MRI Systems III: Gradients

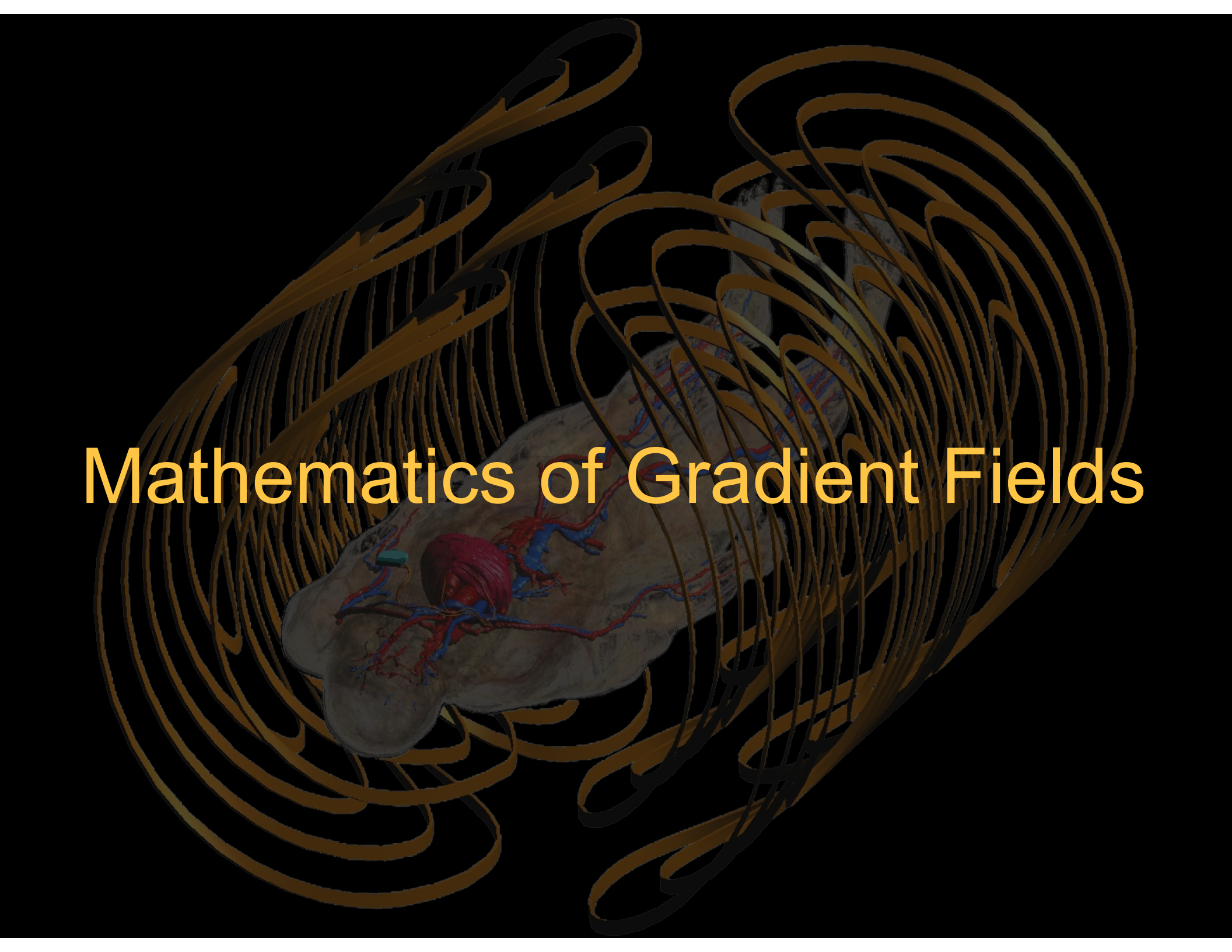
M219 - Principles and Applications of MRI

Kyung Sung, Ph.D.

1/30/2023

Course Overview

- Course website
  - https://mrrl.ucla.edu/pages/m219
- 2023 course schedule
  - https://mrrl.ucla.edu/pages/m219_2023
- Assignments
  - Homework #1 is due today
  - Homework #2 is out
- Office hours, Fridays 10-12pm
  - In-person (Ueberroth, 1417B)
  - Zoom is also available


Mathematics of Gradient Fields

Gradients

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

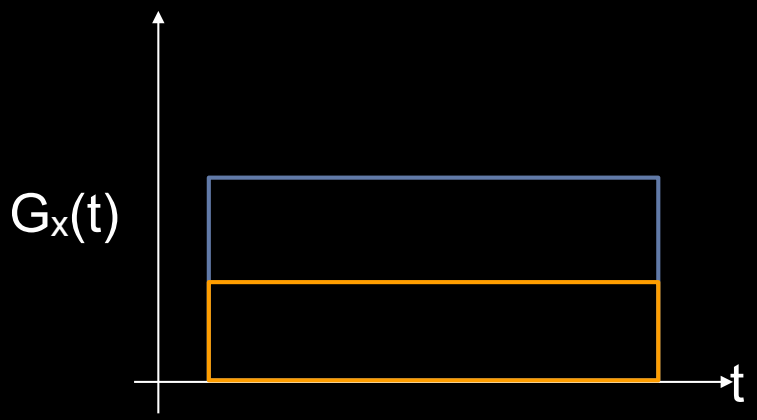
$$\underbrace{B_G}_{\text{B-field from a gradient}},\underbrace{z}_{\text{Points along the z-direction}}\underbrace{(x)}_{\text{Varies with the x-direction}} = \underbrace{G_x}_{\text{x-gradient amplitude}}\underbrace{x}_{\text{x-distance from isocenter}}$$

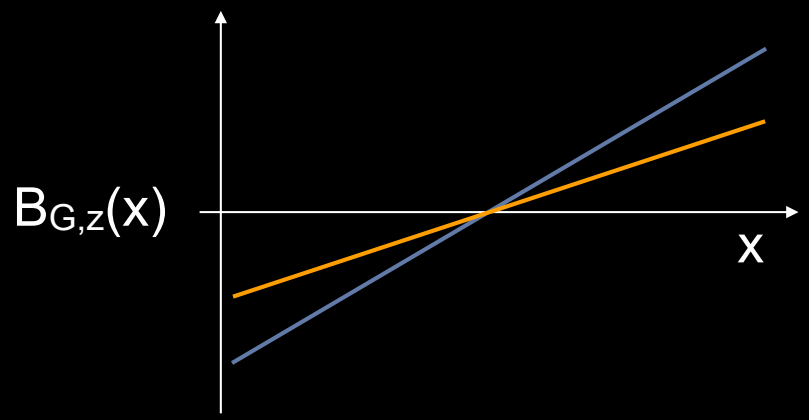
Gradient Induced B-Fields

$$B_{G,z}(x) = G_x x$$ x-gradient

$$B_{G,z}(y) = G_y y$$ y-gradient

$$B_{G,z}(z) = G_z z$$ z-gradient





Gradient Induced B-Fields

- Each gradient coil can be activated independently and simultaneously

$$\begin{aligned} B_{G,z}\vec{k} &= (G_x x + G_y y + G_z z)\vec{k} \\ &= (\vec{G}\cdot\vec{r})\vec{k} \end{aligned}$$

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

Combined B_0 and Gradient Fields

- Gradients contribute to the net B-field, but only along the z-direction

$$\begin{aligned}\vec{B}(\vec{r},t) &= (B_0 + B_{G,z})\,\vec{k} \\ &= \left(B_0 + \vec{G}(t)\cdot\vec{r}\right)\vec{k}\end{aligned}$$

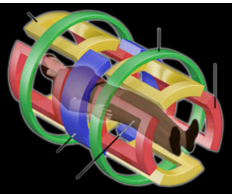
B-Field Assumptions in MRI

- **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

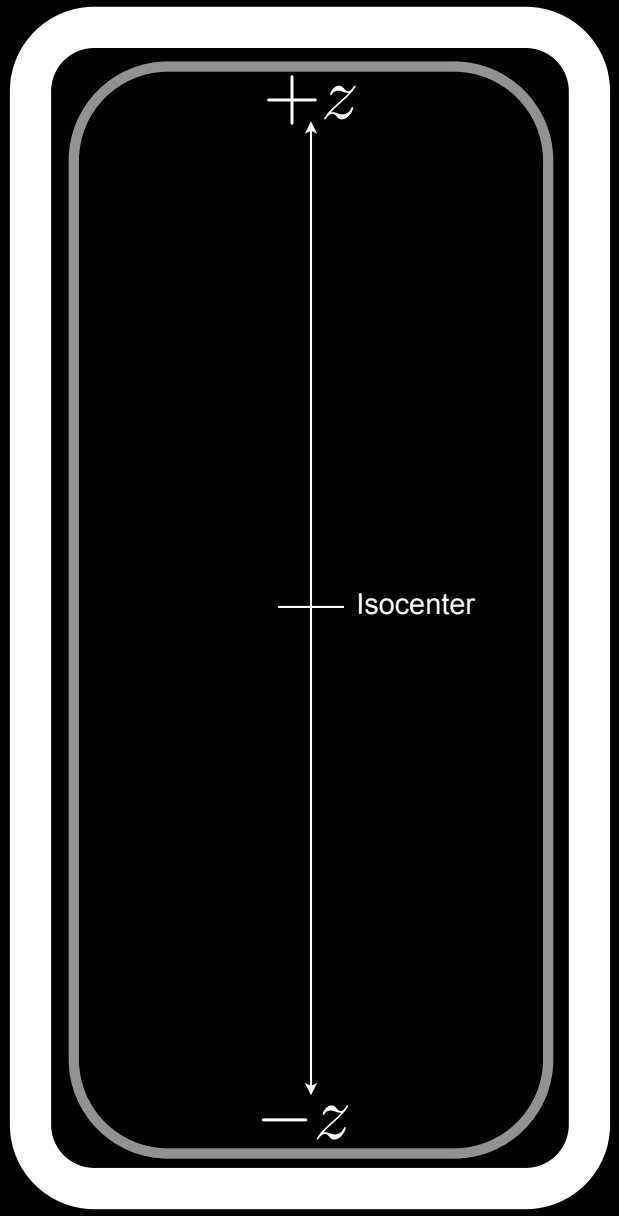
Imperfections of Gradient Fields

- Gradient coils aren't perfect
  - Non-linearity
  - Eddy Currents
  - Maxwell terms (Concomitant fields)
  - But they are small
    - *Much* smaller than B_0

