MRI Hardware: Magnet, Gradient coils, and RF coils

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Basic hardware

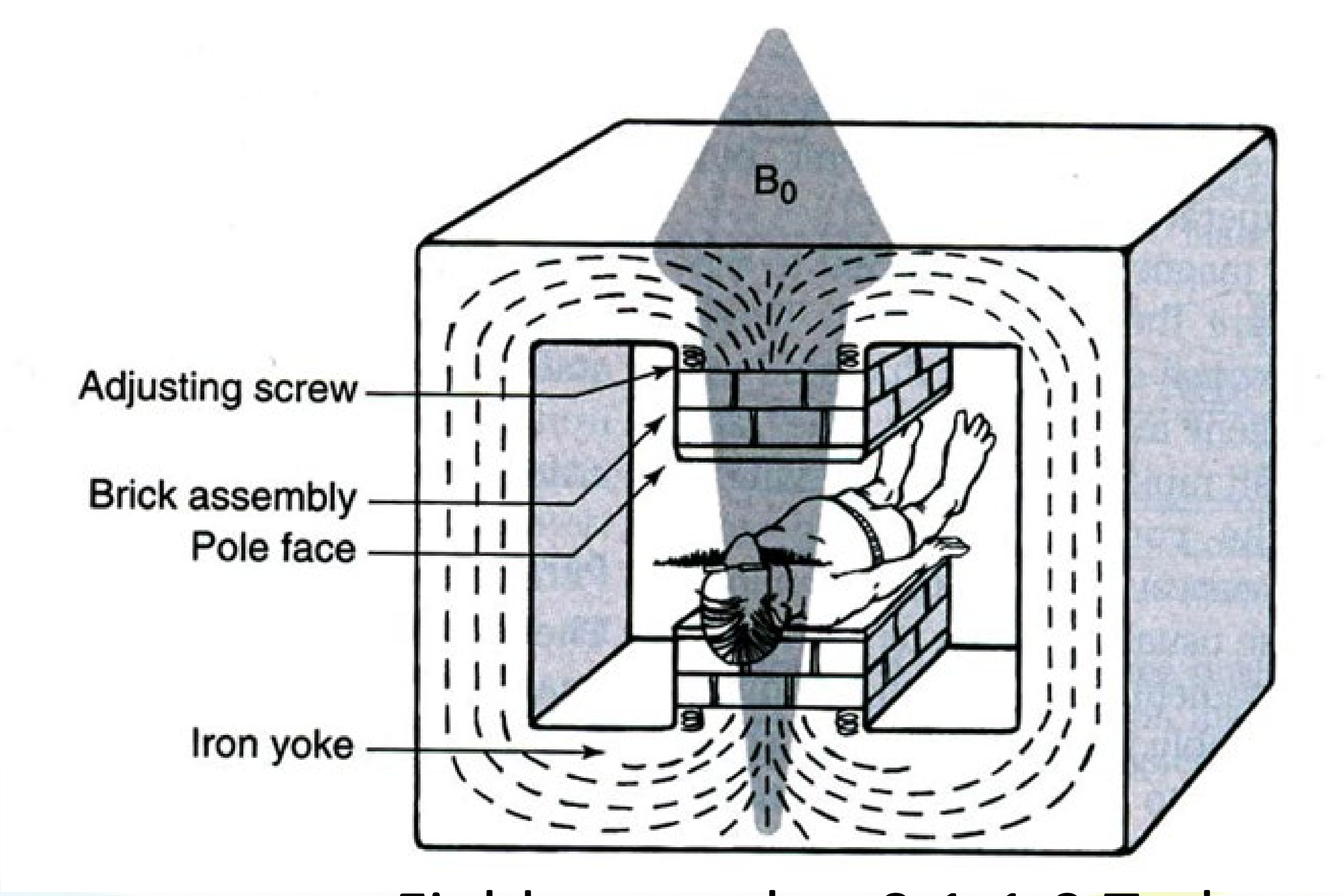
- **Magnetic**: Main magnet
- **Resonance**: RF coils
- **Imaging**: Gradient coils

Main magnet

Siemens Magnetom Lumina

- Strong enough
  - Higher B_0 brings higher signal intensity.
- Big enough
  - Suitable for human scan
- Permanent magnet? Electromagnet?

Permanent magnet



Field strength: ~0.1-1.0 Tesla

Permanent magnet: close bore

Hitachi MRP-5000 (0.2 Tesla)

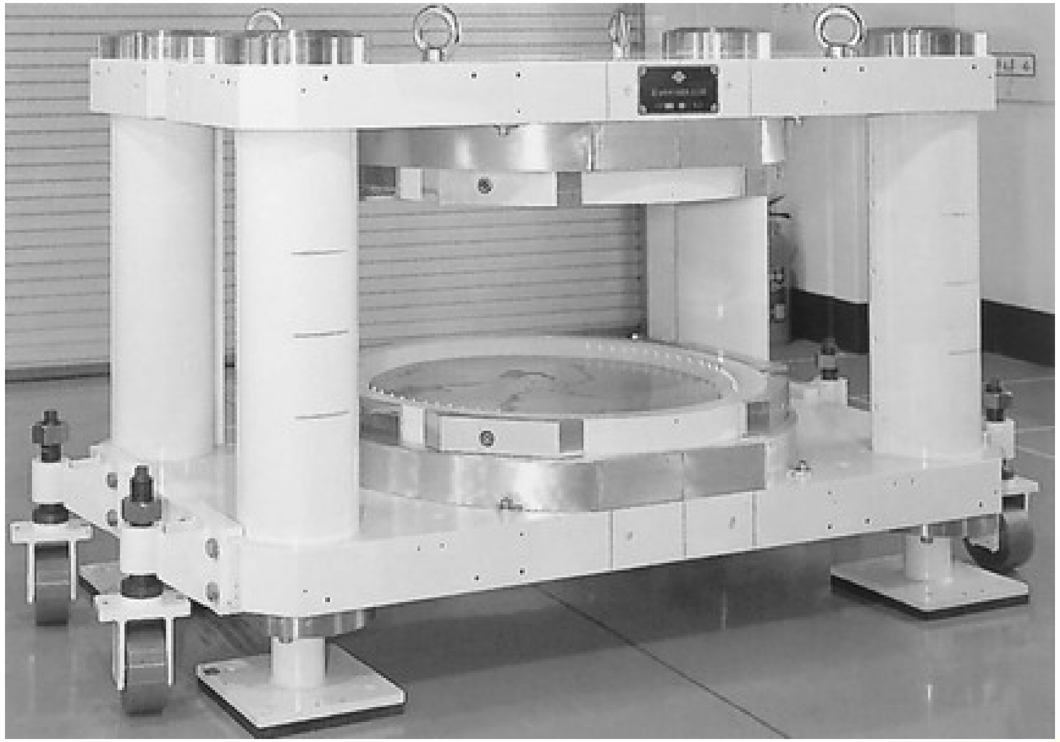
Permanent magnet: open bore

Siemens Magnetom C (0.35 Tesla)

Pros and cons

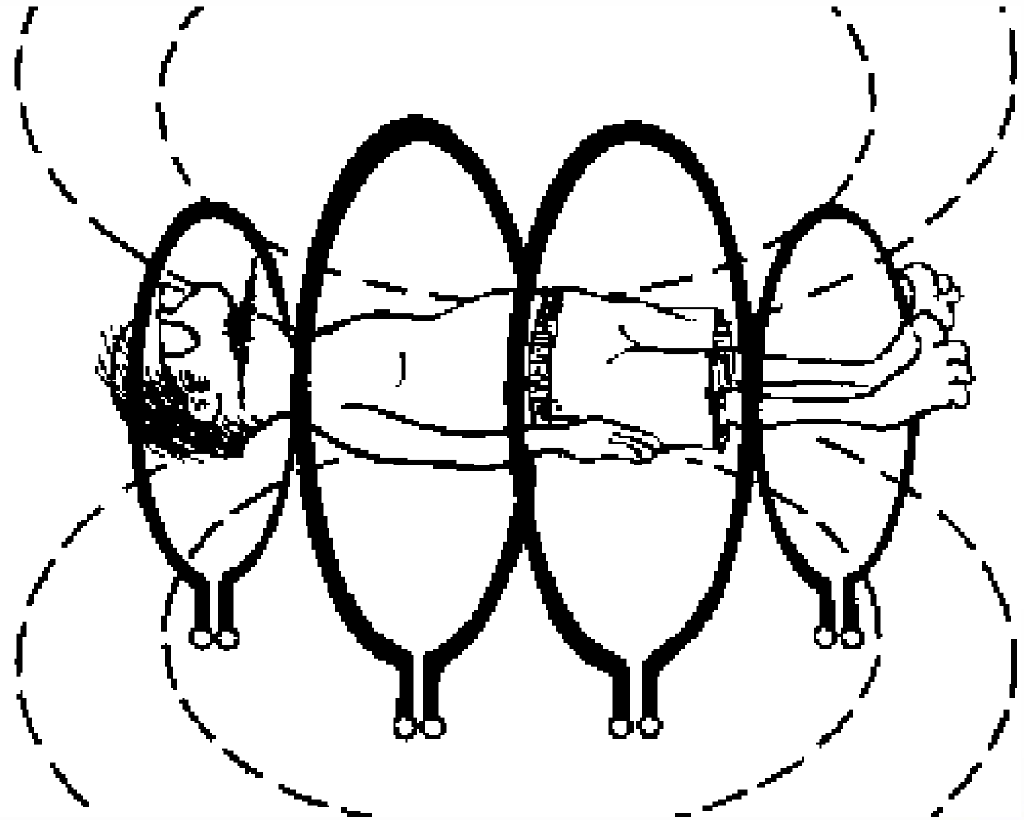
- Not driven by electricity
- Distribution of magnetic field is limited in bore.
- Very heavy! (can reaching 30 tons…)
  - Difficulty in transportation and relocation

