Al-Mustaqbal University

Biomedical Engineering Department

Class: 5th

Subject: Biomedical Instrumentation Design II

Lecturer: Mr. Mahir Rahman Al-Hajaj

1st term – Lect. 5: Gradient Functions

Email: mahir.rahman@uomus.edu.iq

MRI Design: 27. Gradient Functions

- Gradients are coils that alter the magnetic field strength of the magnet in a controlled and predictable way. They add to or linearly subtract from the existing field so that the magnetic field strength at any point along the gradient is known.

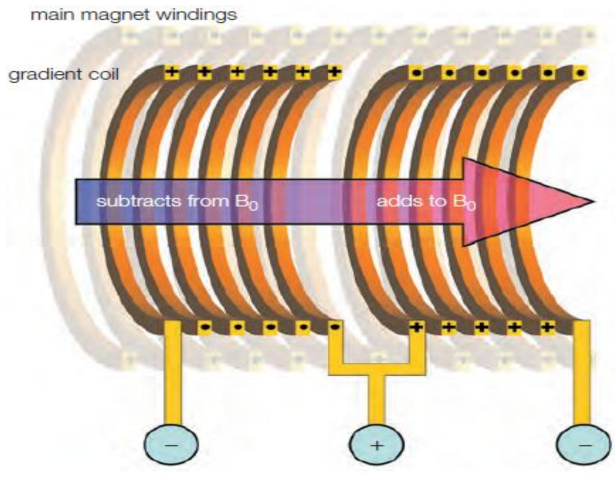
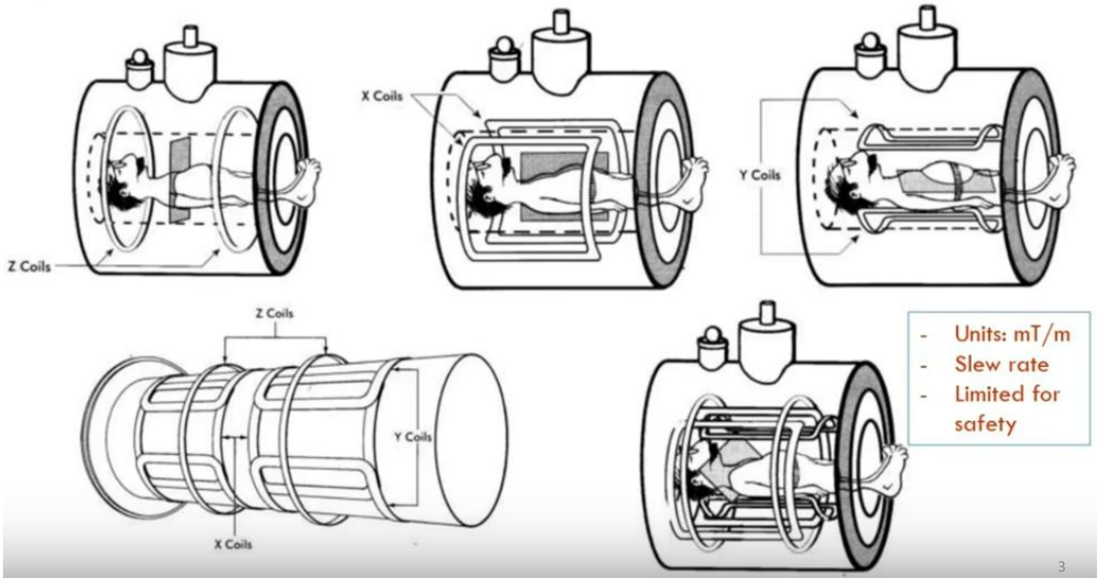


Figure 27.1 A gradient coil.

MRI Design: 27. Gradient Functions



- Units: mT/m
- Slew rate
- Limited for safety

3

MRI Design: 27. Gradient Functions

4

MRI Design: 27. Gradient Functions

- At magnetic isocentre (the centre of all three gradients), the field strength remains unchanged even when the gradient is switched on.
- At a certain distance away from isocentre, the field strength either increases or decreases.
- The magnitude of the change depends on the distance from isocentre and the strength
- The slope of the gradient signifies the rate of change of the magnetic field strength along its length.
- Larger gradient coil currents create steeper gradients, so that the change in field strength over distance is greater. The reverse is true of smaller currents.
- The polarity of the gradient determines which end of the gradient produces a higher field strength than isocentre (positive) and which a lower field strength than isocentre (negative).