Gradient Fields & Spins



No Gradients Turned On



B_0

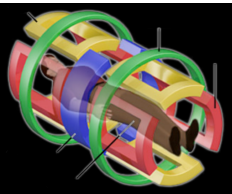
B_0

B_0

z

x

$$\omega = \gamma B_0$$



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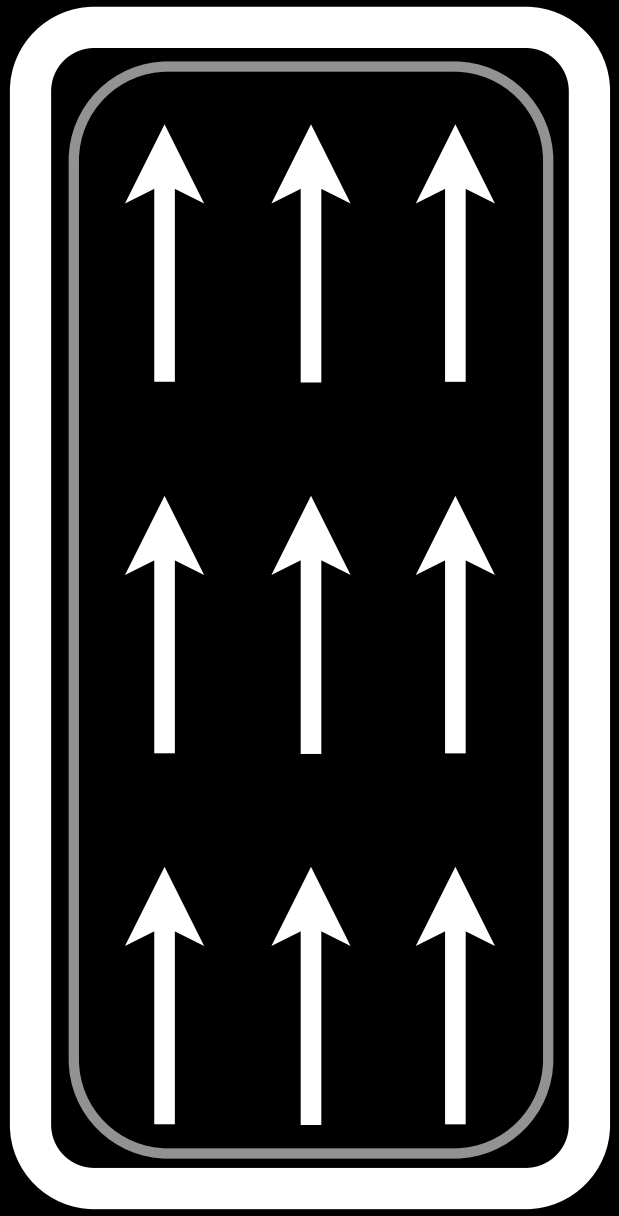

B_0

B_0

B_0

z

x

$$\omega = \gamma B_0$$

Length of arrow indicates strength of local field.

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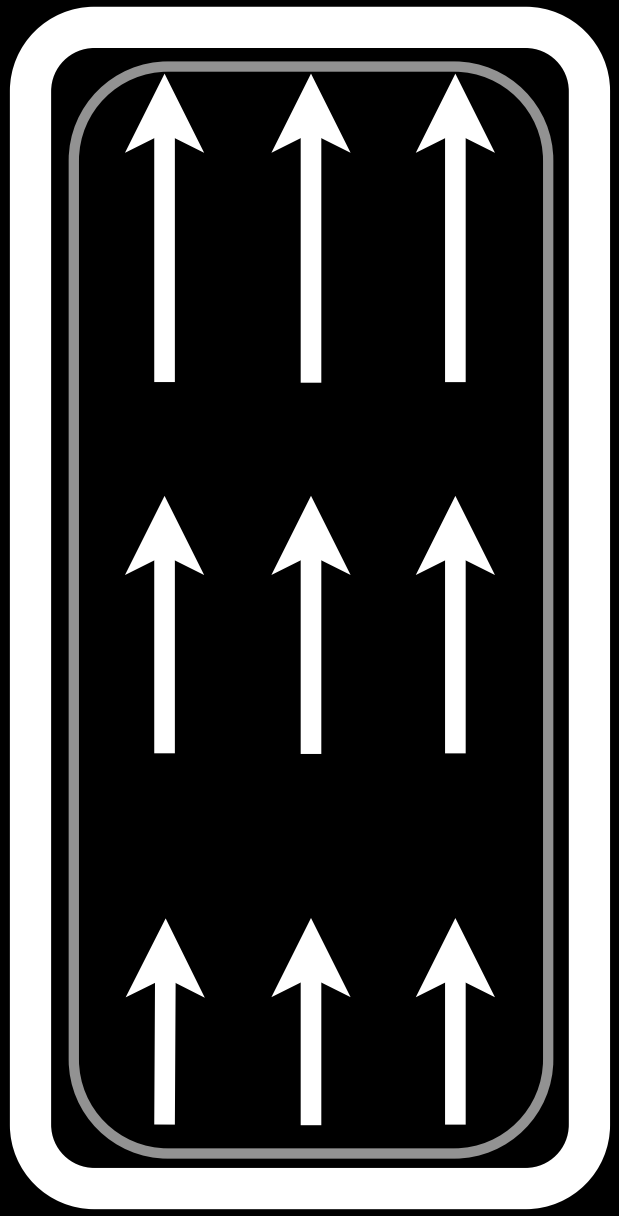
Z-Gradients



$B_0 + \delta B_0$

B_0

$B_0 - \delta B_0$

z

x

$$\omega(z) = B_0 + G_z \cdot z$$

What coordinate frame are we in?

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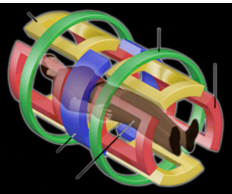
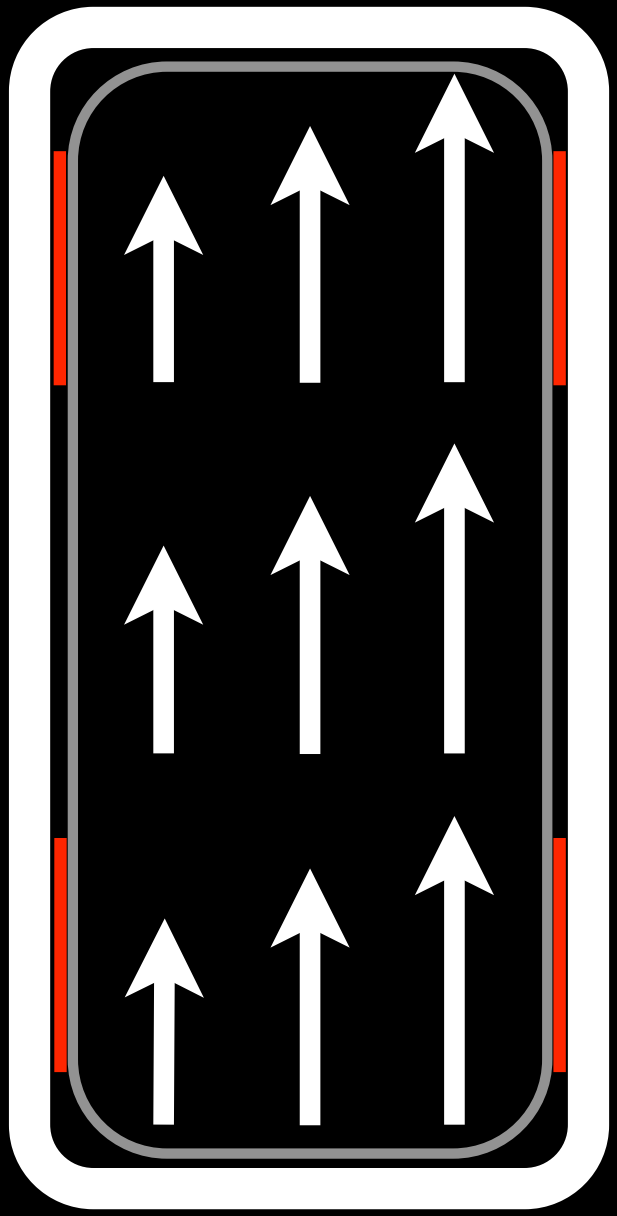
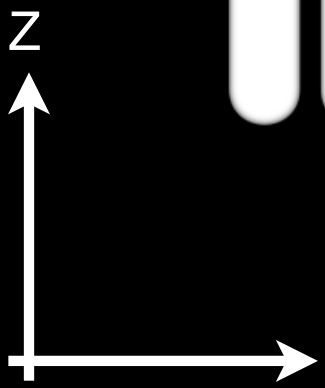


