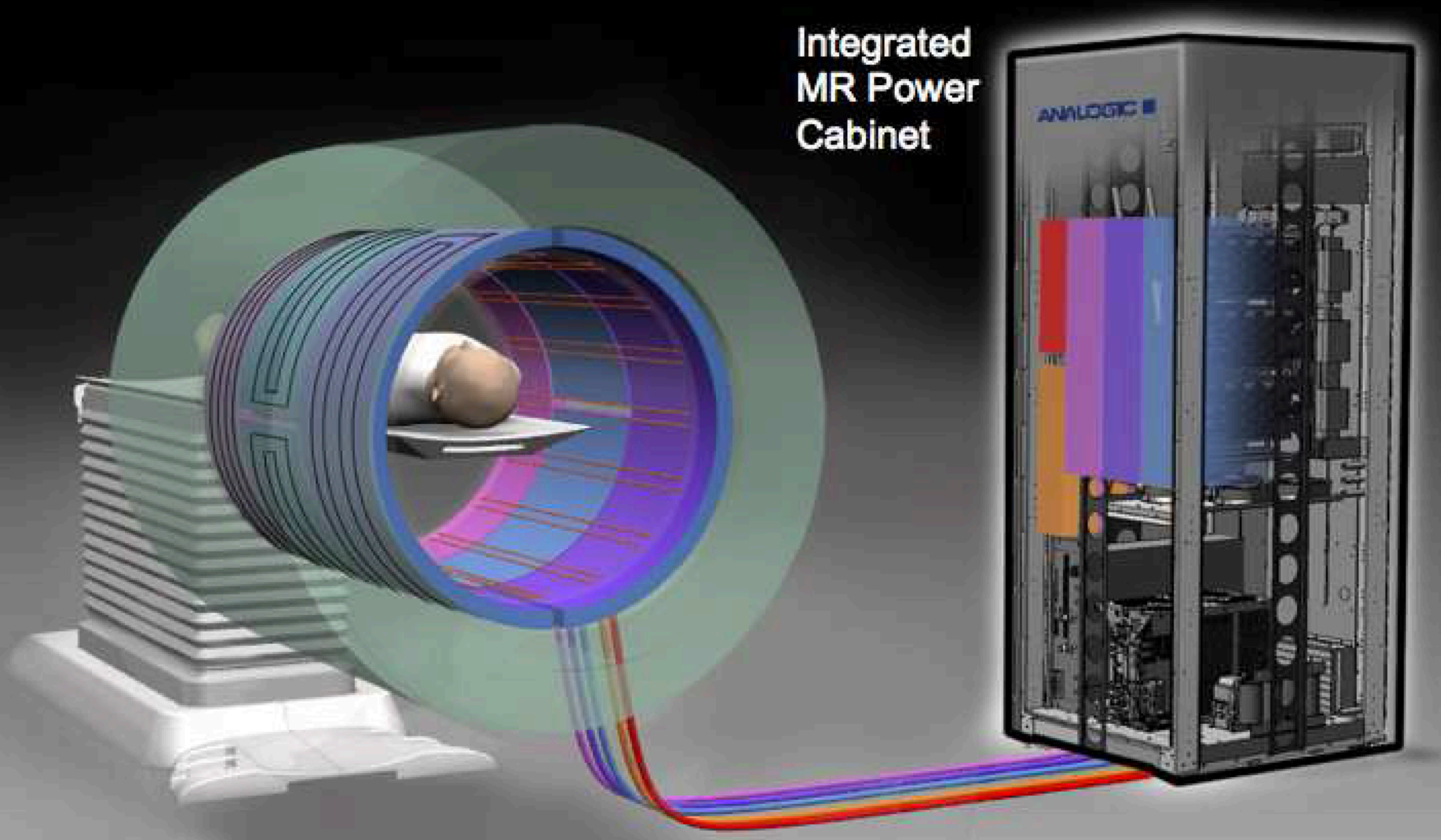


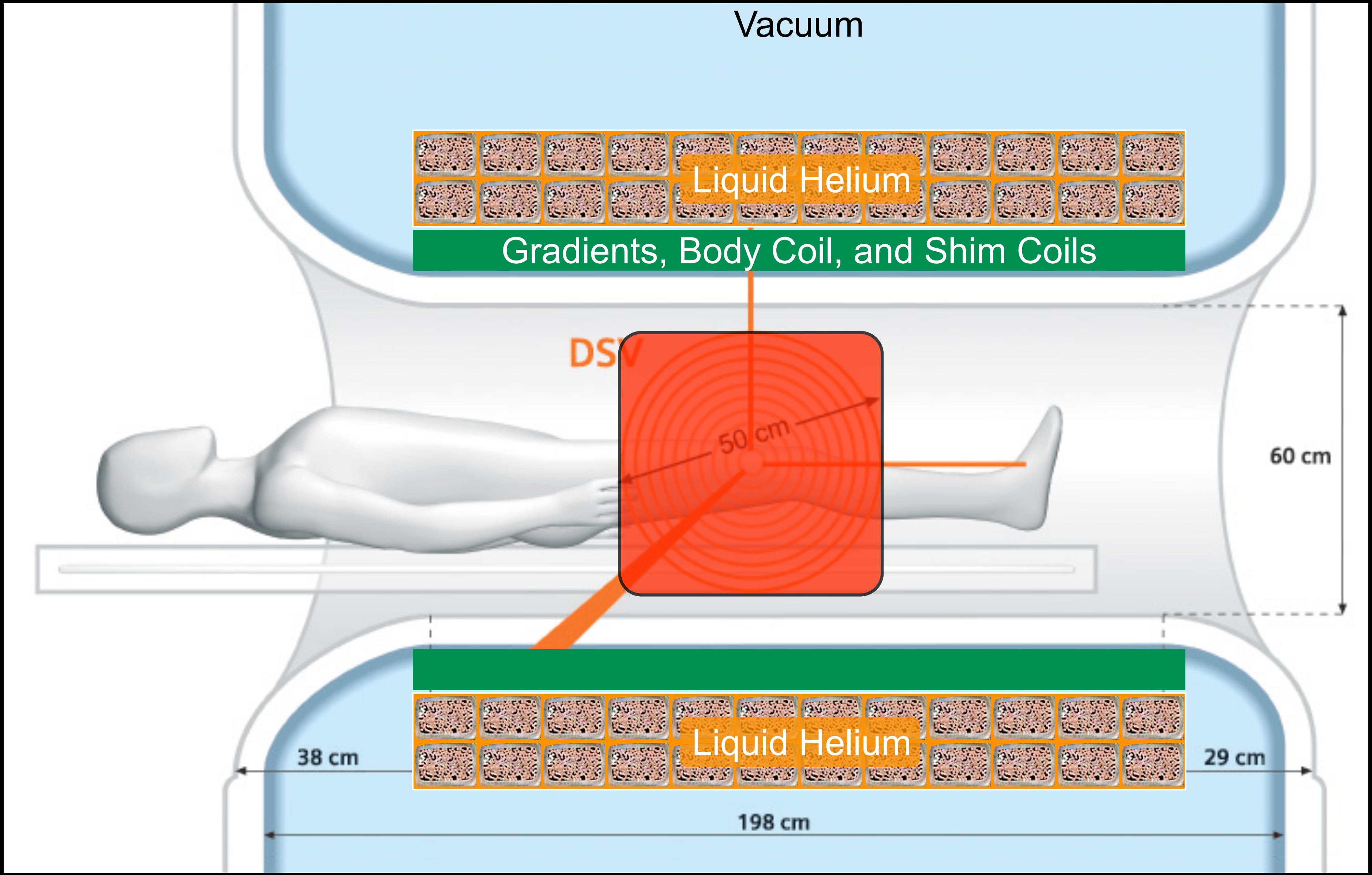
Gradients

- Primary function
  - Encode spatial information
    - Slice selection
    - Phase encoding
    - Frequency encoding
- Secondary functions
  - Sensitize/de-sensitize images to motion
  - Minimize artifacts (crushers & spoilers)
  - Magnetization re-phasing in slice selection
  - Magnetization de-phasing during readout

Gradients

- Gradients are a:
  - Small
    - <5G/cm (<0.0075T @ edge of 30cm FOV)
  - Spatially varying
    - Linear gradients
    - Adds to B_0 only in Z-direction
  - Time varying
    - Slewrate Max. ~150-200mT/m/ms
  - Magnetic field
    - Adds/Subtracts to the B_0 field
  - Parallel to B_0
- Gradients are NOT:
  - Fields perpendicular to B_0

Gradients



Gradients are “linear” over ~40-50cm on each axis.