MRI Design: 27. Gradient Functions

- The *polarity* of the gradient is determined by the *direction of the current* flowing through the coil. As coils are circular, current either flows clockwise or anticlockwise.
- The *maximum amplitude* of the gradient determines the maximum achievable resolution. Therefore, if at least one (and sometimes all three) gradients are steep, small voxels are achieved.
- The maximum speeds at which gradients can be switched on and off are called the rise time and slew rate. Both of these factors determine the maximum scan speeds of a system.

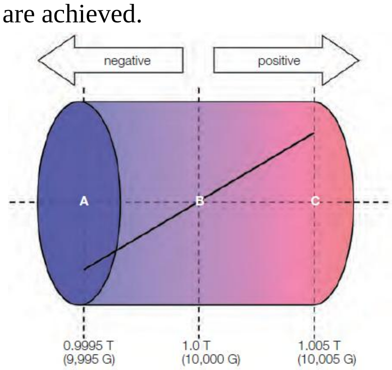


Figure 27.2 Gradients and changing field strength.

MRI Design: 27. Gradient Functions

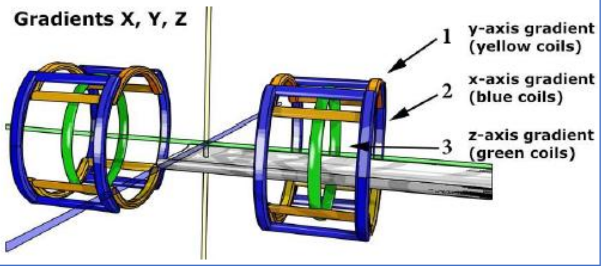
- The precessional frequency of the magnetic moments of nuclei is proportional to the magnetic field strength experienced by them (as stated by the Larmor equation).
- The frequency of signal received from the patient can be changed according to its position along the gradient.
- The precessional phase is also affected, as faster magnetic moments gain phase compared with their slower neighbours.

Table 27.1 Frequency changes along a linear gradient.

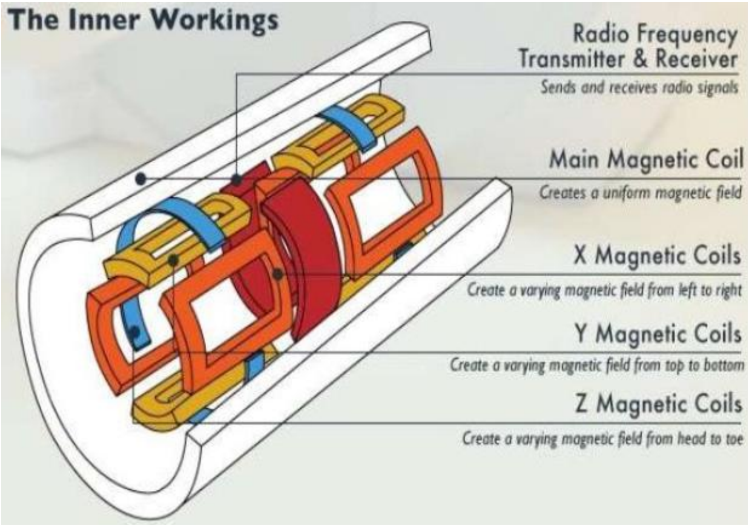
Position along gradient	Field strength (gauss)	Larmor frequency (MHz)
isocentre	10000	42.5700
1 cm negative from isocentre	9999	42.5657
2 cm negative from isocentre	9998	42.5614
1 cm positive from isocentre	10001	42.5742
2 cm positive from isocentre	10002	42.5785
10 cm negative from isocentre	9990	42.5274