X-Gradients

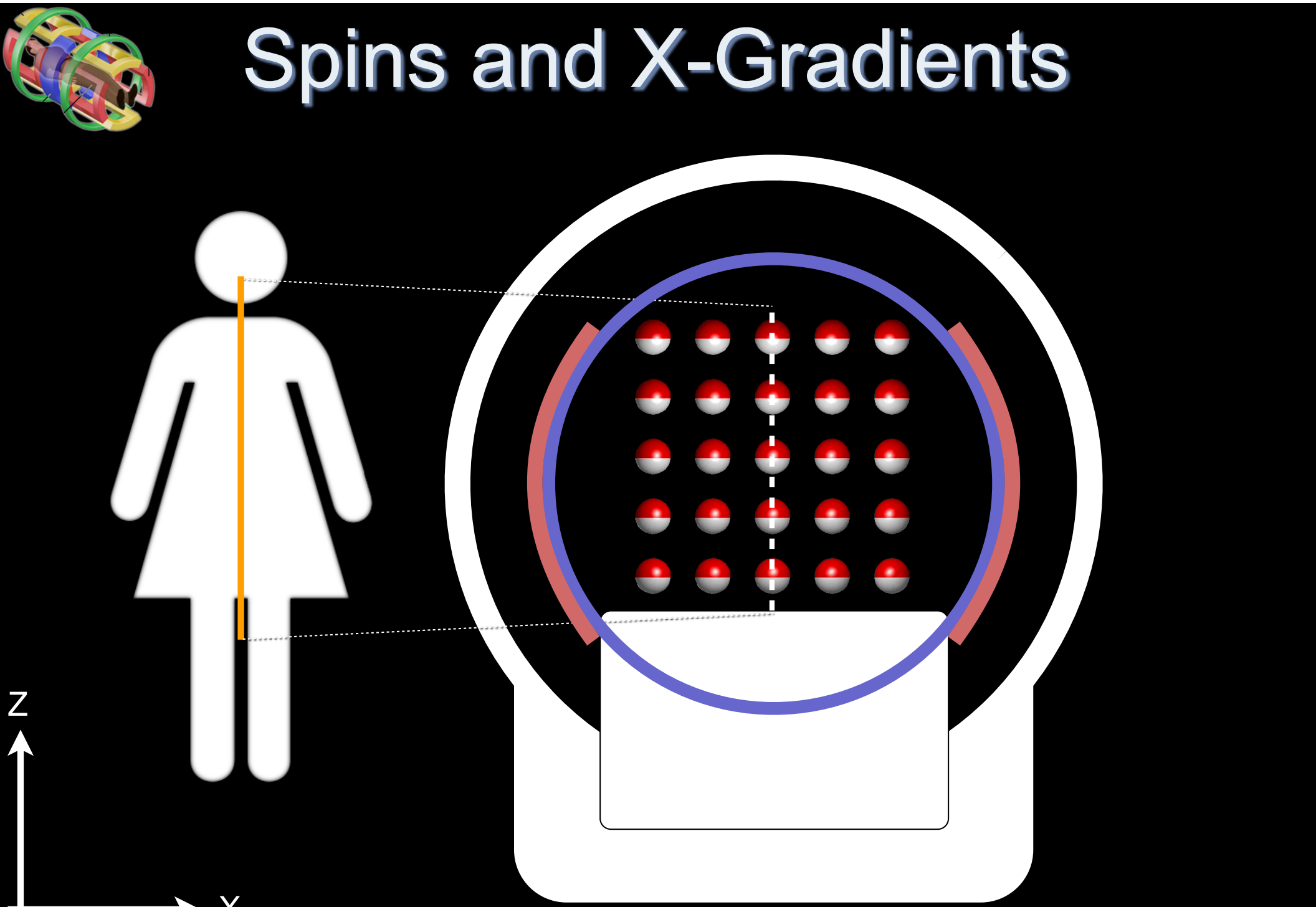




$$\omega(x,z) = B_0 + G_x \cdot x + G_z \cdot z$$

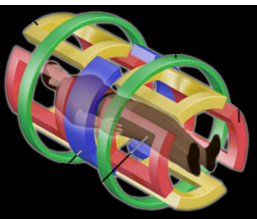
$B_0 - \delta B_0 \quad B_0 \quad B_0 + \delta B_0$

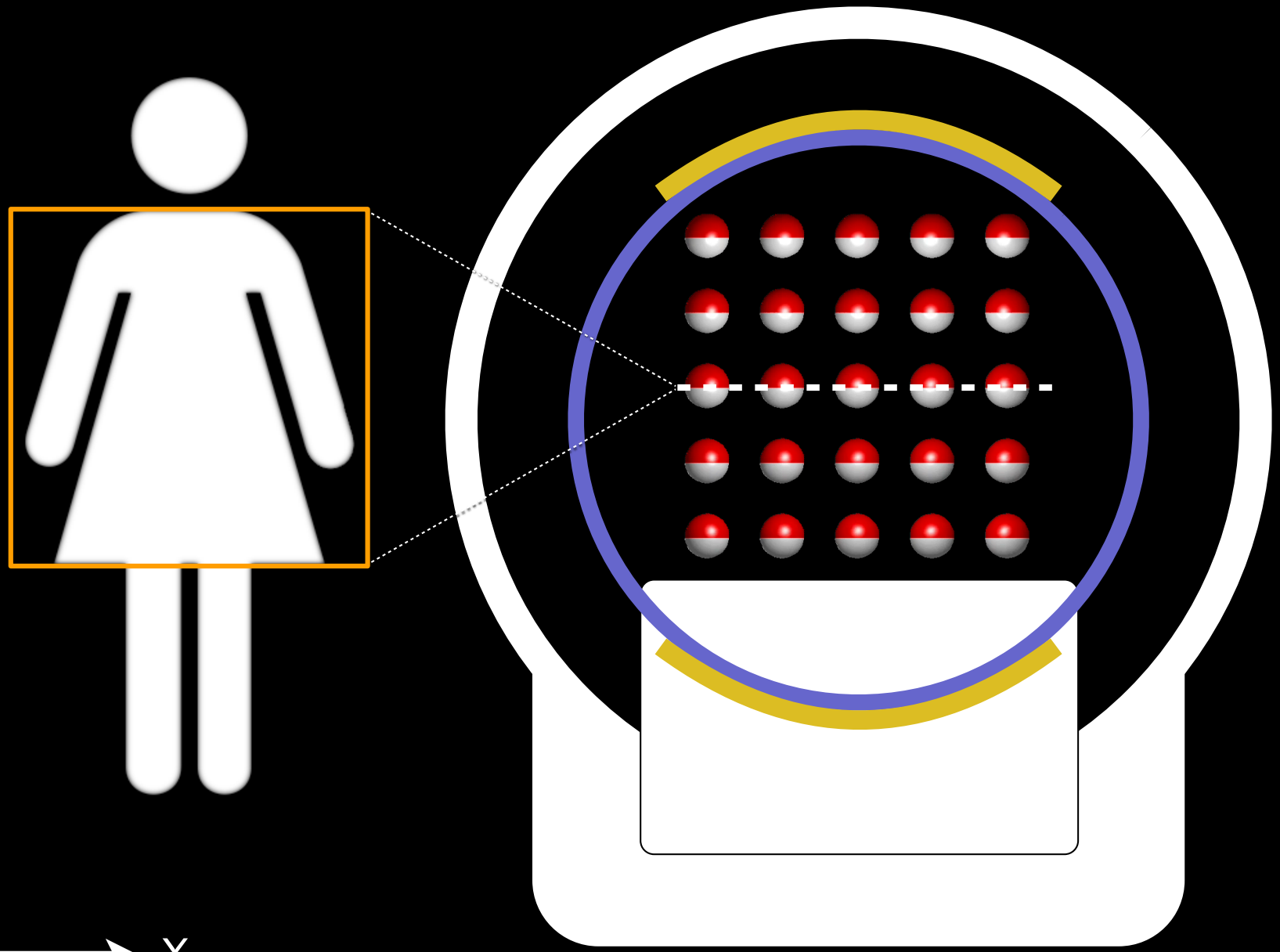
Spins and X-Gradients



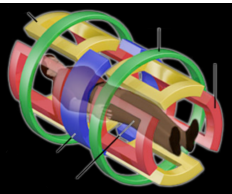
Gradients give rise to isochromats (planes of common frequency).