B-Field Assumptions in MRI

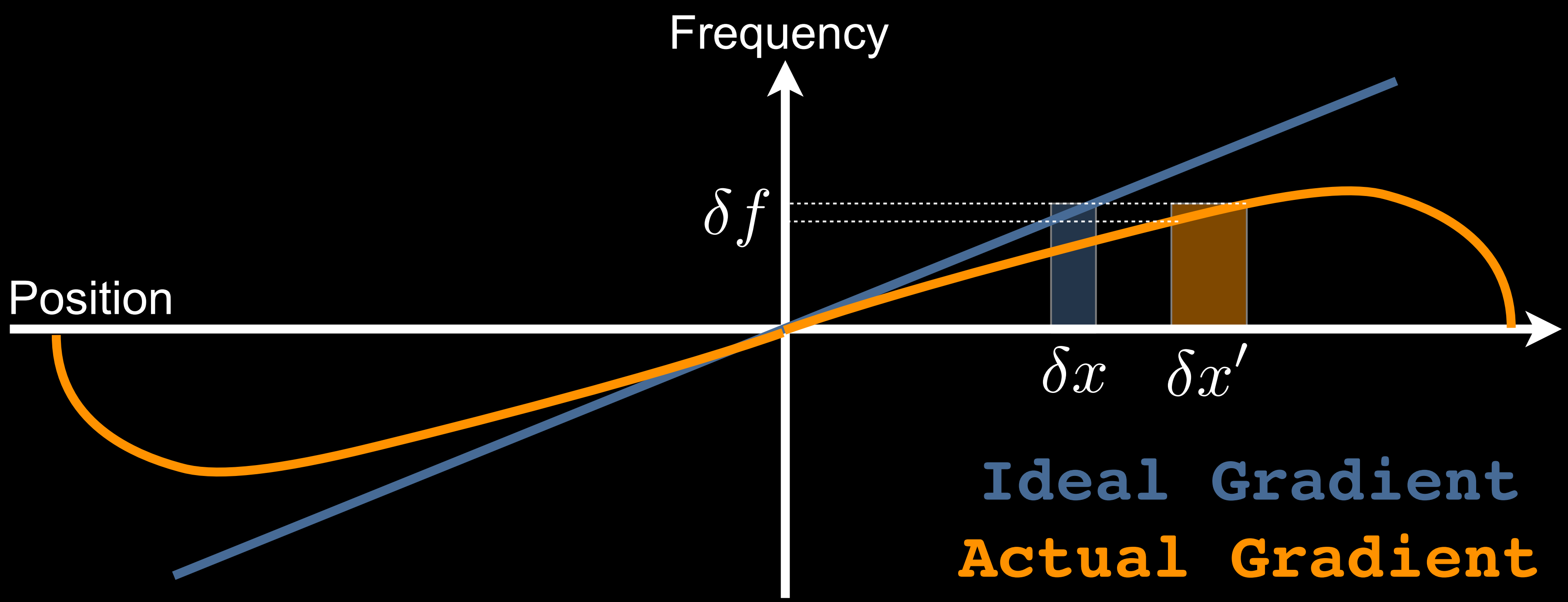
- **B_0-field is:**
  - Perfectly uniform over space.
    - "B_0 homogeneity"
  - Perfectly stable with time.
- **B_1-field is:**
  - Perfectly uniform over space.
    - "B_1 homogeneity"
  - Temporally modulated exactly as specified.
- **Gradient Fields are:**
  - Perfectly linear over space.
    - "Gradient linearity"
  - Temporally modulated exactly as specified

Imperfections of Gradient Fields

- Gradient coils aren't perfect
  - Non-linearity
  - Eddy Currents
  - Maxwell terms (Concomitant fields)
  - But they are small
    - *Much* smaller than B_0
    - We will ignore them...but they exist...

Gradient Non-linearity

Gradient Non-linearity

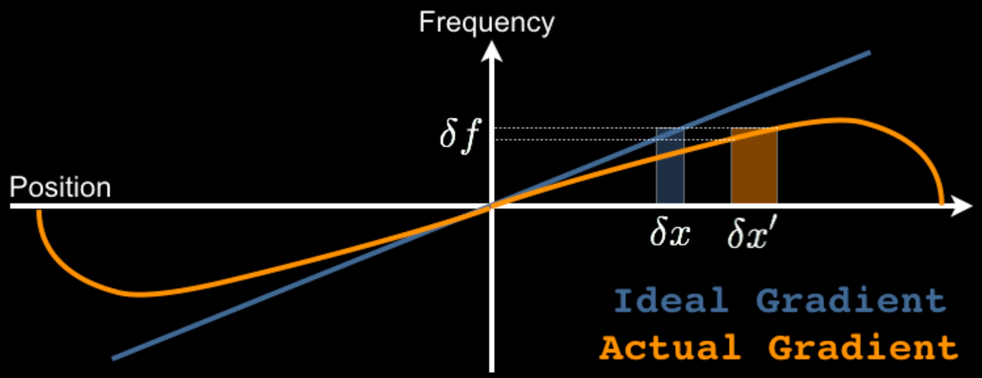


Ideally spatial position is linearly related to frequency.