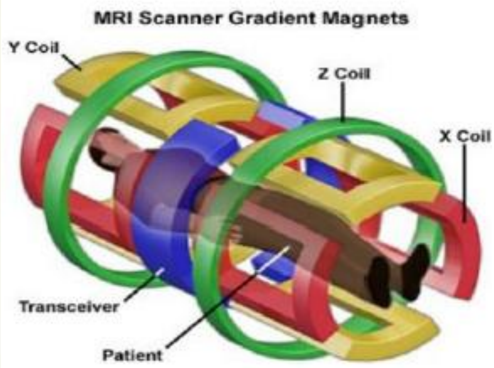
MRI Design: 27. Gradient Functions

- Three orthogonal sets of gradient coils situated within the bore of the magnet are used to **encode** the MR signal in three dimensions.
  - The *Z gradient* alters the magnetic field strength along the *Z axis.*
  - The *Y gradient* alters the magnetic field strength along the *Y axis.*
  - The *X gradient* alters the magnetic field strength along the *X axis.*
- The **magnetic isocentre** is the centre of all three gradients.



MRI Design: 27. Gradient Functions



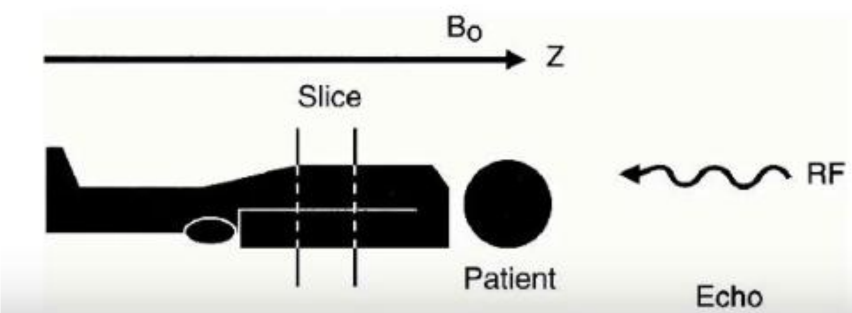


9

MRI Design: 28. Slice Selection

10

- As a gradient alters the magnetic field strength of the magnet linearly, the magnetic moments of spins within a specific slice location along the gradient have a unique precessional frequency when the gradient is on.
- Transmitting RF at that unique precessional frequency, therefore, selectively excites a slice.



MRI Design: 28. Slice Selection

- The precessional frequency of magnetic moments between slices A and B has changed by 2.6 MHz.
- To excite nuclei in slice A, an RF pulse of 41.20 MHz must be applied.

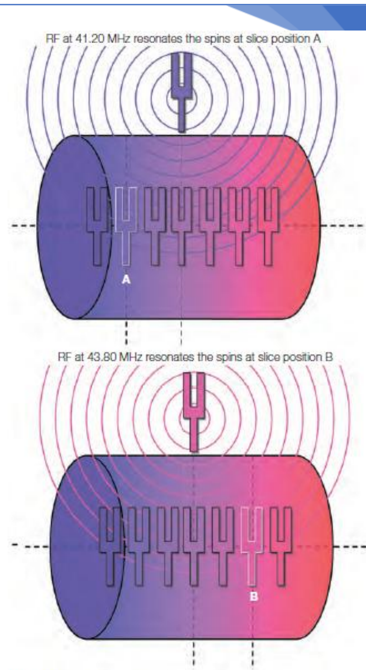
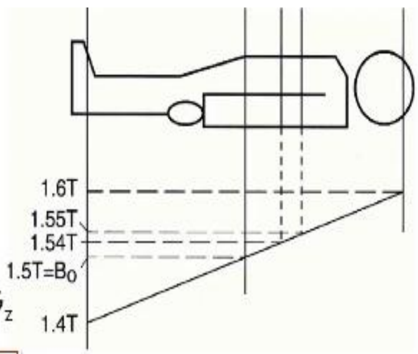


Figure 28.1 Slice selection.

MRI Design: 28. Slice Selection

- Larmor equation:

$$\omega_o = \gamma B_0$$



- Larmor equation with gradient G_z

$$\omega_o(z) = \gamma(B_0 + G_z \cdot z)$$

  - Larmor frequency depends on location
  - Send RF pulse with desired frequency range to excite a slice !