Spins and Y-Gradients

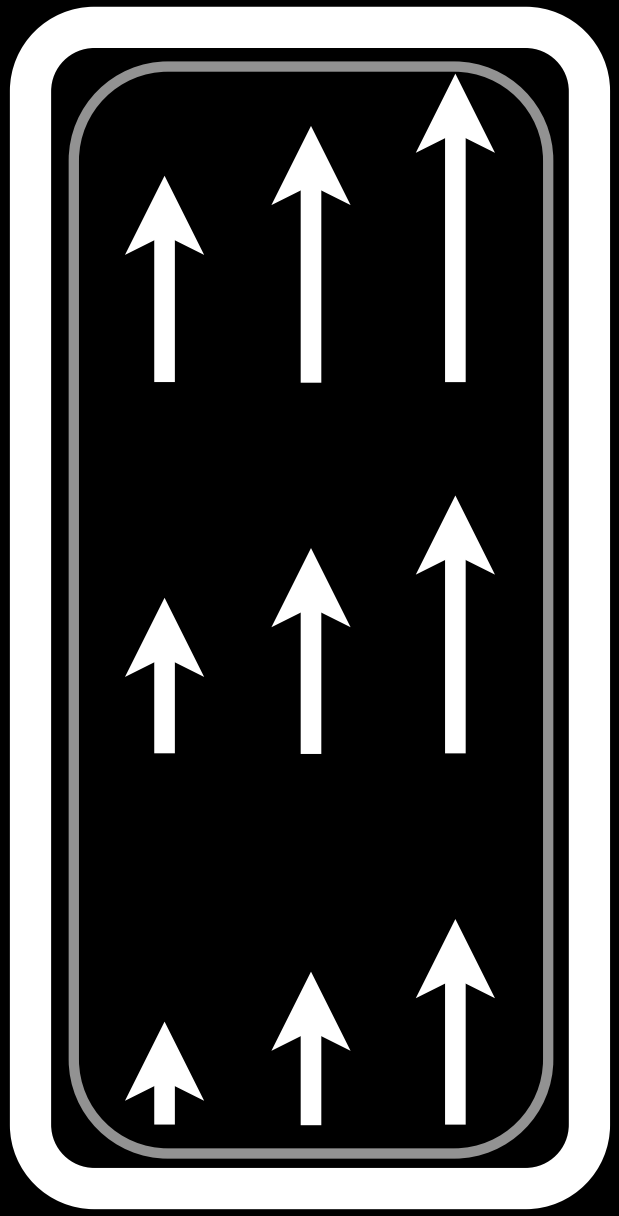


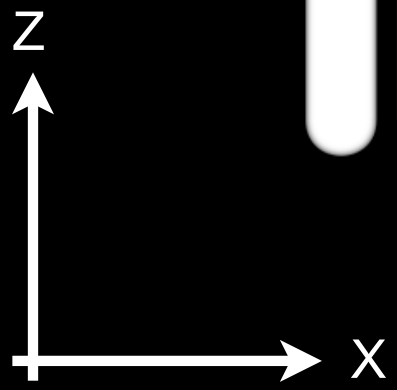


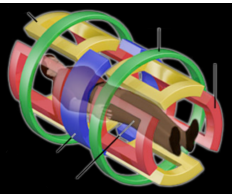
Gradients add/subtract to B_0 along a specific direction.



How do we do this?