Gradient Non-linearity

- **Basic _assumption_ in MRI is that the z-component of the B-field created by the gradient coils varies linearly with x, y, or z over the FOV.**
- **Higher gradient amplitudes and slewrates can be achieved by compromising on spatial linearity.**
- **Gradient non-linearity causes geometric and intensity distortions.**

Gradient Non-linearity



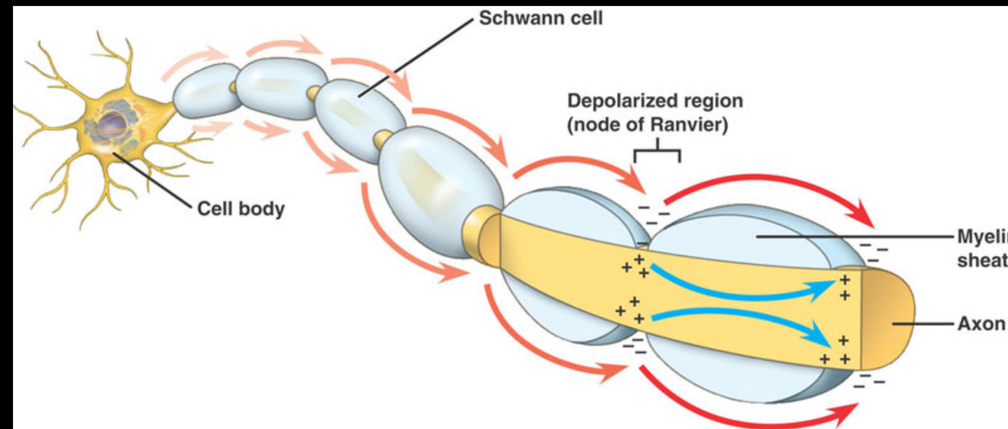
Solution

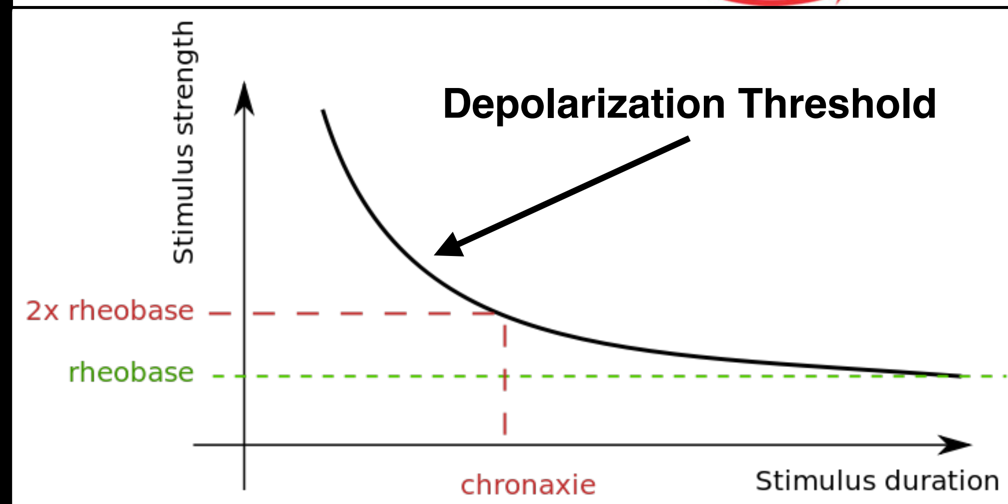
- **Improve hardware and linearity!**
- **Pay attention to FOV!**
- **Image warping parameters that are system specific and applied to all images.**
  - **Works well qualitatively.**
  - **Can be problematic quantitatively.**

Gradient Safety

Gradient Safety

- **Noise**
- **Peripheral nerve stimulation (PNS)**





Solution: De-rate gradient slew rates, but this increases scan time.

Solution: Ear plugs Head phones

Time-varying gradients induce mechanical vibrations and PNS.

MRI Gradient Noise

Switching the gradients on ms time scales (kHz) generates acoustic noise.