Reducing weight for permanent magnets



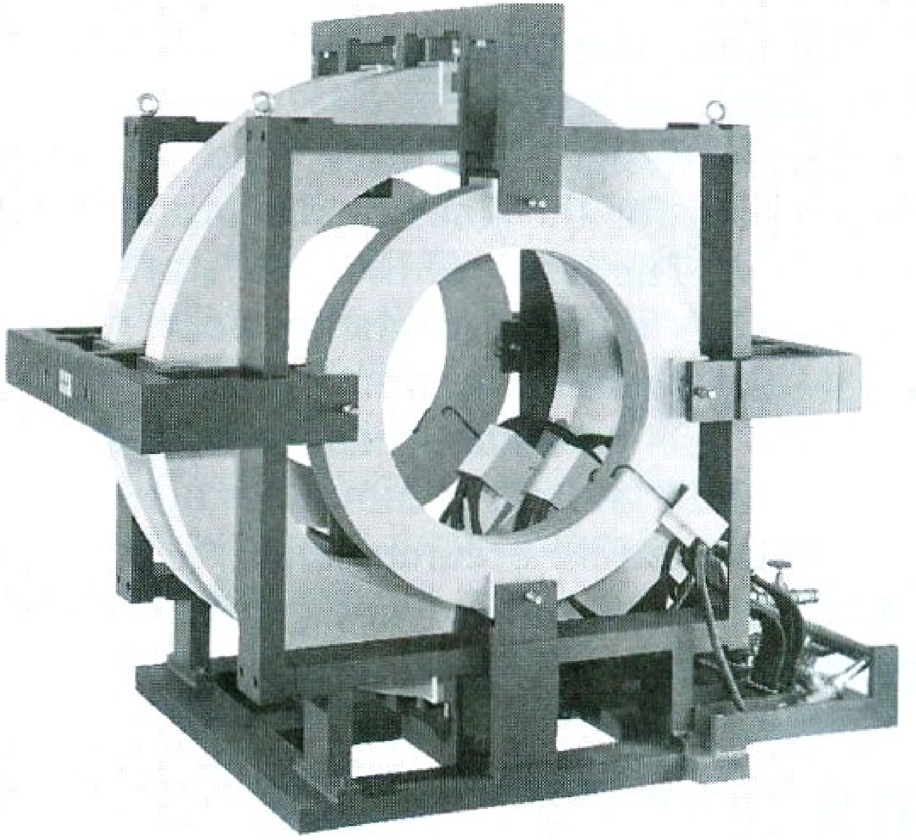
Open space MRI

Electromagnets



Maximum ~ 0.3 Tesla

Electromagnets

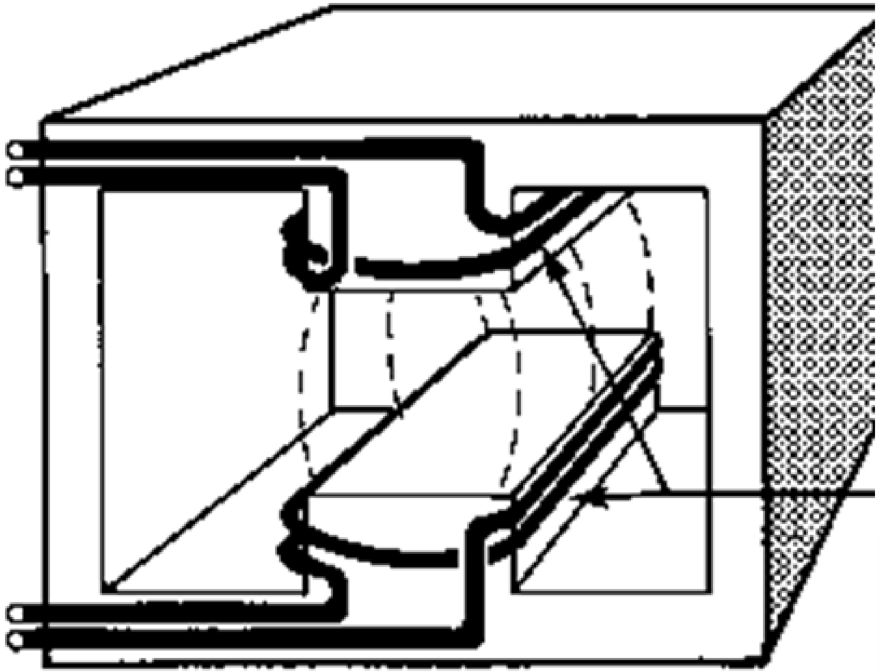


Bruker Electromagnet MRI

Pros and cons (vs permanent magnet)

- Less weight and less expensive
- Require high electricity ($$)
- Strong fringe fields
- Large current generates heat, increasing temperature and causing instability.

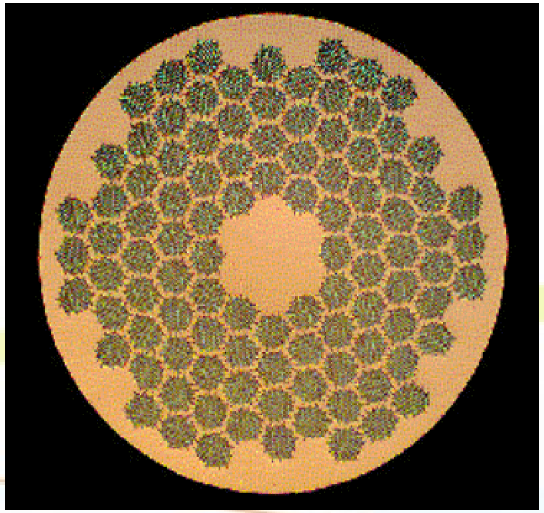
Wiring on ferromagnetic materials?



Reducing weight, but not able to increase B_0

Superconducting magnet

- An electromagnet made by superconducting materials (e.g., Nb-Ti alloy)
- Superconductivity: no electrical resistance
  - – No power dissipation!
  - – No electric supply required!
  - – No heat accumulation!

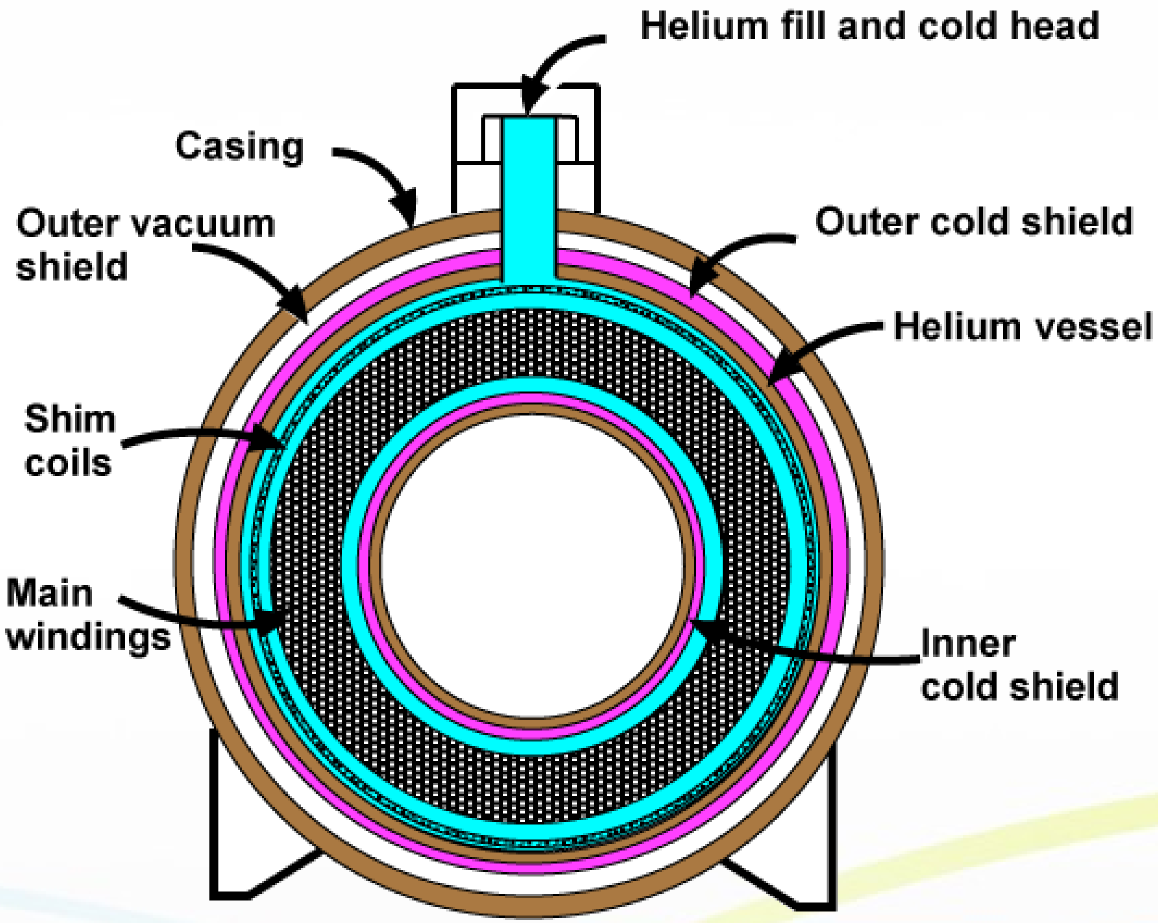


Courtesy: Questions and Answers in MRI
https://mriquestions.com/superconductive-design.html

Superconductivity

- Usually exist at very low temperature
  - Superconducting temperature for NbTi: 9.4 K
- Superconducting coils have to be bathed in liquid helium (boiling point: -269°C)
- Vacuum layer and liquid nitrogen (BP: -196°C) can be also used for heat insulation.