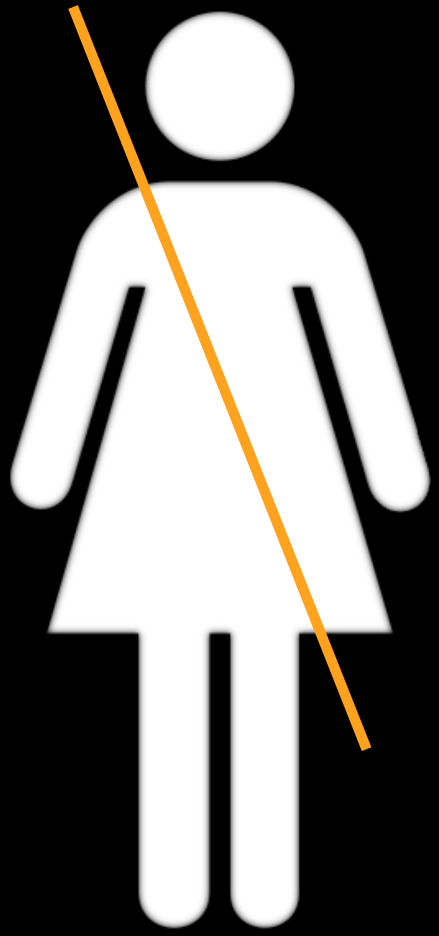


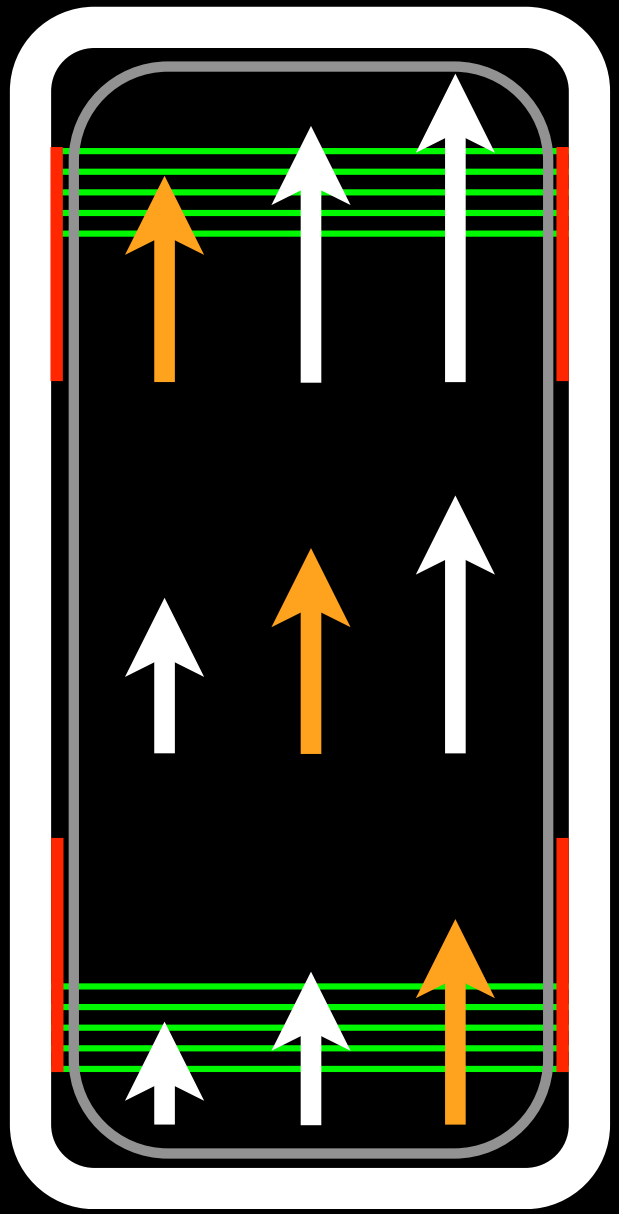




X+Z-Gradients

Possible Slice





Spin Isochromat

z

x

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

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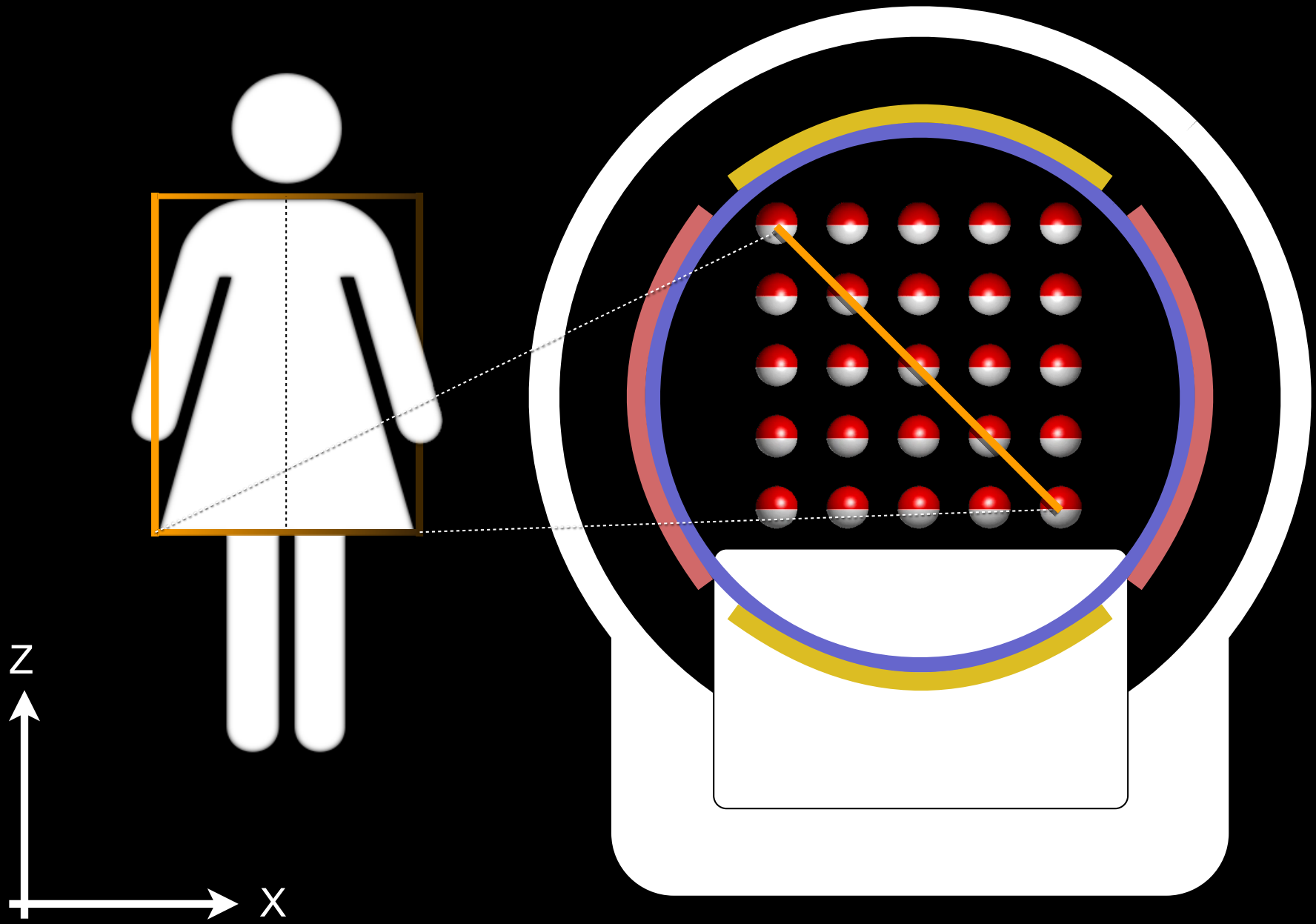
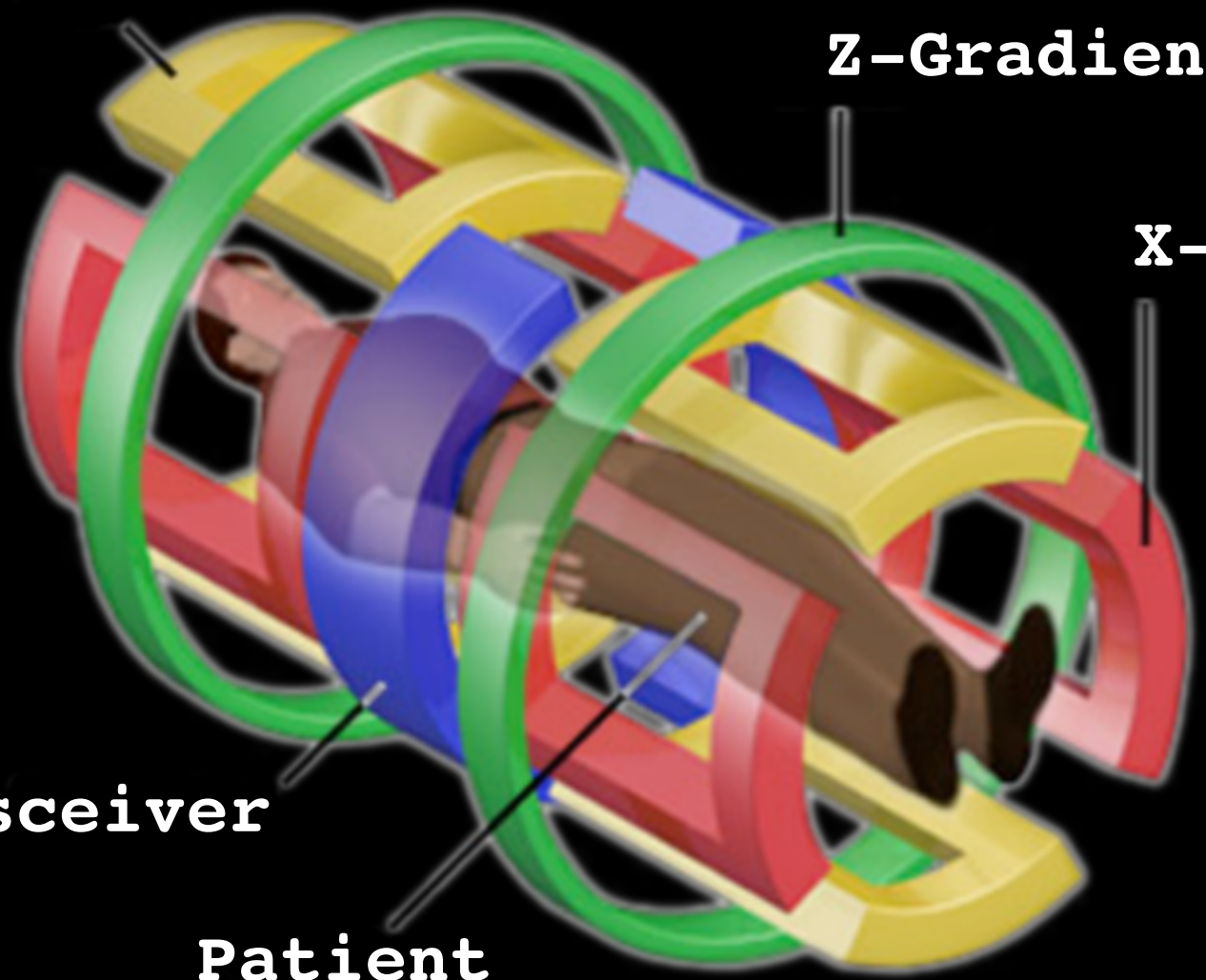
Spins and X- & Y-Gradients



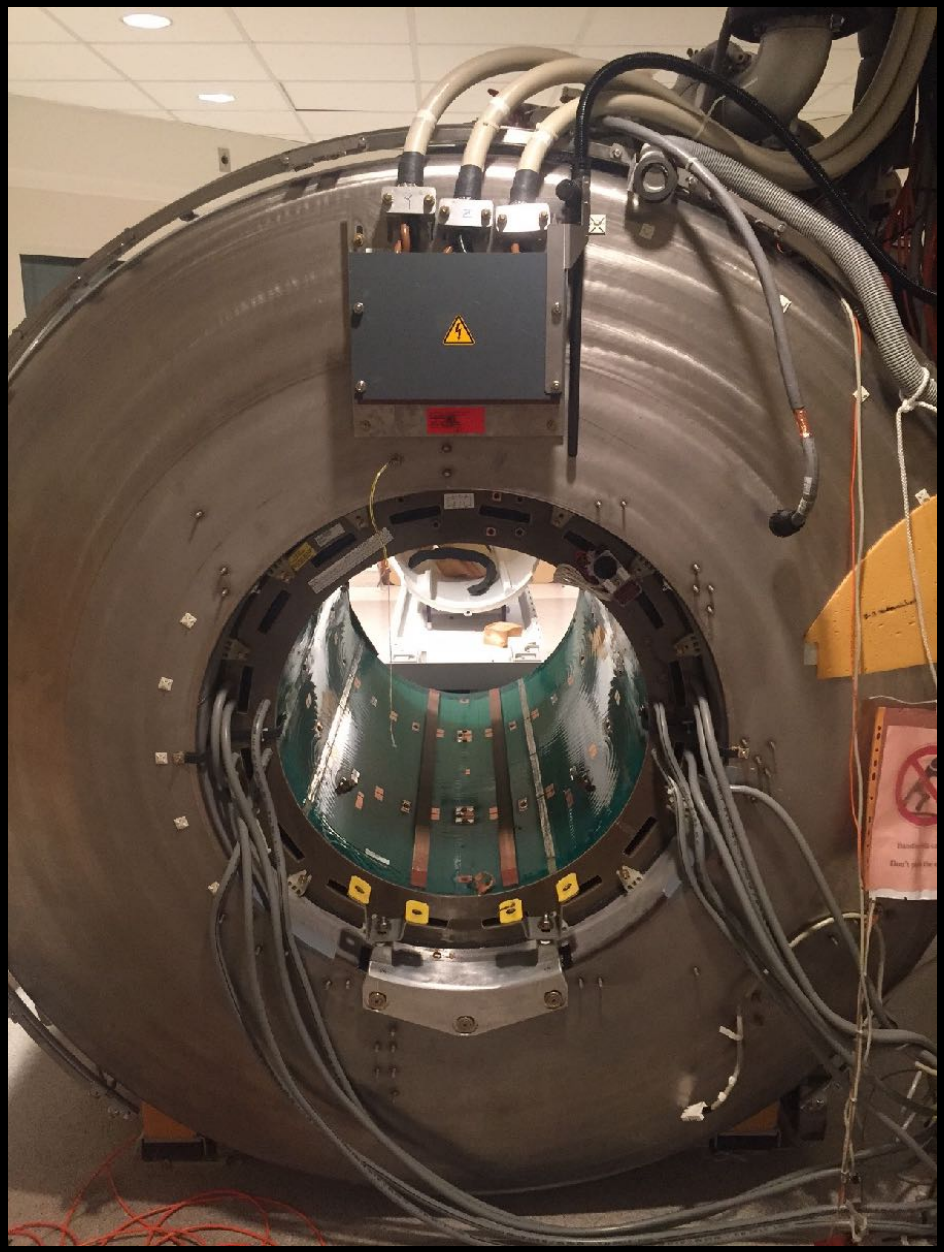
Simultaneous gradients create an arbitrary isochromat plane.