MRI Design: 28. Slice Selection

- The scan plane selected determines which gradient performs slice selection.
- In a superconducting system the following usually apply:

  - The Z gradient selects axial slices, so that nuclei in the patient's head spin at a different frequency to those in the feet.
  - The Y gradient selects coronal slices, so that nuclei at the back of the patient spin at a different frequency to those at the front.
  - The X gradient selects sagittal slices, so that nuclei on the righthand side of the patient spin at a different frequency to those on the left.

- A combination of any two gradients selects oblique slices.

MRI Design: 28. Slice Selection

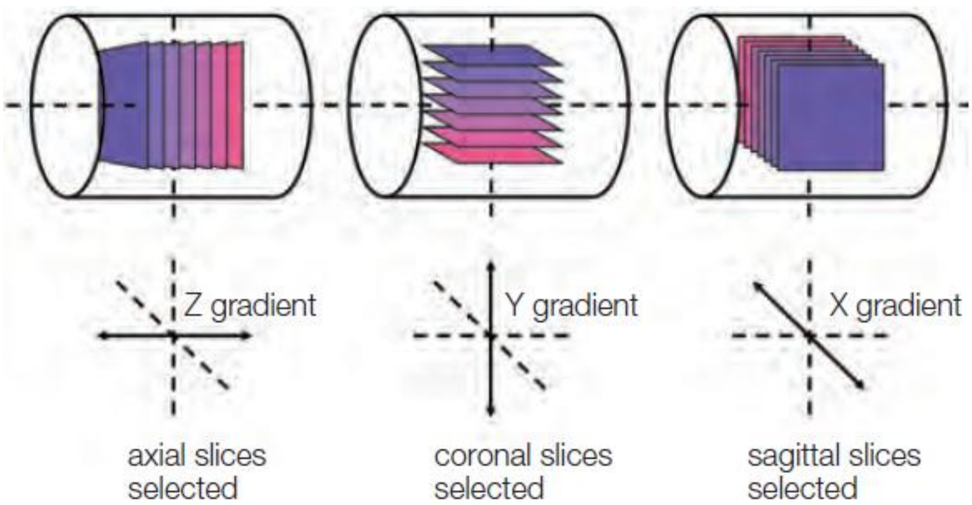
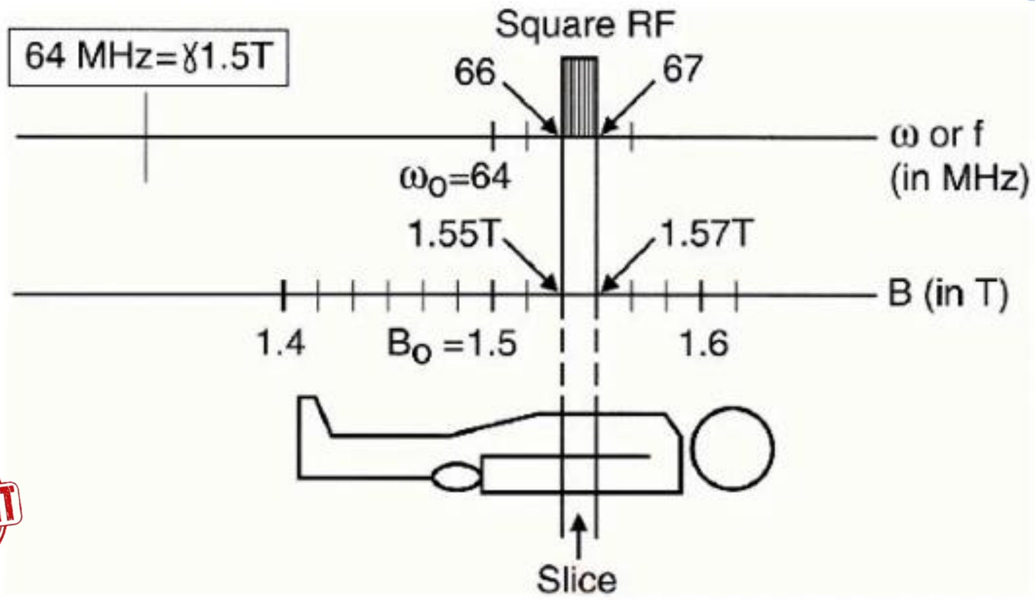


Figure 28.2 Using X, Y and Z gradients to select slices.