Superconducting magnet: cryostat

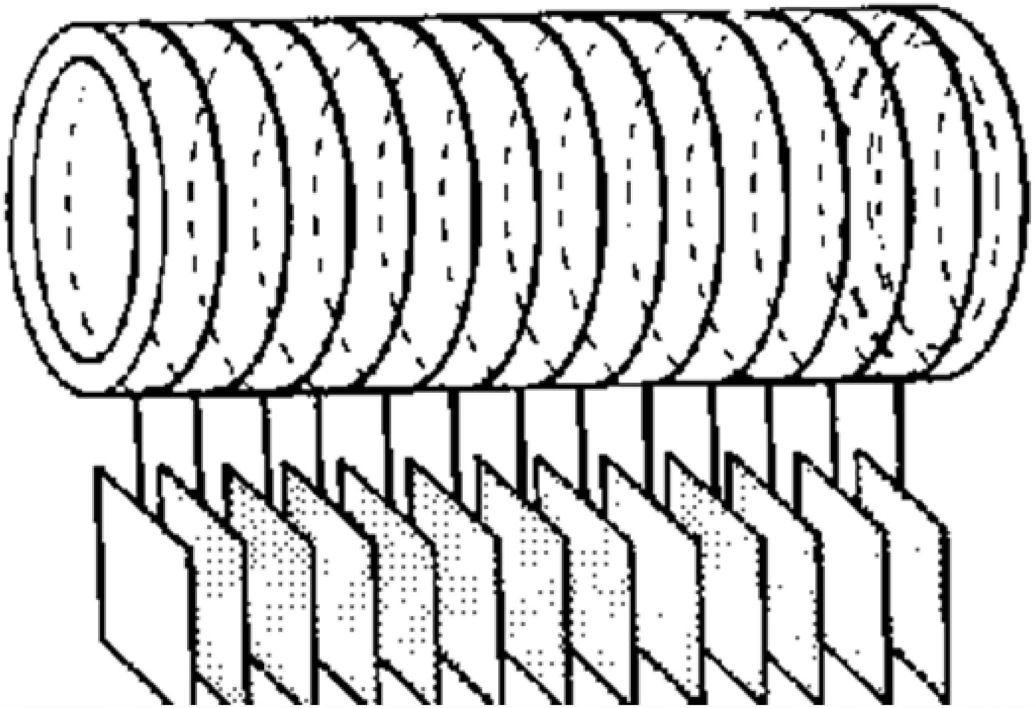


Courtesy: Questions and Answers in MRI
https://mriquestions.com/superconductive-design.html

Shimming

- Shimming is performed to improve the homogeneity of the main magnetic field (B_0).
- **Passive** shimming: small pieces of ferromagnetic metal fixed within the bore
- **Active** shimming: adjusting currents in specialized shim coils

Shim coils



Current of each shim coil element is adjusted independently

Installation of an MRI system

Courtesy: Brigham and Women‘s Hospital, Boston, MA

Superconducting magnet MRI: 1T to >11 T

GE Signa HDx 1.5 T

Courtesy: General Electric Company

Siemens Magnetom Lumina 3T

Courtesy: Siemens Healthcare

MRI with superconducting magnet

- **Strong** magnetic field (FDA approval: 7T)
- Minimal power required after installation
- Good stability
- Less weight than permanent magnet (<10 tons)
- > 90% of MRI scanners use superconducting magnet.

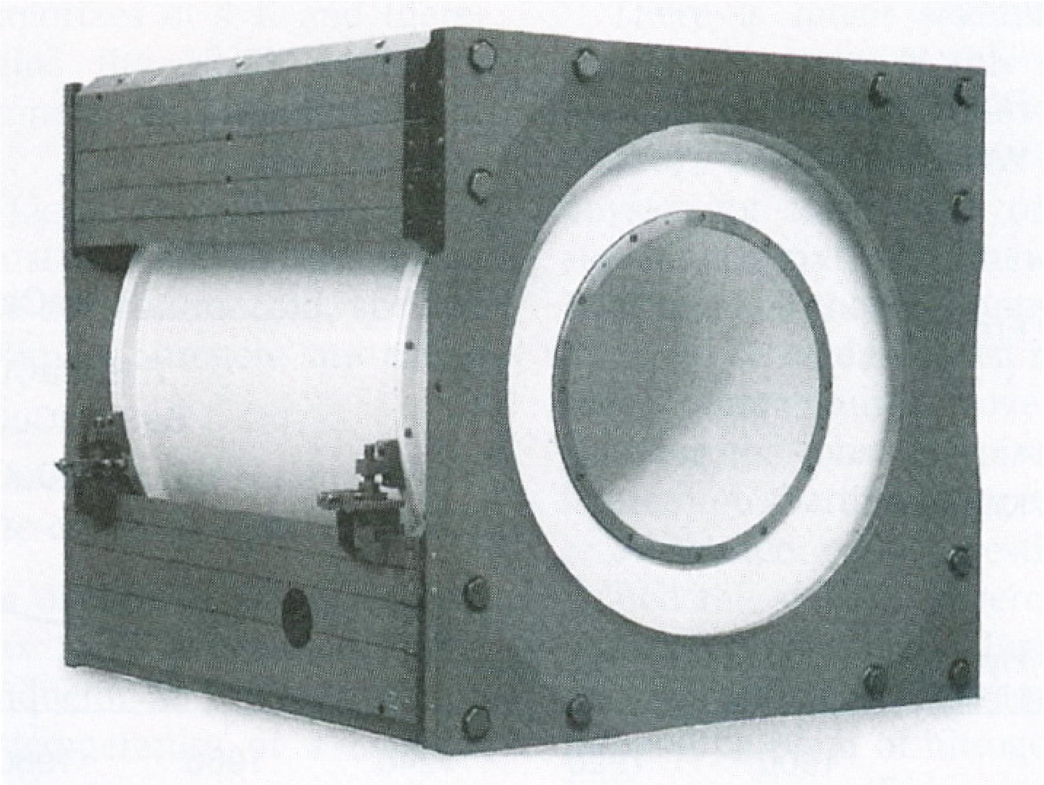
Weakness of superconducting magnet

- Strong fringe fields
- Close-bore design could induce intense fear of enclosed space.
  - Claustrophobia
- Very expensive
  - Not only the scanner, but also liquid helium

Magnetic shielding

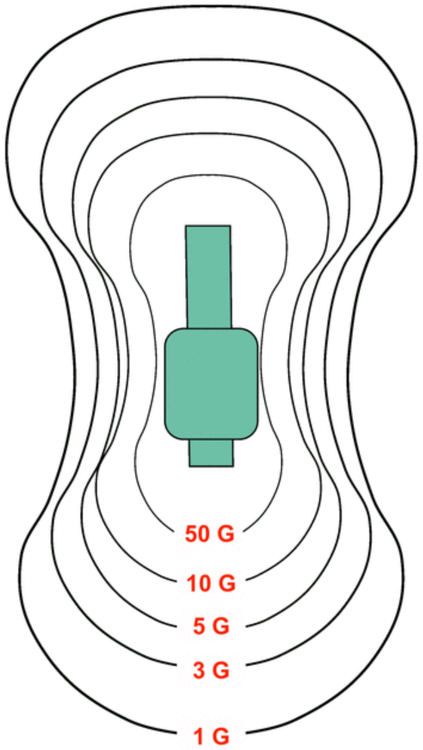
- Magnetic shielding is developed to reduce the fringe field.
- **Passive** shielding: steel panels are covered on the cryostat to concentrate magnetic flux
- **Active** shielding: additional coils are designed to cancel the external field