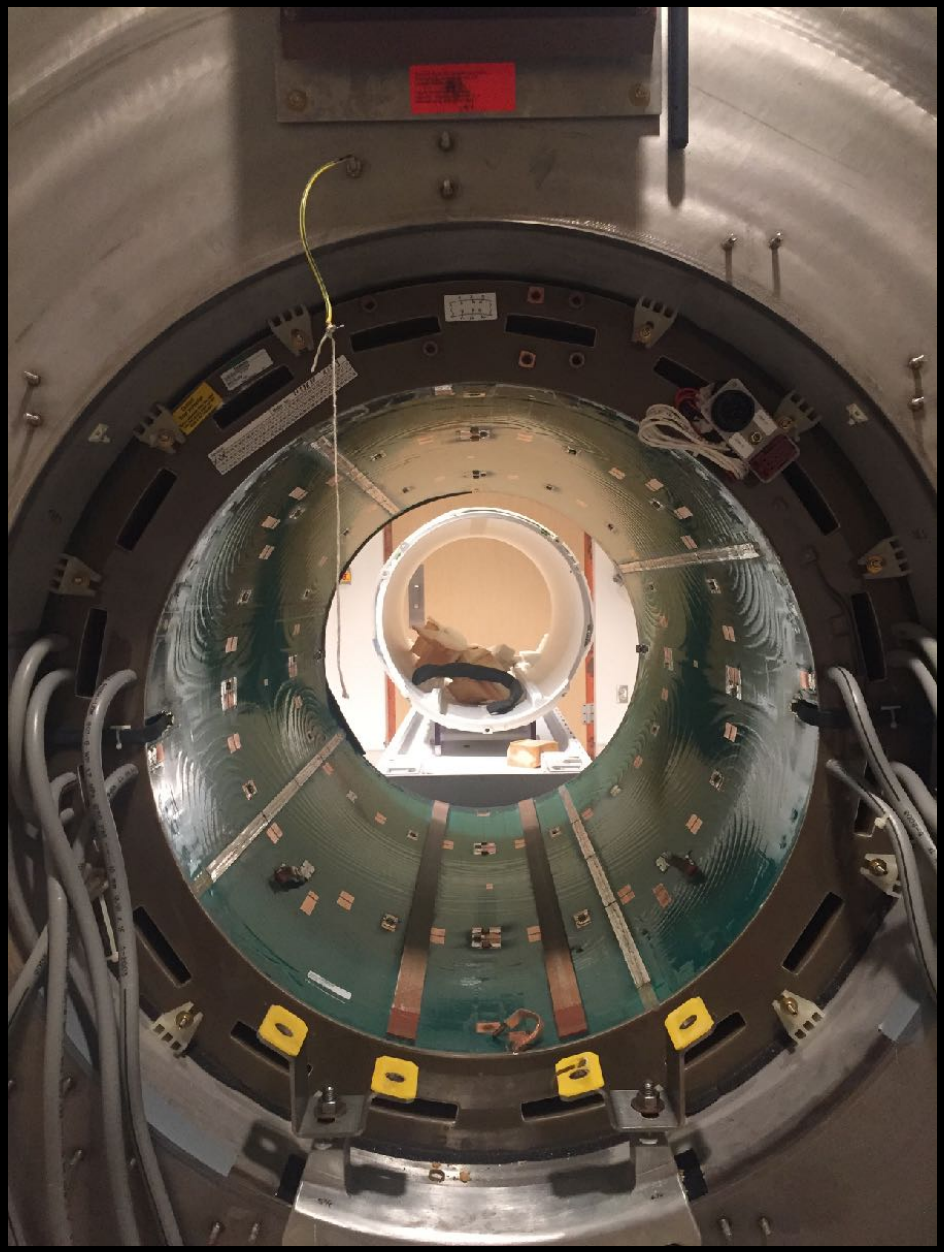
To the Board

Gradient Hardware

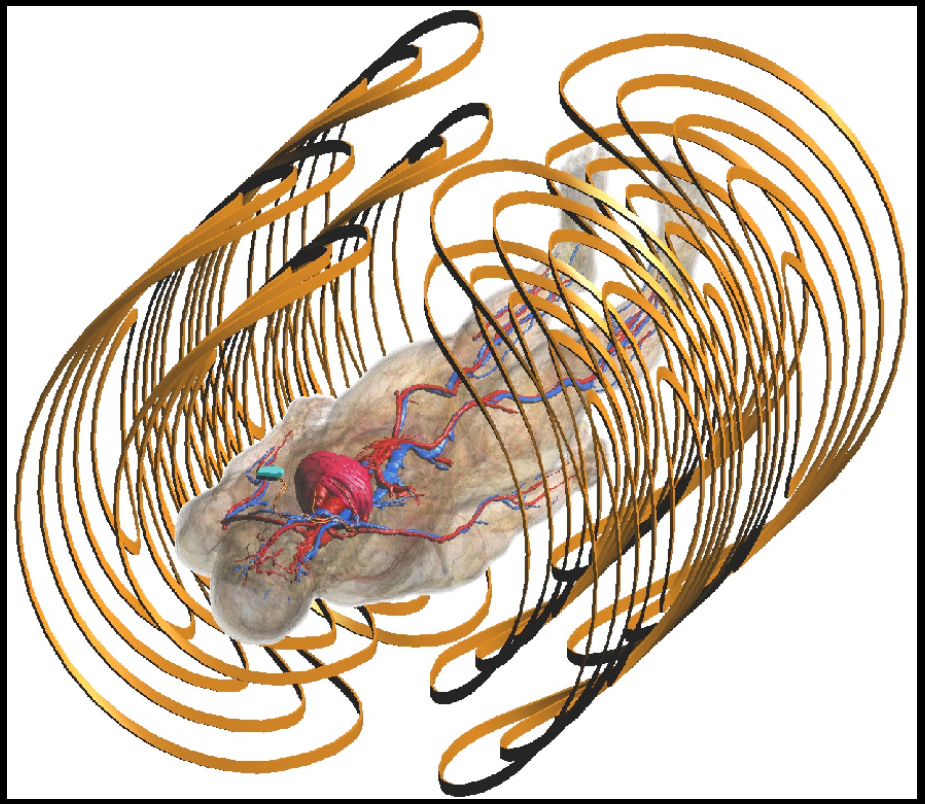


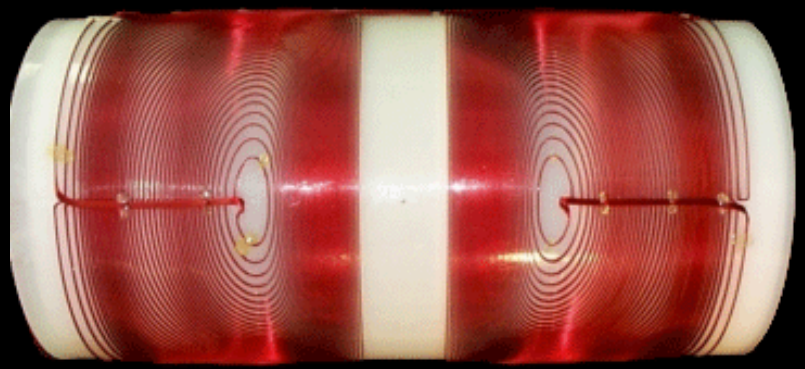
Gradient Hardware



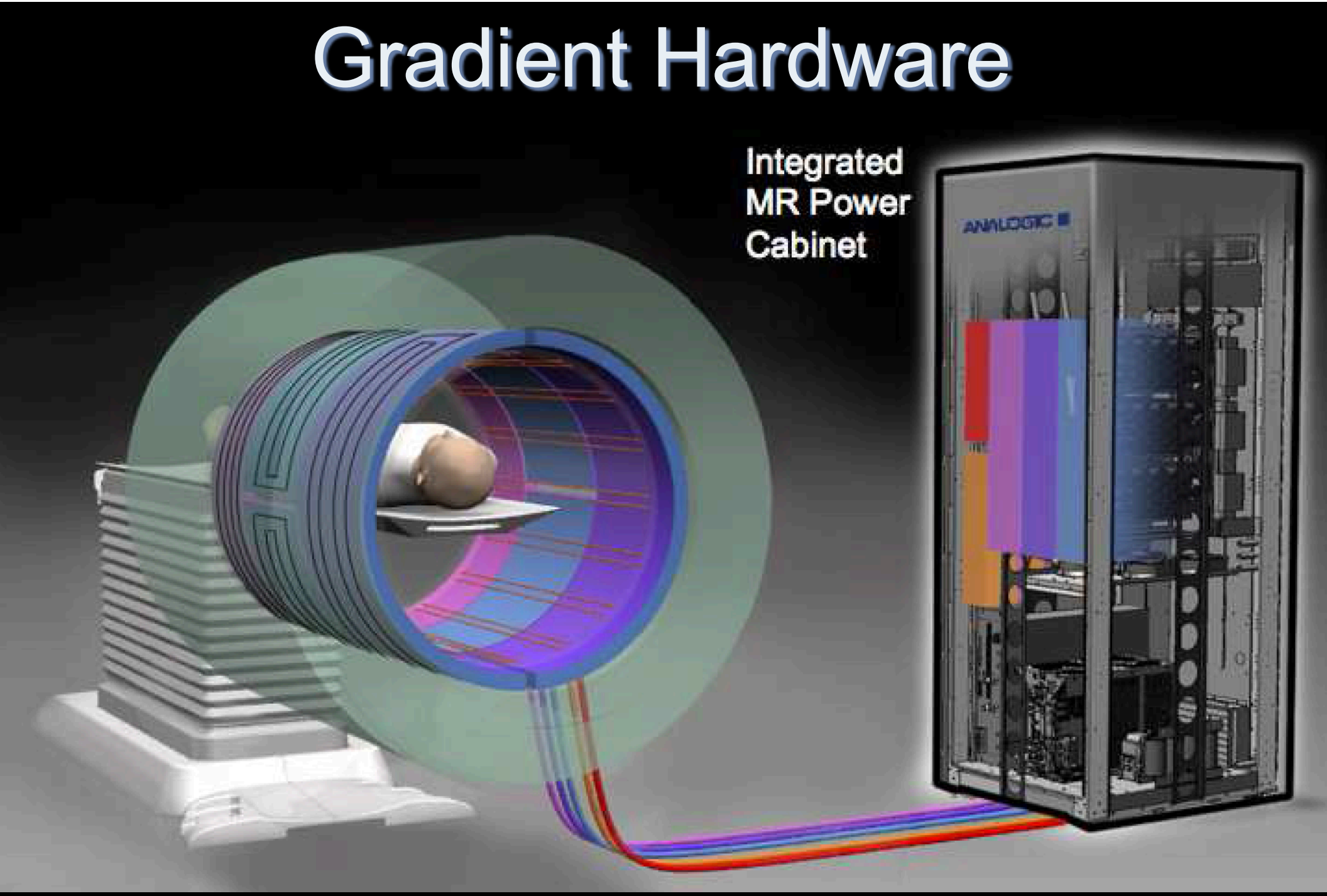


Gradient Hardware





Gradient Hardware



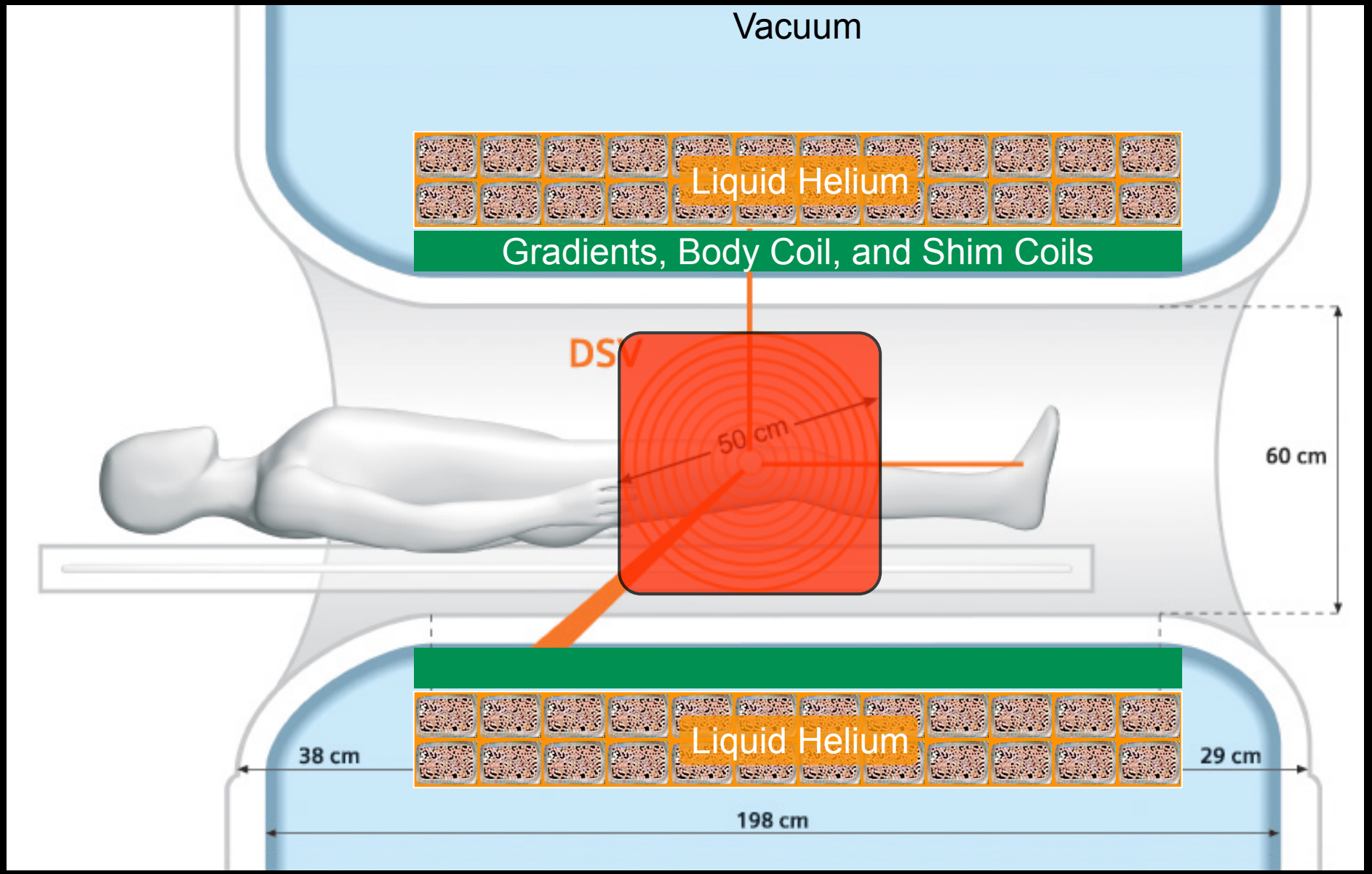
Gradients

- 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

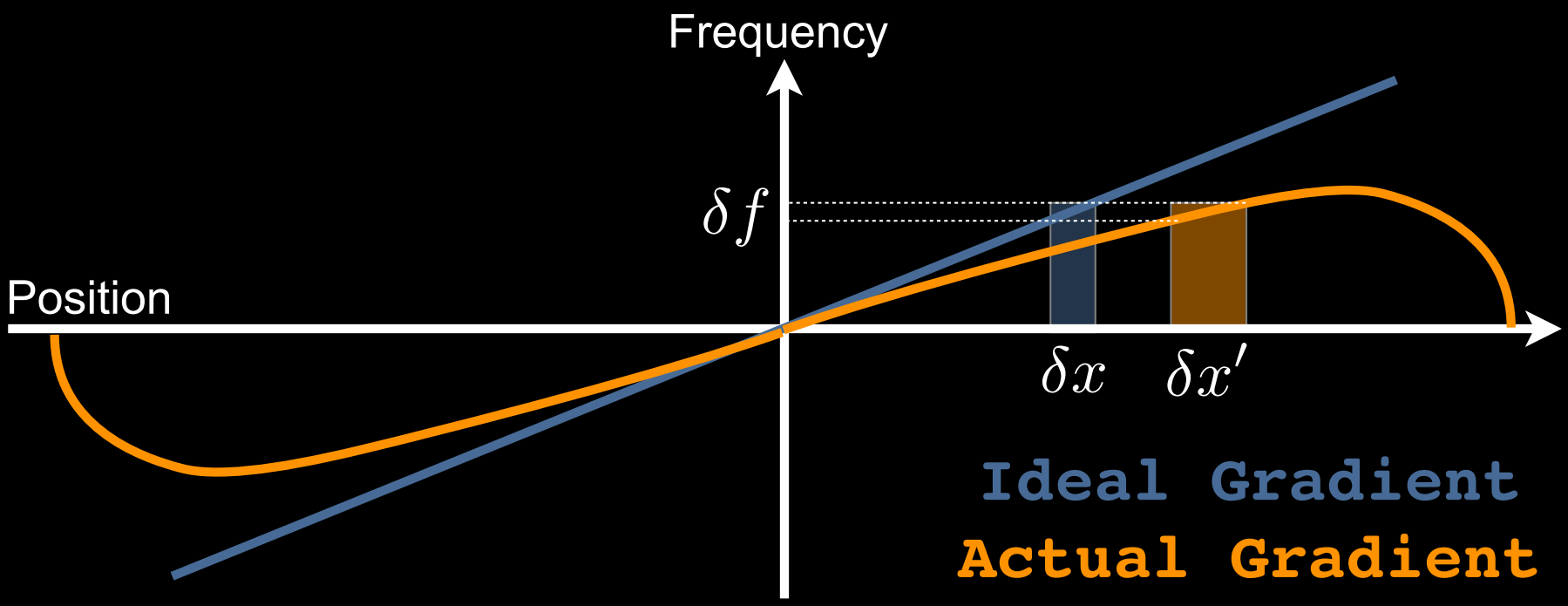
Gradients



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

Gradient Non-linearity

Gradient Non-linearity

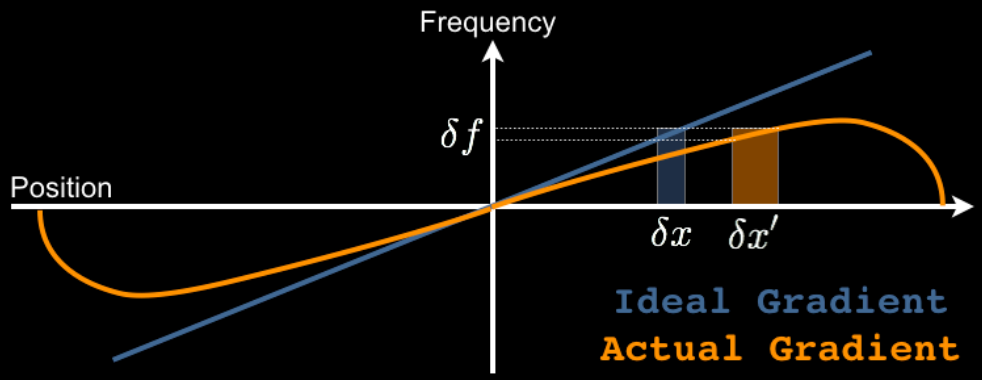


Ideally spatial position is linearly related to frequency.