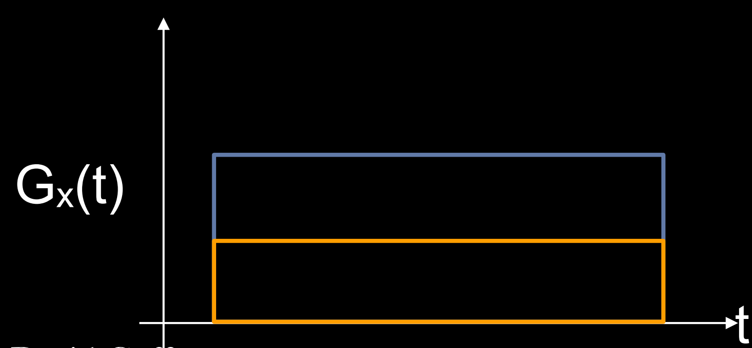
Gradient Noise

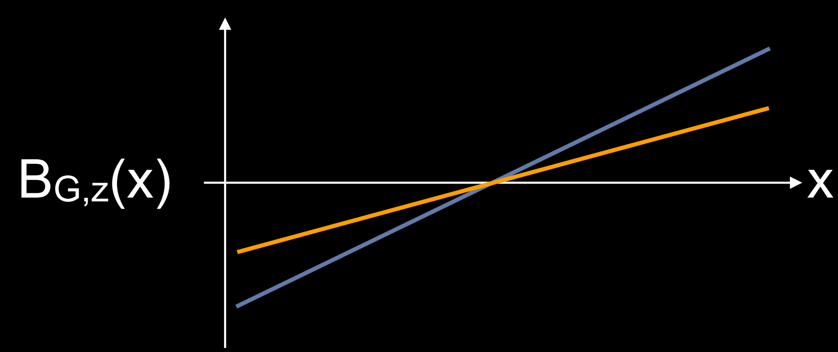
• Jet take-off @ 25m	~150 dB (eardrum rupture)
• Car horn @ 1m	~110 dB (borderline painful)
• Live rock band	~100 dB
• MRI gradients full load	≤99 dB
• Garbage disposal	~80 dB
• MRI gradients basic load	≤75 dB
• Radio or TV Audio	~70dB

Siemens: mri-magnetom-essenza-environmental_product_declaration-00079271.pdf

Gradient Safety – G_{Max}

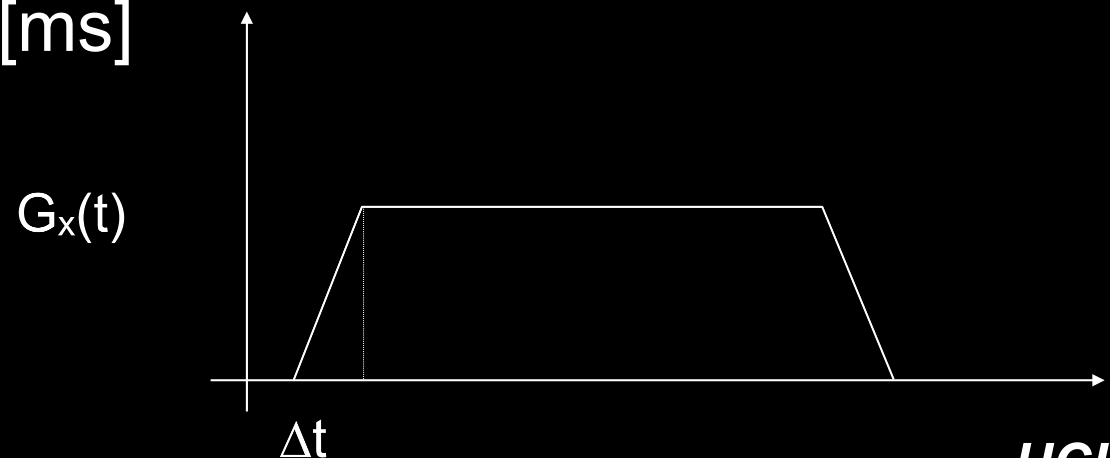
- **G_{max} limitations:**
  - Concern: None known.
    - B_0 is already pretty big.
  - Conventional Gradients
    - G_{Max} = 4 to 5G/cm (=50mT/m)
  - Cutting Edge Gradients
    - G_{Max} = 8G/cm (=80mT/m)
  - Connectome Gradients
    - G_{Max} = 30G/cm (=300mT/m)
  - Consider the ΔB contributed by a gradient...





Gradient Slewrate

- **Gradient slew rate**
  - T/m/s (or G/cm/s)
  - dG/dt – Rate of change of gradient amplitude
- **Slew rate limited by dB/dt:**
  - Concern: Peripheral Nerve Stimulation
  - Regulated by FDA
  - Normal Mode: dB/dt=16 T/s•(1+0.36/ß)
  - First Level Mode: dB/dt=20 T/s•(1+0.36/ß)
  - ß=stimulus duration [ms]



Questions?

- Related reading materials
  - Nishimura - Chap 5

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