Passive shielding

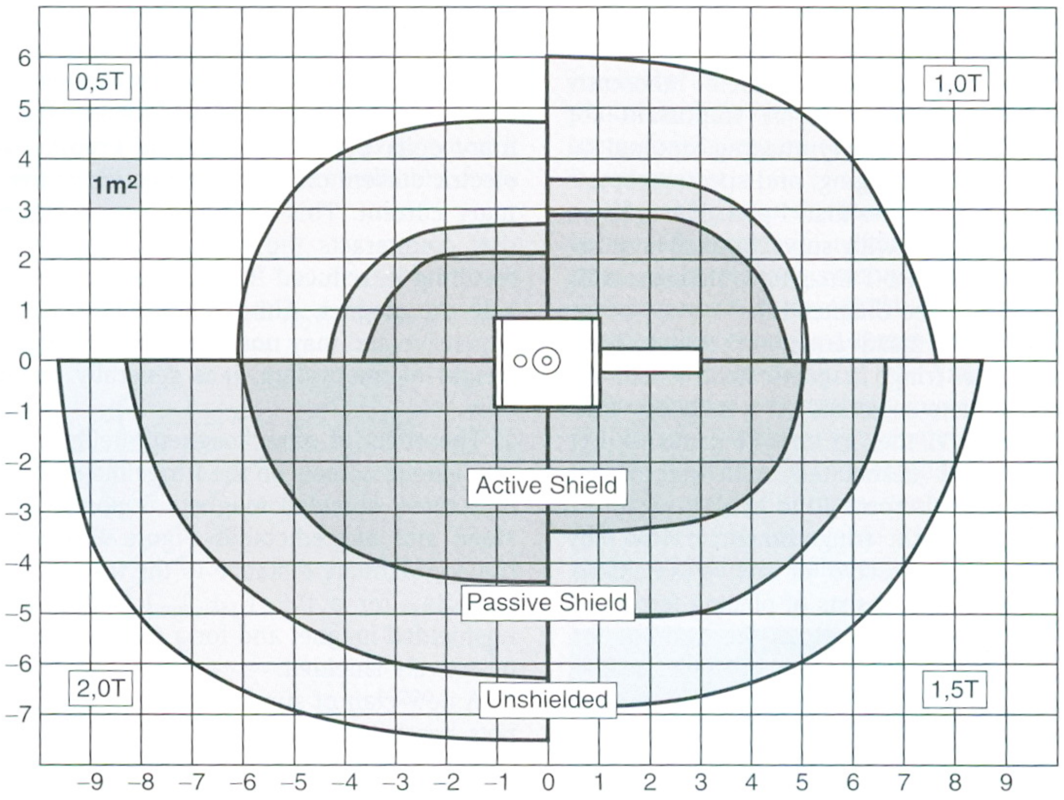


1-cm thick steel panels could reduce around half of fringe fields

The effect of magnetic shielding

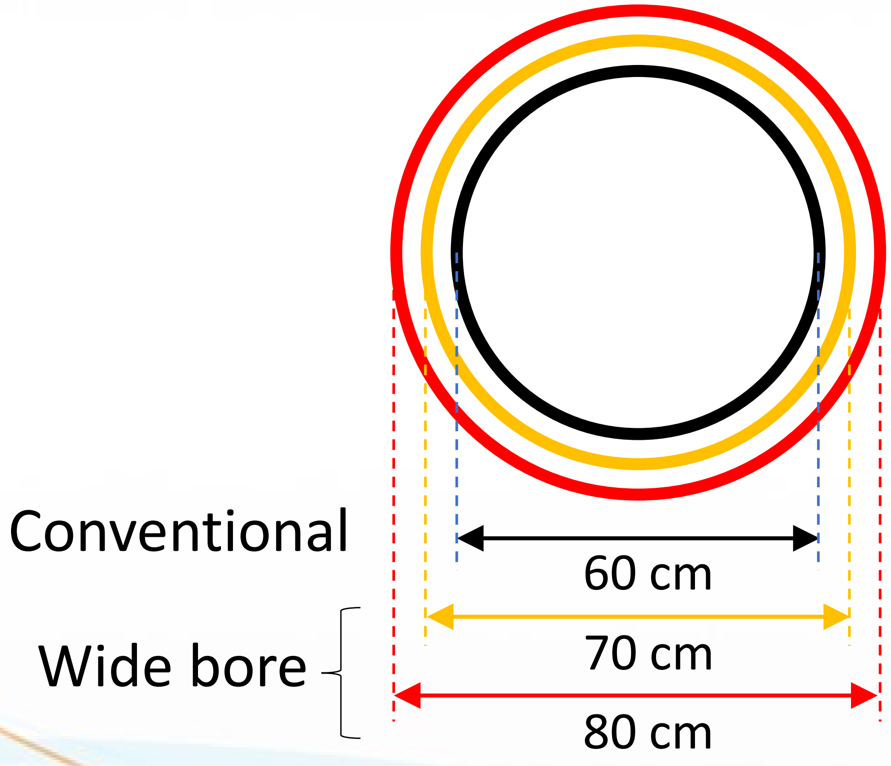


Fringe field of a 1.5T scanner



0.5-mT (5 Gauss) fringe line

Wide-bore technology



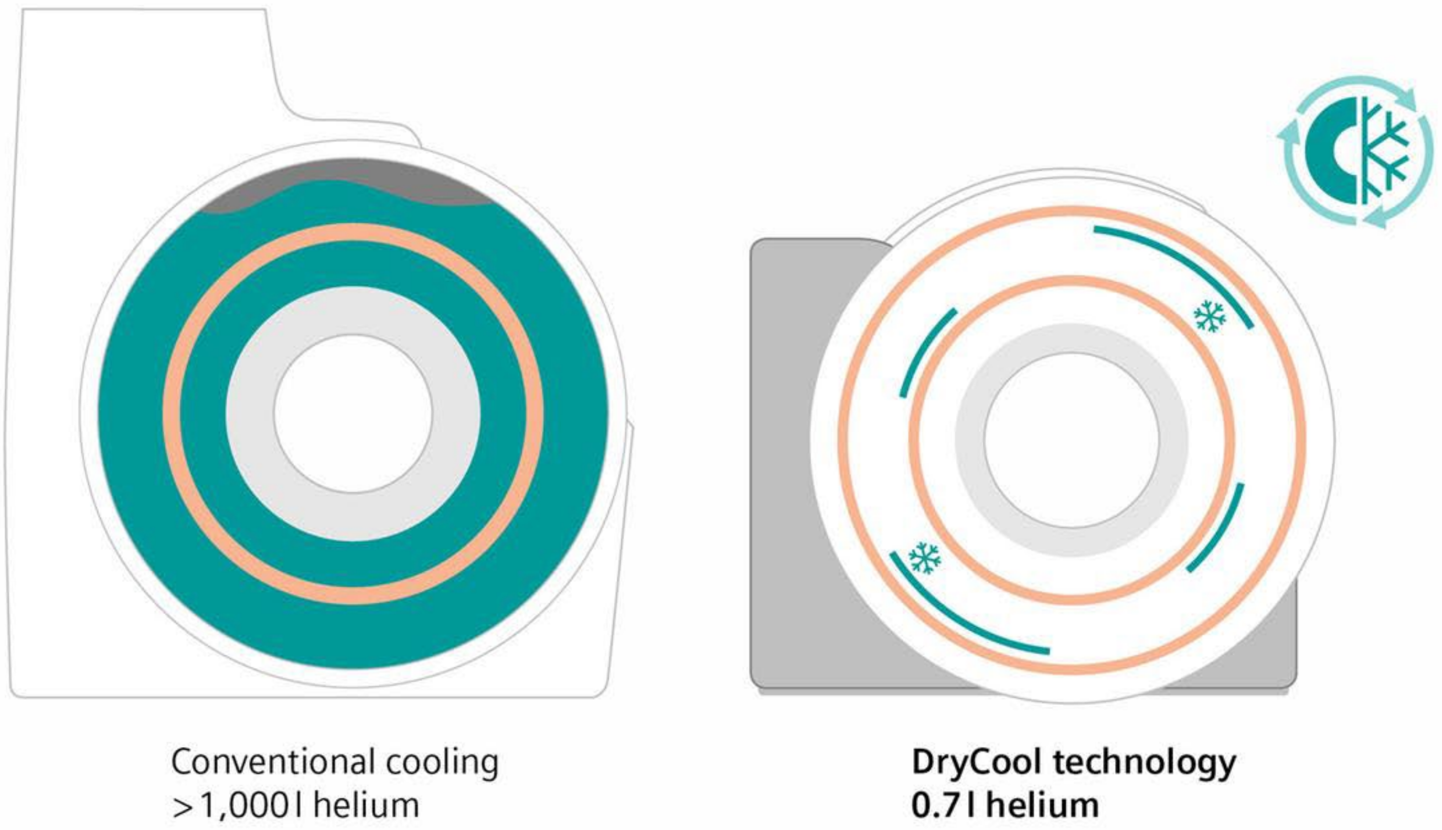
Siemens Magnetom Free.Max (0.55 Tesla)

Open-bore system (open MRI)

Siemens Magnetom C (0.35 Tesla)

ASG MROpen EVO (0.5 Tesla)

Reduced use of liquid helium



Courtesy: Siemens Healthcare

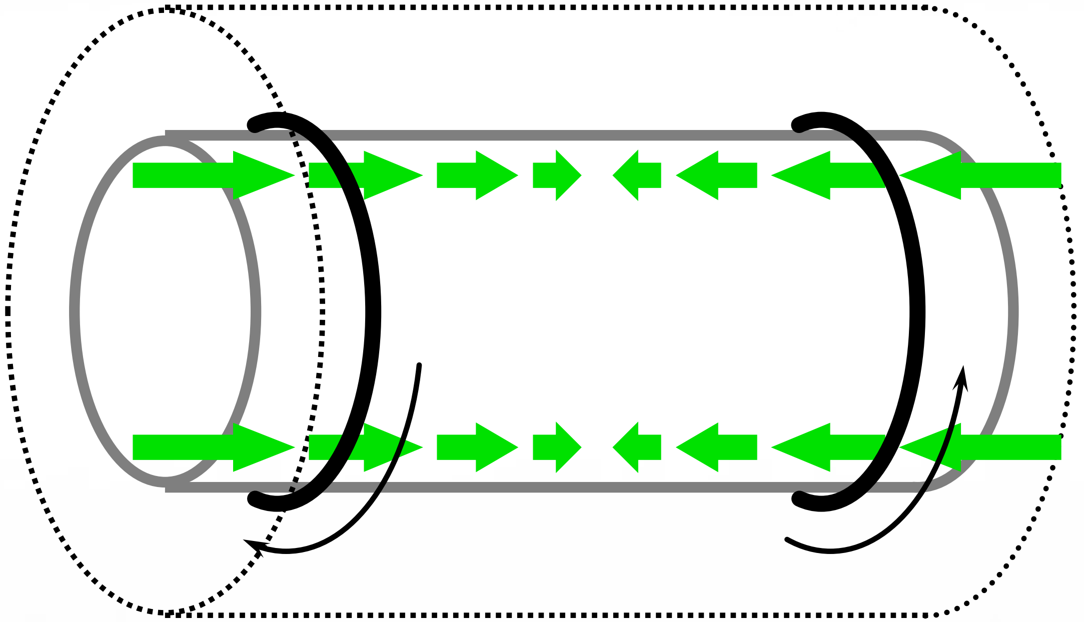
Summary: main magnet

- Superconducting magnet can produce higher magnetic field strength
  - Better SNR
  - Dominant in both clinical and research usage even though it is expensive

Gradient coils

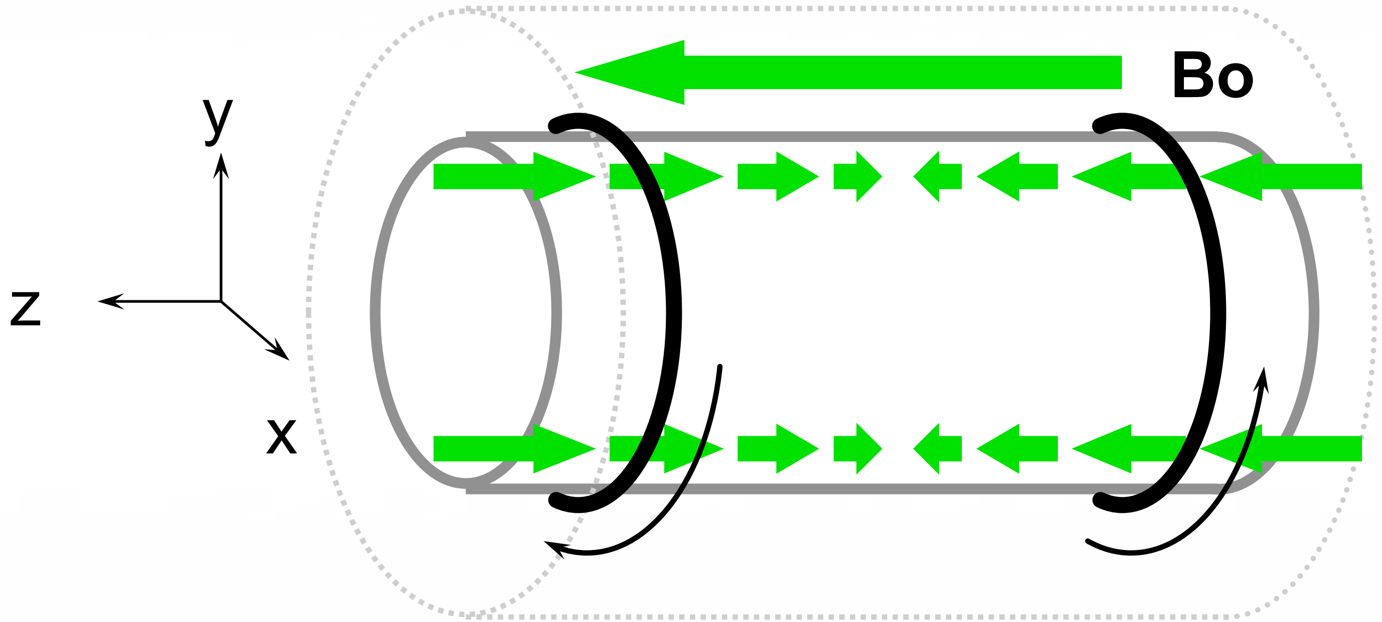
- To generate a spatial-dependent magnetic field for spatial encoding
  - Gradient: changing as a function of position
- Electromagnetic coil
- Three sets of independent gradient coils: x-, y-, and z-gradients

How to generate a spatial-dependent field?