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



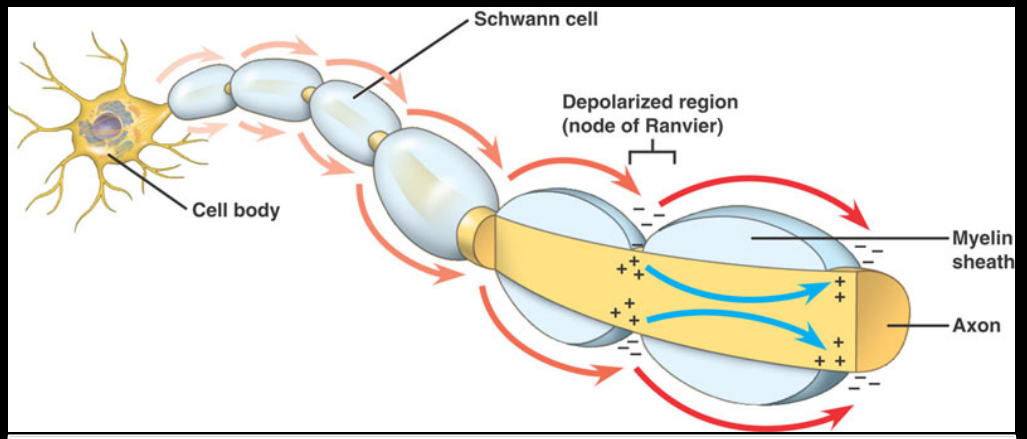
Solution

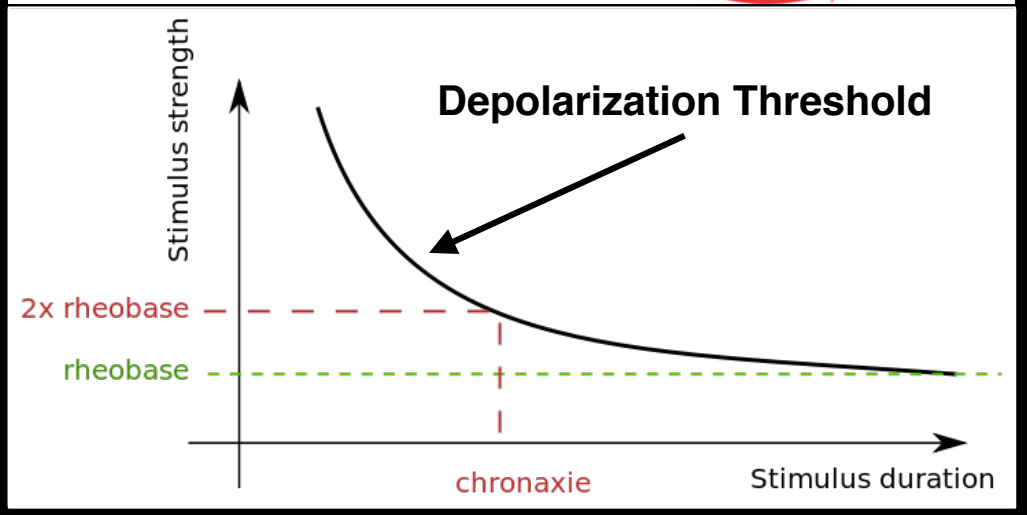
- Improve hardware and linearity!
- Pay attention to FOV!
- Image warping parameters that are system specific and applied to all images.
  - Works well qualitatively.
  - Can be problematic quantitatively.

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

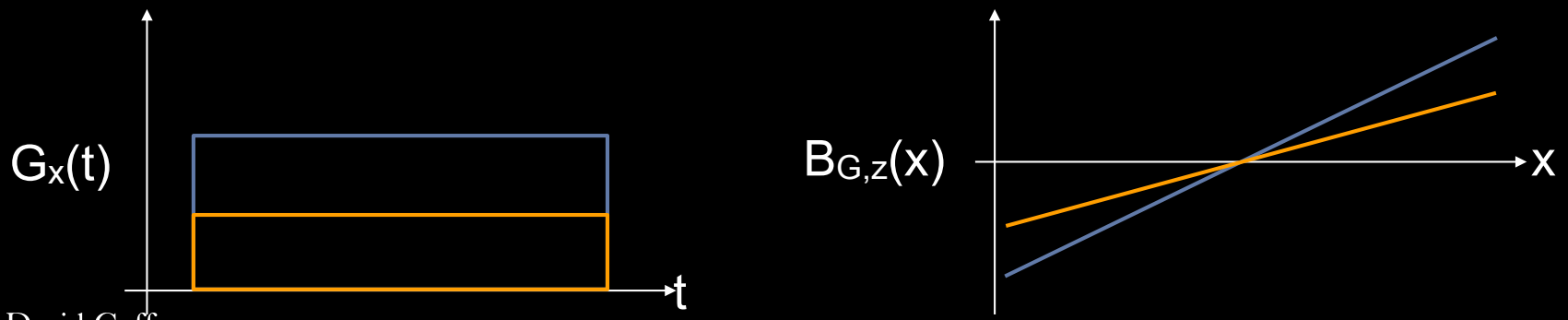
Switching the gradients on ms time scales (kHz) generates acoustic noise.

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