MRI Design: 28. Slice Selection

15



MRI Design: 28. Slice Selection

16

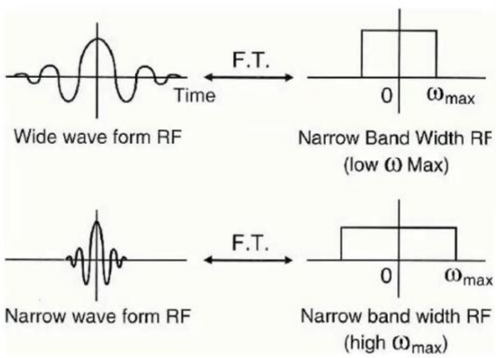
- In order to attain ***slice thickness***, a range of frequencies must be transmitted to produce resonance across the whole slice (and therefore to excite the whole slice).
- A bandwidth of RF is transmitted, and called the transmit bandwidth.
- The slice thickness is determined by the slope of the slice select gradient and the transmit bandwidth.
  - Thin slices require a steep slope or a narrow transmit bandwidth, and improve spatial resolution.
  - Thick slices require a shallow slope or a broad transmit bandwidth, and decrease spatial resolution.
- The slice gap or skip is the space between slices. Too small a gap in relation to the slice thickness can lead to an artefact called **cross-talk**.

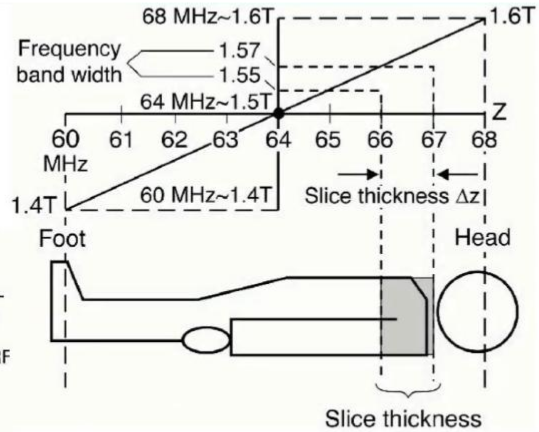
IMPORTANT

MRI Design: 28. Slice Selection

17

- Slice definition
  - Slice location
  - Slice thickness
  - Slice profile





MRI Design: 28. Slice Selection

18

- The slice select gradient is always switched on during the delivery of the RF excitation pulse in the pulse sequence. It is switched on in the positive direction.
- The slice select gradient is also applied during the 180° pulse in spin echo sequences so that the RF rephasing pulse can be delivered specifically to the selected slice.

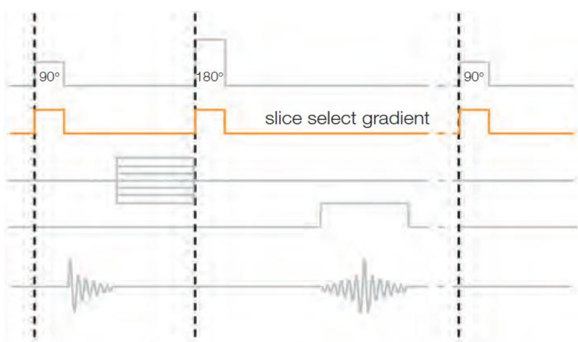


Figure 28.4 Timing of slice selection in a spin-echo pulse sequence.

MRI Design: 50. Contrast Agents

- In order to increase the contrast between pathology and normal tissue, enhancement agents may be introduced that selectively affect the T1 and T2 relaxation times in tissues.
- Both T1 recovery and T2 decay are influenced by the magnetic field experienced locally within the nucleus.
- The local magnetic field responsible for these processes is caused by:
- • the main magnetic field;
- • fluctuations as a result of the magnetic moments of nuclear spins in neighbouring molecules.