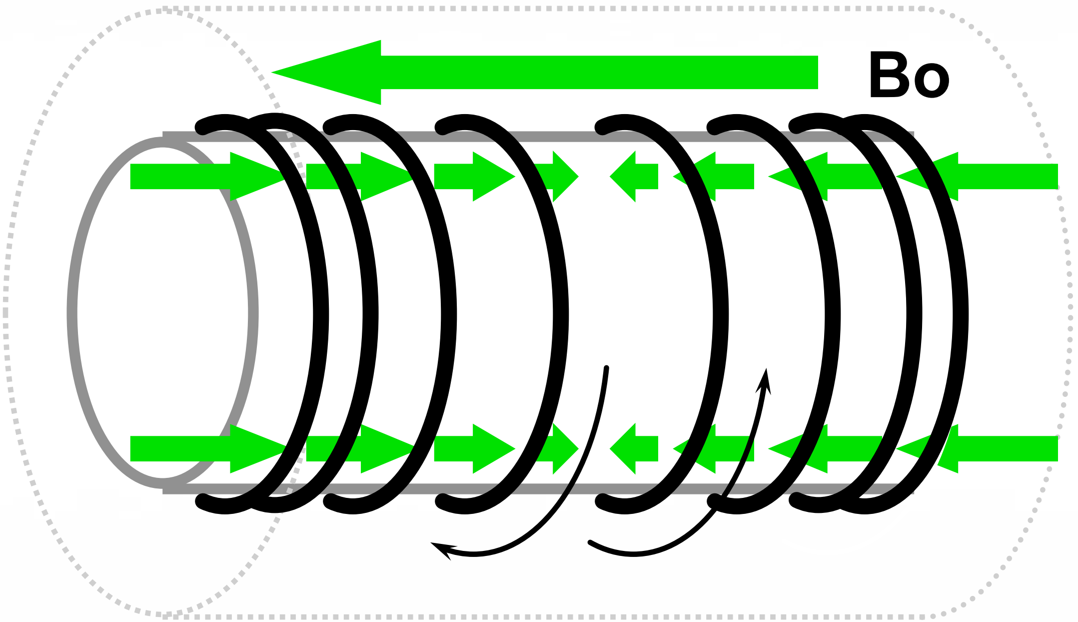
Maxwell pair

Z gradient



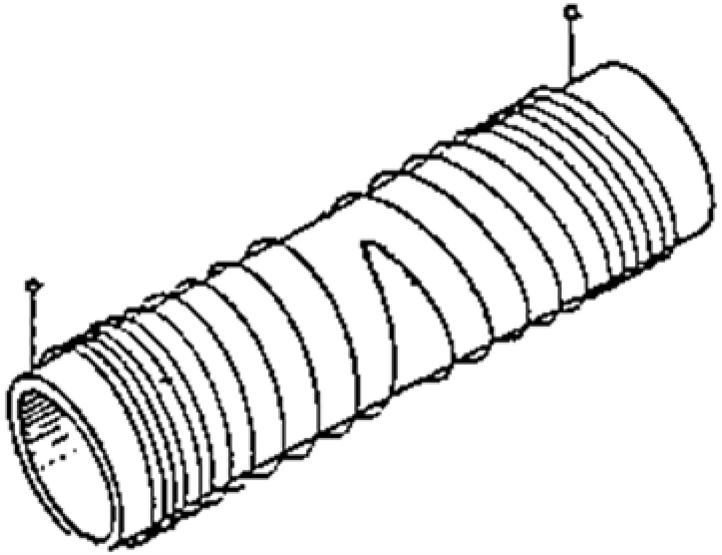
The magnitude of gradient field varies in z direction.

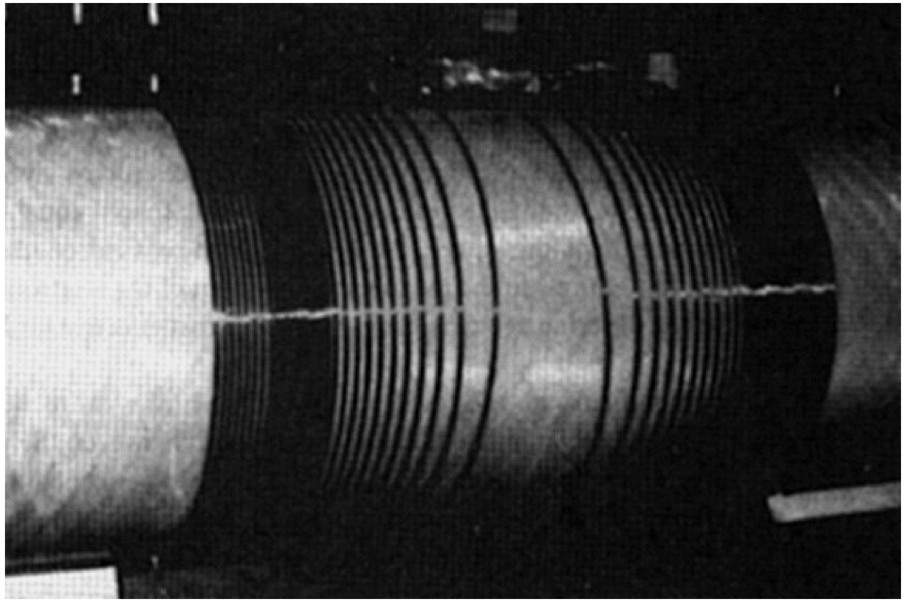
Linear z gradient field



The magnitude of gradient field varies in z direction.

Z gradient coil

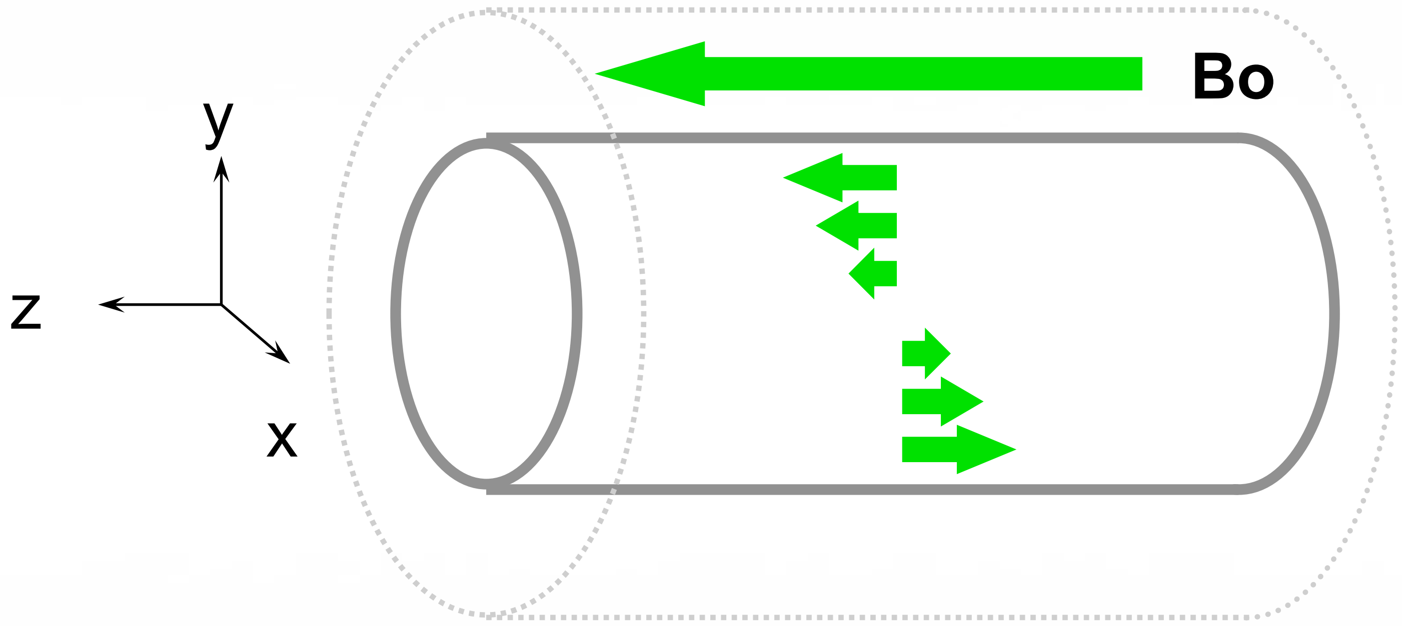




Direction of gradients

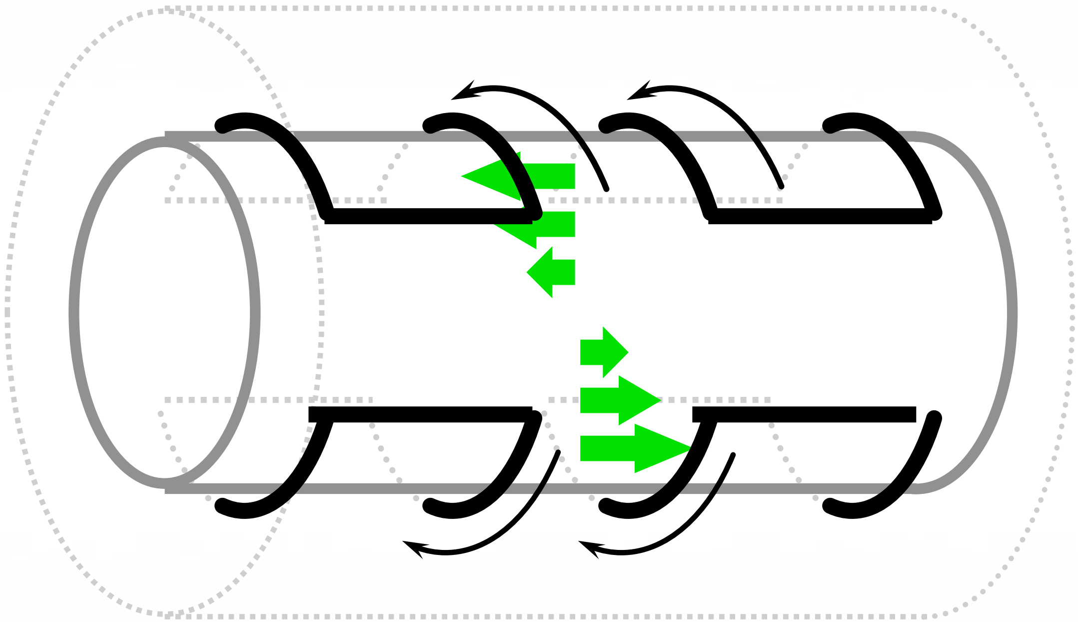
- The direction of magnetic field produced by a gradient coil is **always** along z direction
  - Parallel to B_0
- The magnitude of gradient field (z-component) varies linearly along certain direction.
  - For example, y gradient produces a field with its magnitude varying along y direction.