Gradient Safety – G_{Max}

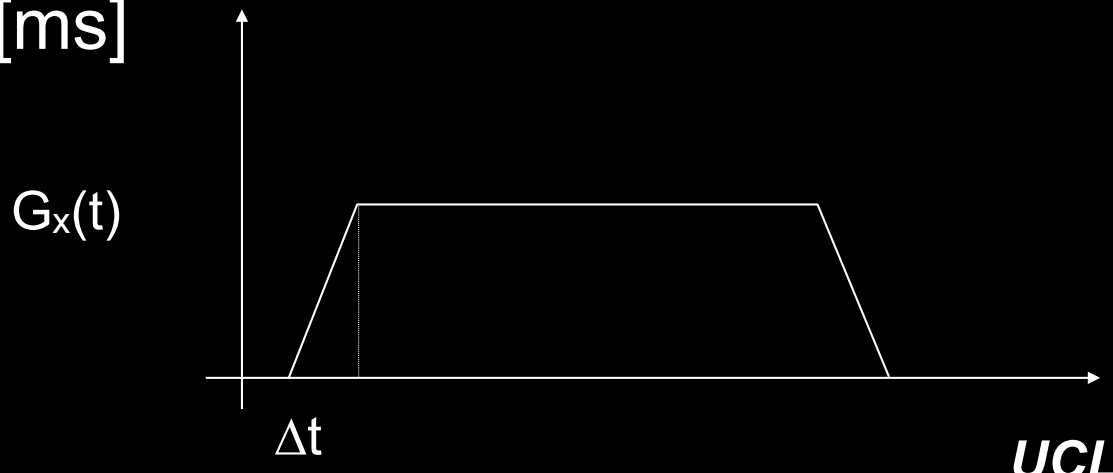
- **G_{max} limitations:**
  - Concern: None known.
    - B_0 is already pretty big.
  - Conventional Gradients
    - G_{Max} = 4 to 5G/cm (=50mT/m)
  - Cutting Edge Gradients
    - G_{Max} = 8G/cm (=80mT/m)
  - Connectome Gradients
    - G_{Max} = 30G/cm (=300mT/m)
  - Consider the ΔB contributed by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



http://www.aapm.org/meetings/02AM/pdf/8356-48054.pdf

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

Kyung Sung, Ph.D.
KSung@mednet.ucla.edu
http://mrrl.ucla.edu/sunglab