MRI Design: 50. Contrast Agents

- These molecules rotate or tumble, and the rate of rotation of the molecules is a characteristic property of the solution. It is dependent on:
- magnetic field strength;
- viscosity of the solution;
- temperature of the solution

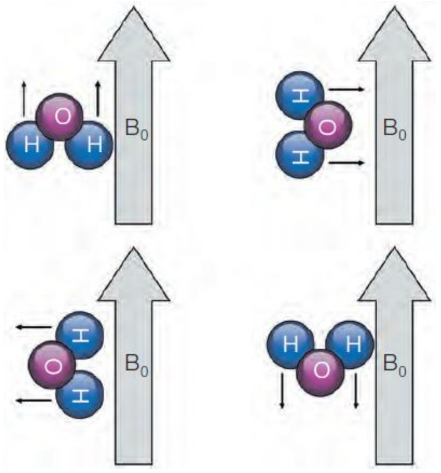


Figure 50.1 Tumbling of water molecules.

MRI Design: 50. Contrast Agents

- The excited protons are affected by nearby excited protons and electrons (dipole-dipole interaction).
- If a tumbling molecule with a large magnetic moment, such as gadolinium, is placed in the presence of water protons, local magnetic field fluctuations occur near the Larmor frequency.
- T1 relaxation times of nearby protons are therefore reduced, and so they appear bright on a T1-weighted image.
- This effect on a substance whereby relaxation rates are altered is known as relaxivity.

MRI Design: 50. Contrast Agents

- Gadolinium (Gd) is a paramagnetic agent that has a large magnetic moment, and when it is placed in the presence of tumbling water protons, fluctuations in the local magnetic field are created near the Larmor frequency.
- The T1 relaxation times of nearby water protons are therefore reduced, resulting in an increased signal intensity on T1-weighted images.
- Thus, Gadolinium is known as a T1 enhancement agent.
- Clinical indications for gadolinium include: • tumurs; • infection; • arthrography; • post-operation lumbar disc; • breast disease; • vessel patency and morphology.

MRI Design: 50. Contrast Agents

23

- Iron oxides shorten the relaxation times of nearby hydrogen atoms and, therefore, reduce the signal intensity in normal tissues.
- This results in a signal loss on proton density-weighted or heavily T2-weighted images. Super-paramagnetic iron oxides are known as T2 enhancement agents.
- Iron oxide is taken up by the reticuloendothelial system and excreted by the liver so that the normal liver is dark and liver lesions are bright on T2-weighted images.

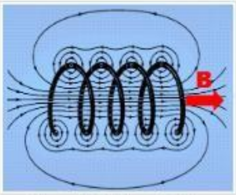
MRI DESIGN: Magnets

› MR scanners are broadly classified into closed- and open-bore systems.

› Over 90% of scanners worldwide are of the closed-bore cylindrical design and generate their fields by passing current through a solenoid kept at superconducting temperatures. The coils are bathed in liquid helium allowing a stable, homogeneous field to be created, typically 1T and higher.

› Open bore magnets contain an air gap between two magnetic poles. These may utilize permanent magnets or electromagnets

GE Signa 1.5T superconducting scanner



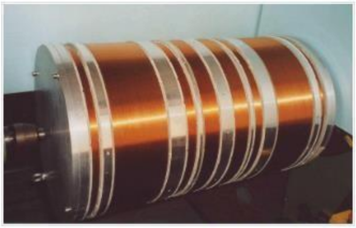
Magnetic field created by solenoid

MRI DESIGN: Magnets

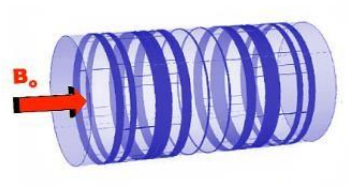
› The homogeneity problem is solved by breaking up the main coil into 6-10 separate windings with gaps in between as shown below.

› This configuration maintains symmetry of the field along the z-axis (B_0 direction), minimizes fringe fields at the ends of the scanner, and improves homogeneity centrally.

› There are, as expected, some minor fluctuations in field strength along the z-axis, with minimally higher fields directly under the bands and minimally lower fields within the gaps.



Solenoidal superconducting magnet under construction before being placed in cryostat.



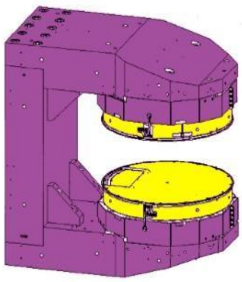
Rather than a single large/continuous winding, 6-10 large and small solenoidal bands are typically placed to create a more uniform central field with minimized fringe.