Y gradient



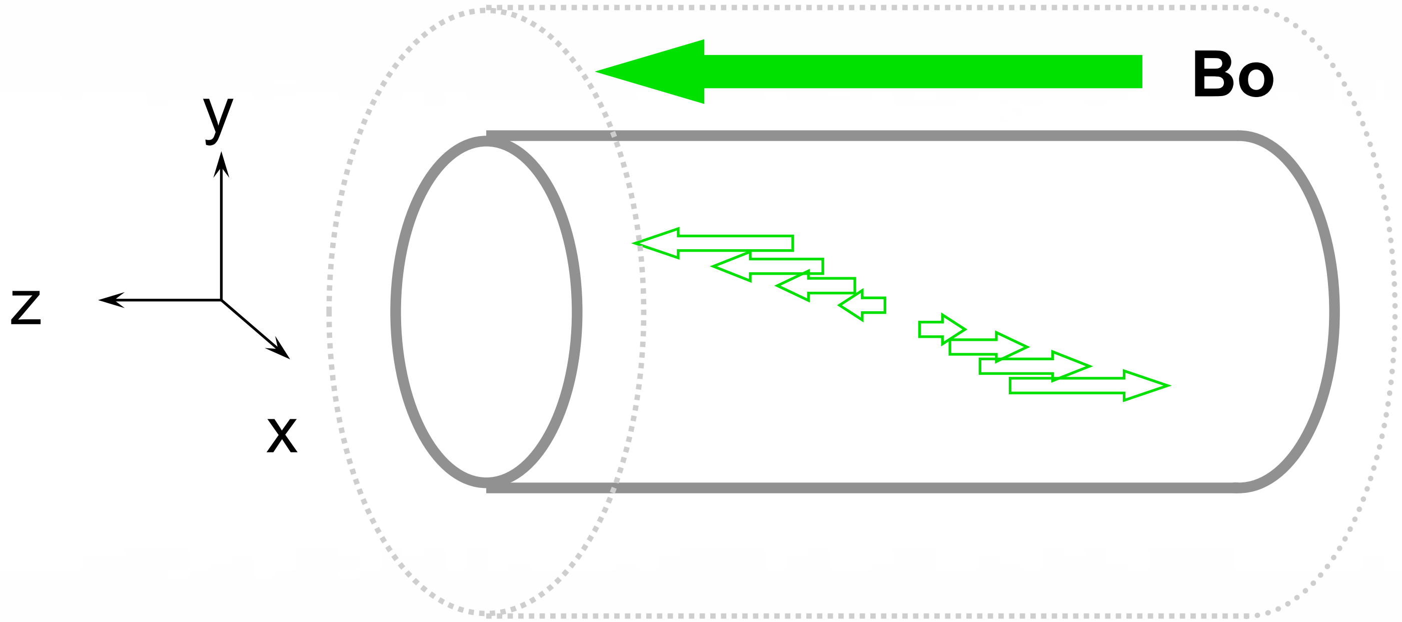
The magnitude of gradient field varies in y direction.

Y gradient coil



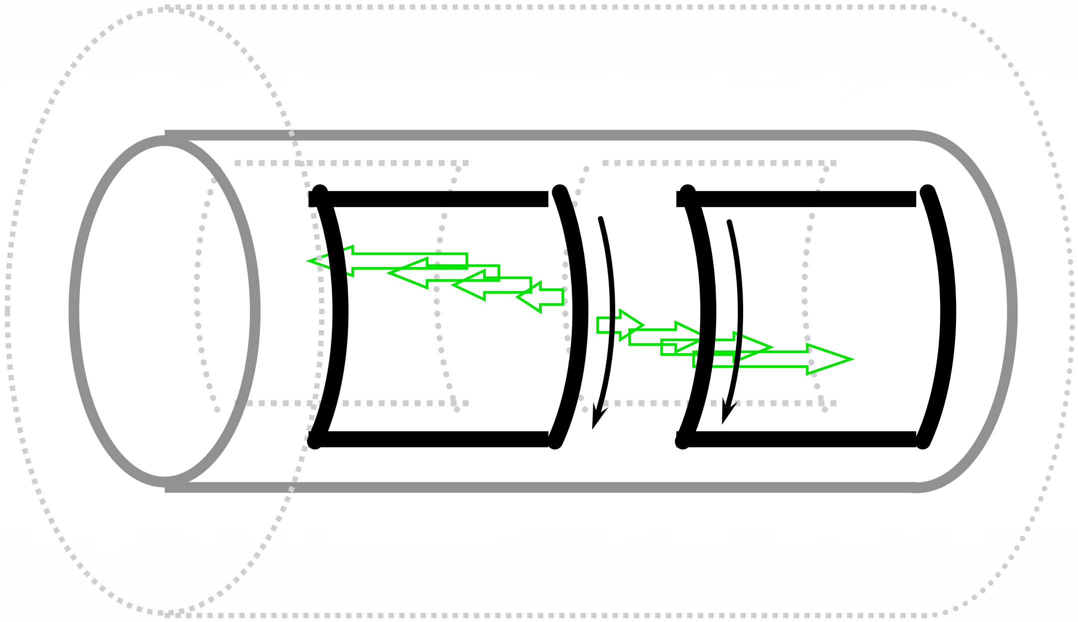
Saddle (Golay) coil configuration

X gradient



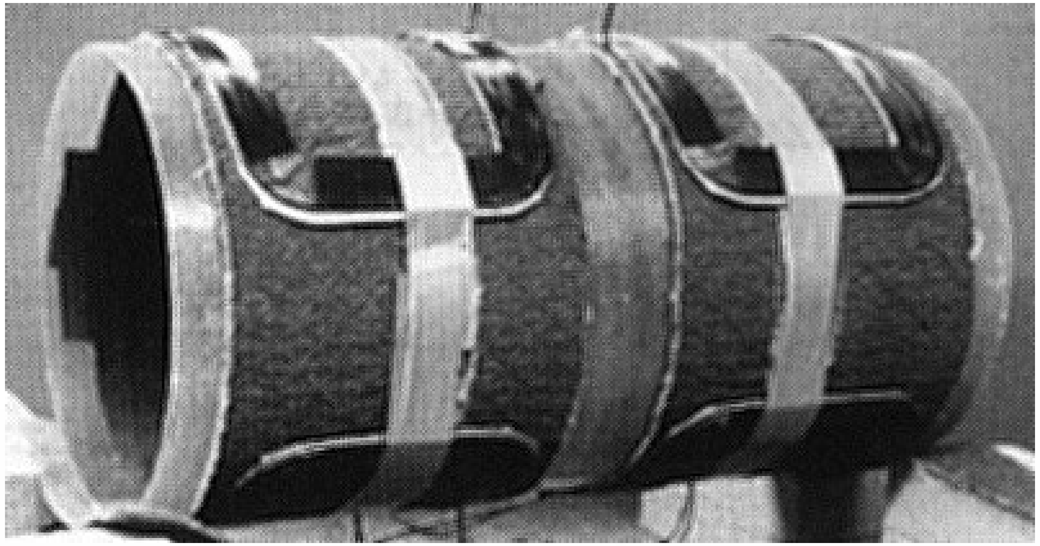
The magnitude of gradient field varies in x direction.

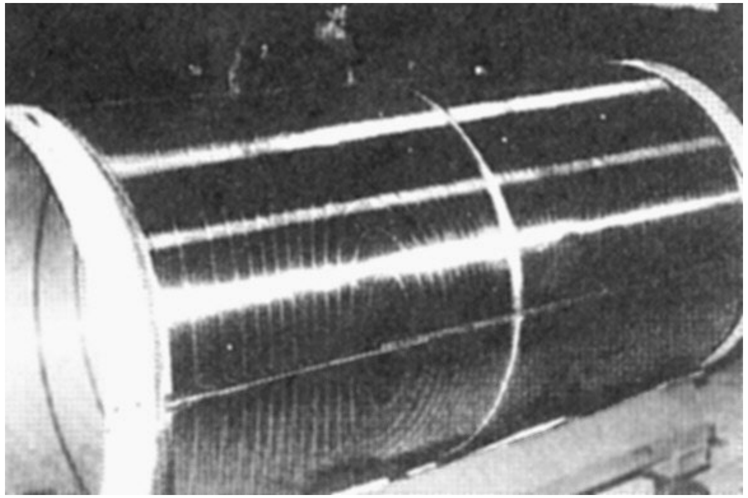
X gradient coil



Saddle (Golay) coil configuration

X or y gradient coil

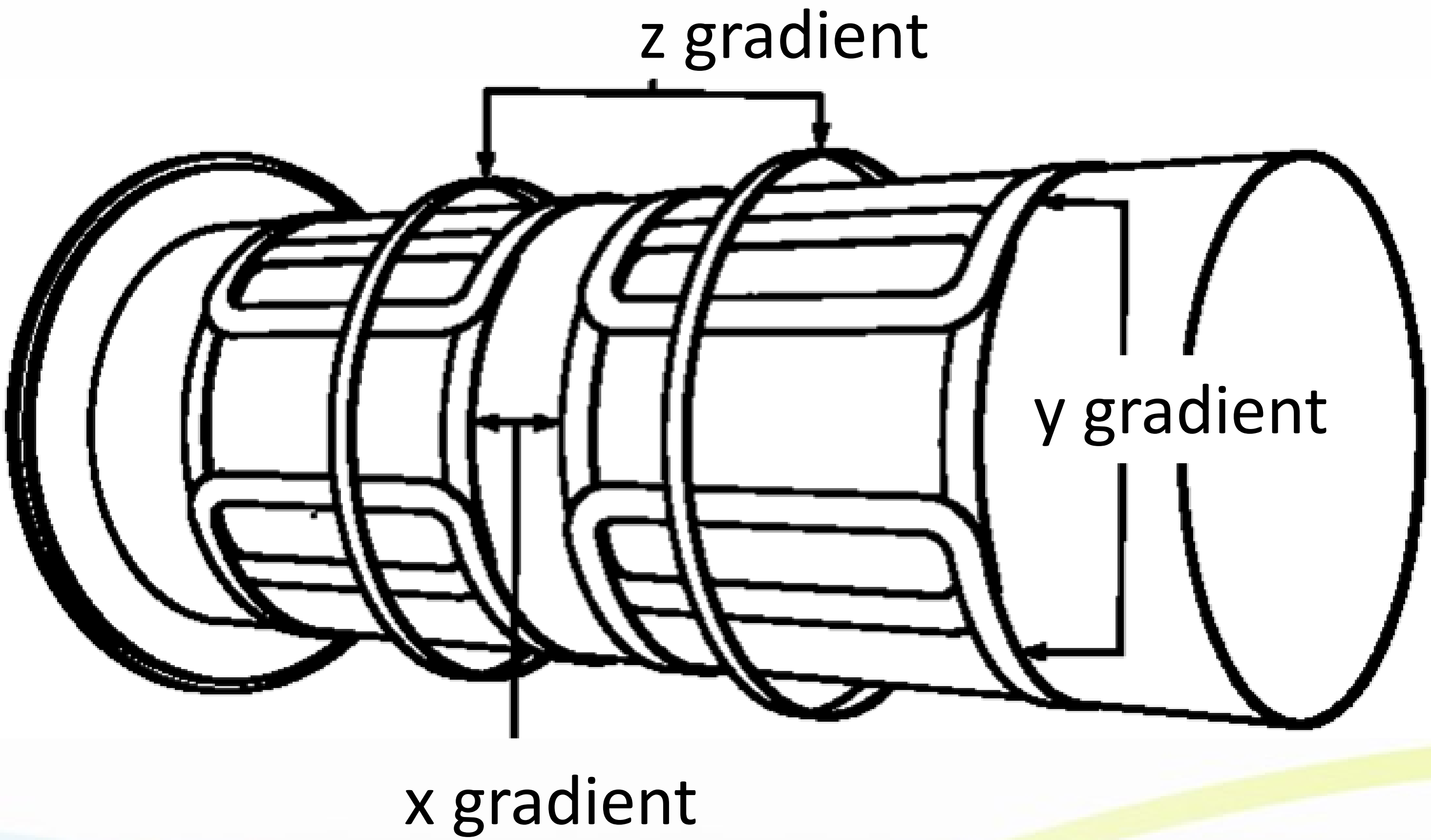




Winding etched into copper sheets

Modern fingerprint pattern

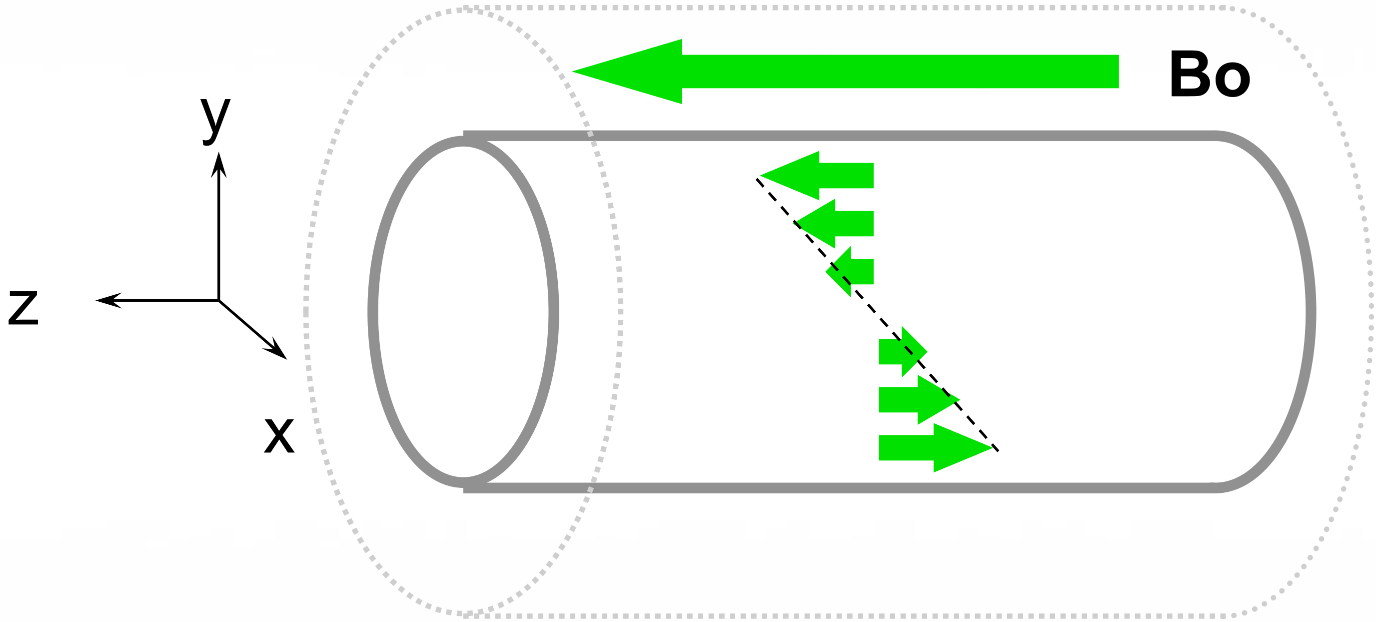
Combination of three gradient coils



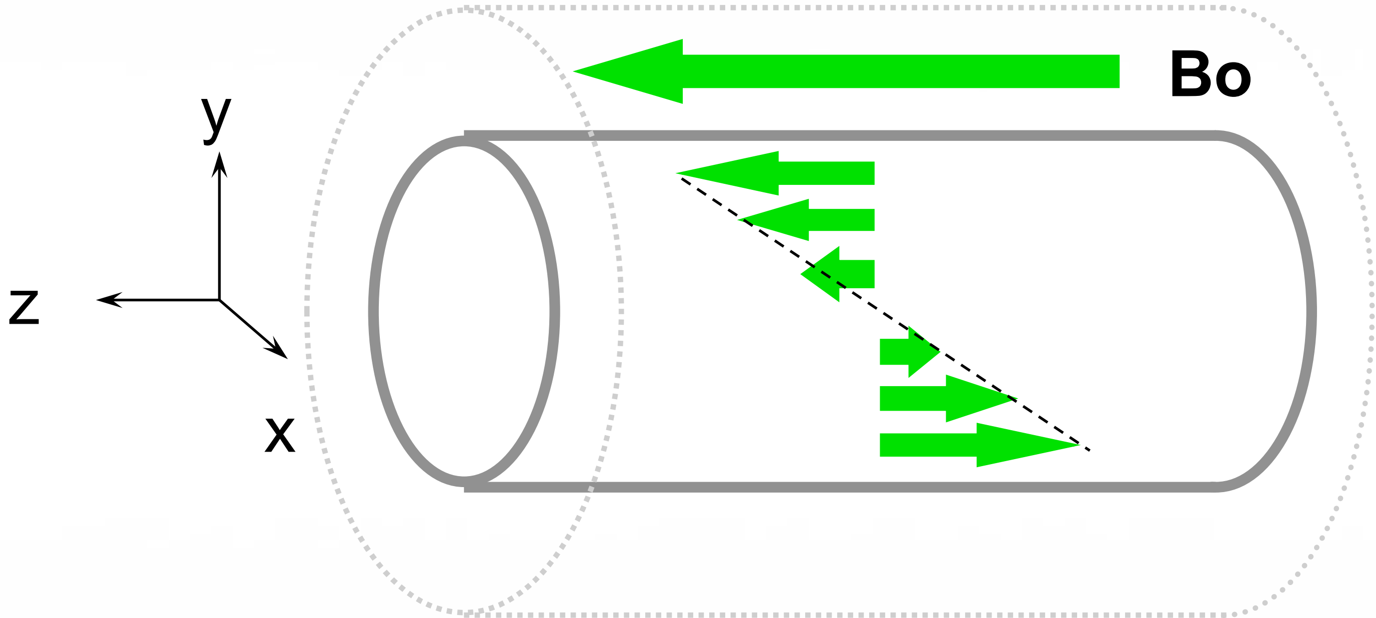
Strength of gradient

- Stronger gradient benefits higher resolution.
  - You will realize it soon with your homework…
- How to increase the gradient strength?
  - Increase the density of winding
  - Create rapidly changing fields