MRI DESIGN: Magnets

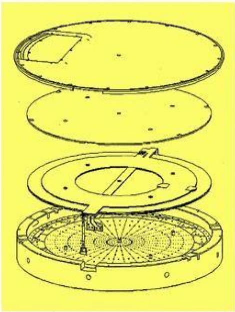
› Open-bore scanners utilize permanent magnets in a C-shaped or horseshoe configuration.

› These operate at field strengths typically ranging from 0.064T to 1.0T.

› Field generation is created by a pair of magnets located at the ends of the yoke on both sides of the air gap.



C-shaped open magnet scanner showing iron yoke (magenta) with pole pieces (yellow).



Exploded view of pole piece showing an array of neodymium-boron-iron magnetic blocks.

Closed	Open
Widely available	Quieter
Can diagnose more problems	Suits larger people
Scan may be quicker	Suits those with mobility issues
Higher-quality imaging	Child-friendly
Can scan all areas of a body	Less anxiety and claustrophobia
	Fewer image artifacts

MRI DESIGN: Magnets

› Magnetic Field Homogeneity

› Homogeneity refers to the uniformity of a magnetic field in the center of a scanner when no patient is present.

› Magnetic field homogeneity is measured in parts per million (ppm) over a certain diameter of spherical volume (DSV).

› For example, a 3.0T magnet may be guaranteed to have homogeneity of <1 ppm over a 40 cm DSV.

› This means that no two points within ± 20 cm of the magnet isocenter differ in magnetic field strength by more than one part in a million, or by no more than 3.0T x (1/1,000,000) or 0.000003T.

MRI DESIGN: Magnets

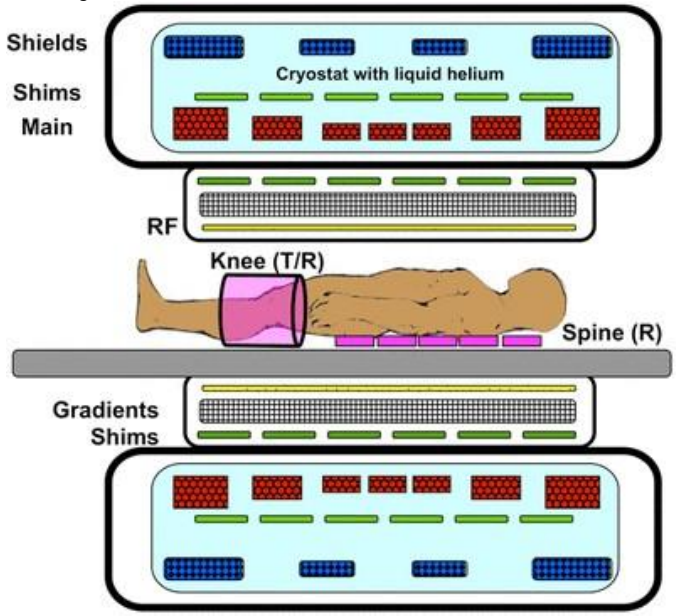
Shimming

- Even following the most rigorous manufacturing tolerances, once the magnet is sited in the imaging suite, its field will be further distorted by the presence of metal in pipes, wires, ducts, and structural beams in the immediate environment.
- Fringe fields of nearby scanners may also affect the field of the newly installed magnet.
- Shimming is the process by which the main magnetic field (Bo) is made more homogenous.
- Shimming may be passive, active, or both.

MRI DESIGN: Magnets

- **In passive shimming**, small pieces of sheet metals or ferromagnetic pellets are affixed at various locations within the scanner bore to improve homogeneity.
- **In active shimming**, currents are directed through specialized coils to further improve homogeneity by generating a "corrective" magnetic field.
- Active shim coils can be:
- 1) superconducting, located within the liquid helium-containing cryostat; or
- 2) resistive, mounted on the same support structure as the gradient coils within the room-temperature inner walls of the scanner.
- Both types of active shims require their own power supplies and are controlled by special circuitry. Some scanners use both types.

MRI DESIGN: Magnets



THANK YOU