Weak gradient



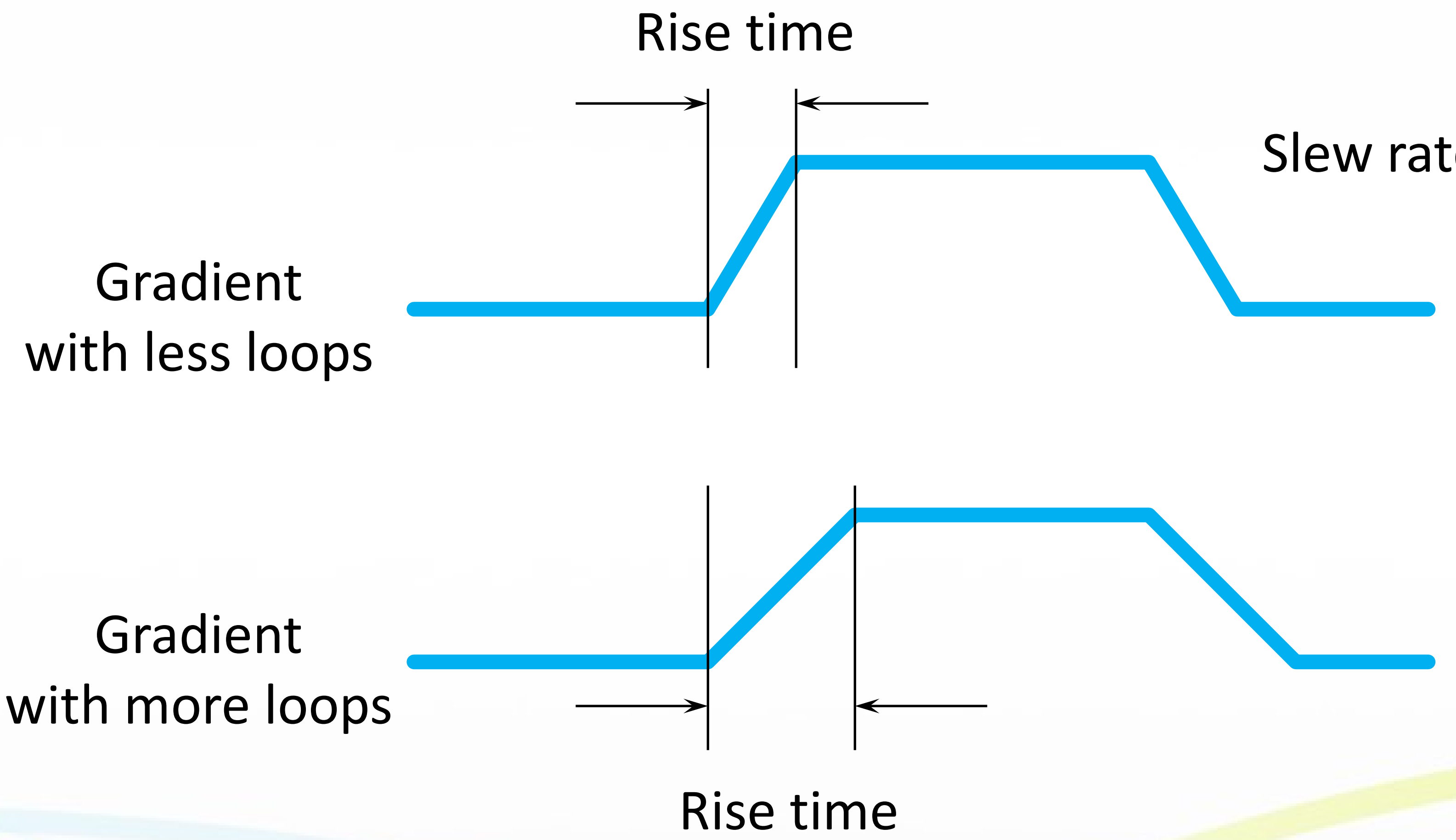
Strong gradient



Wiring of gradient coils

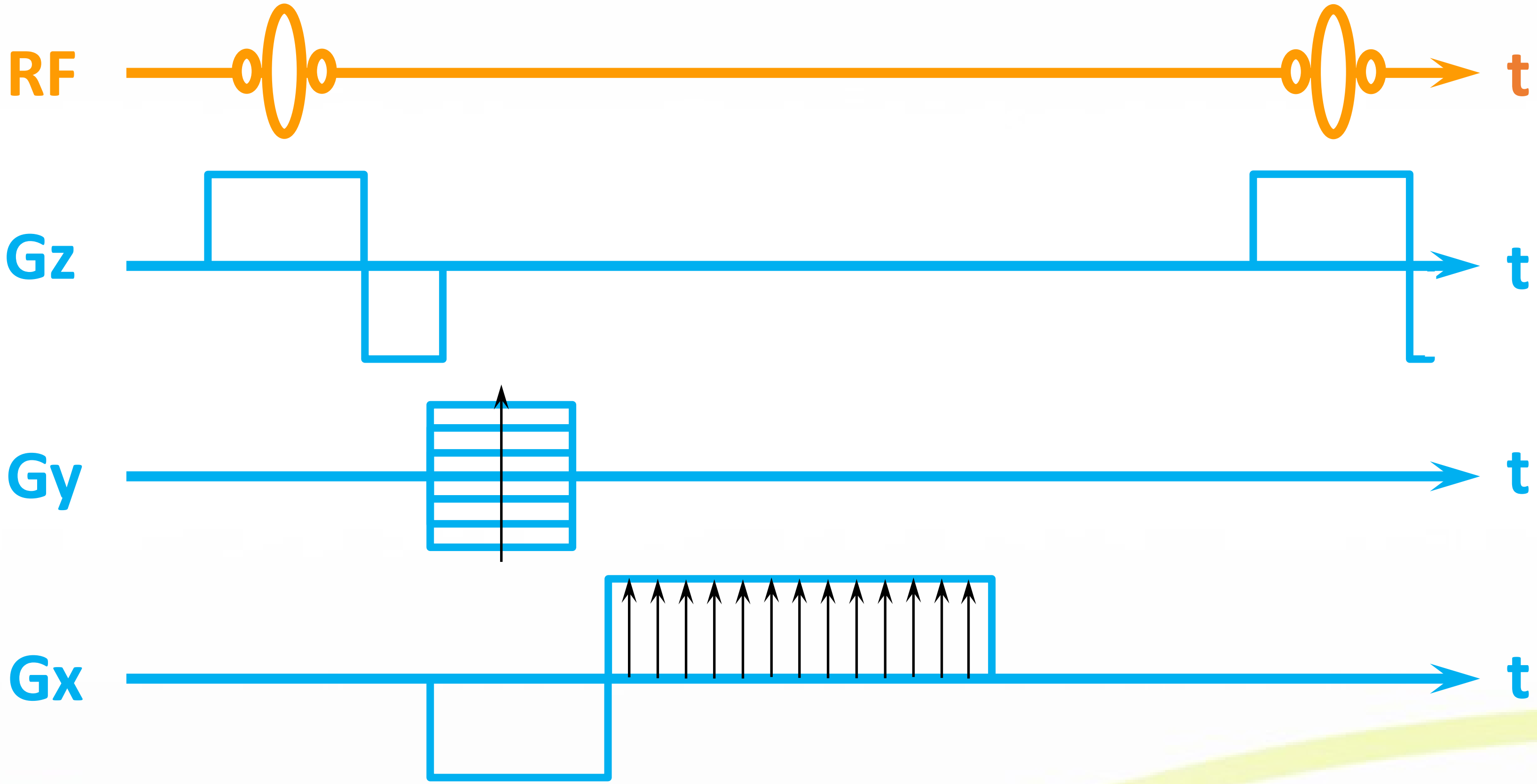
- Gradient coils are basically loops/helix of wire.
  - Self inductance
- Lenz's law: the direction of induced current opposes the changing of applied current
- Gradient fields won't change as fast as you want.

Rise time and slew rate



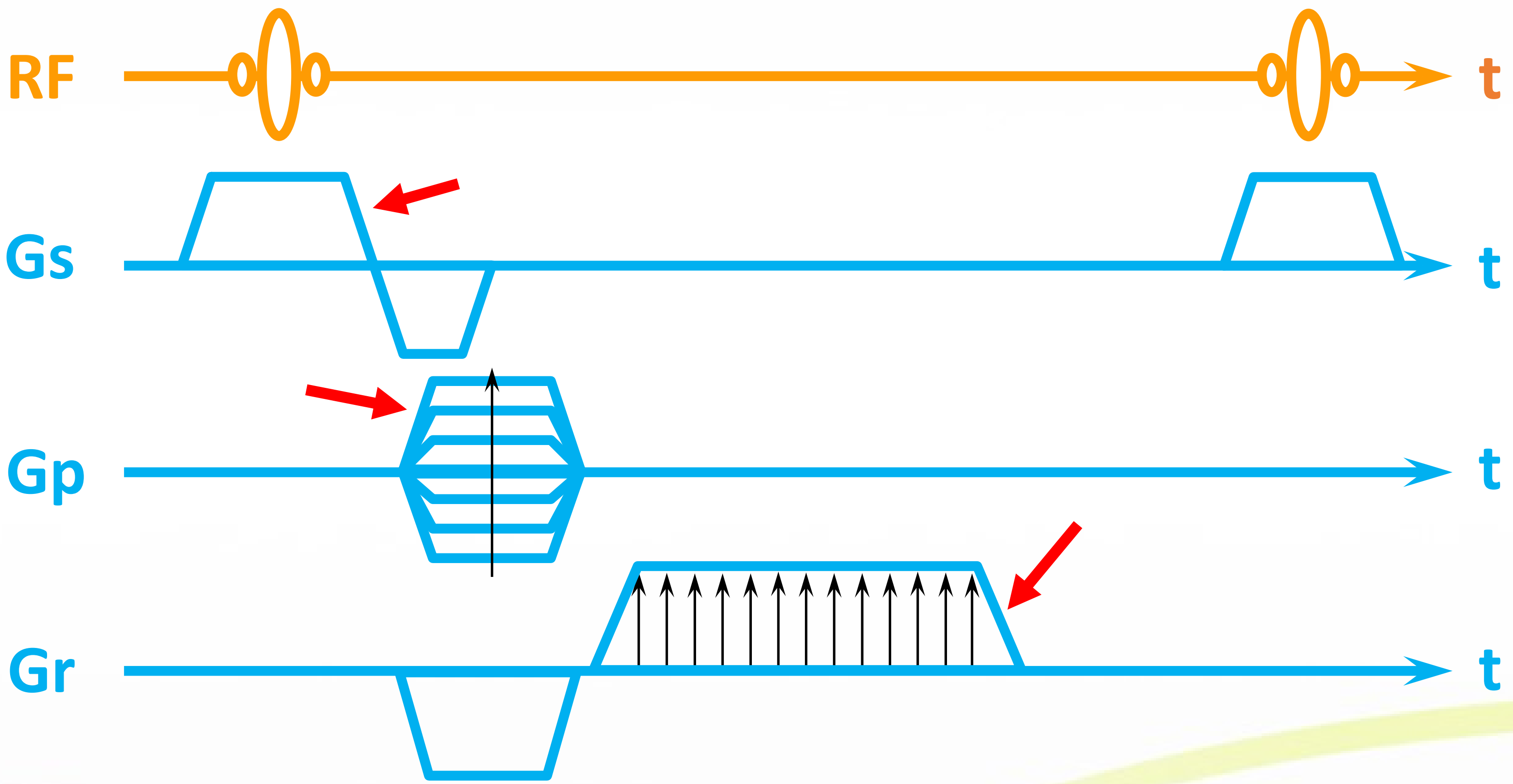
$$\text{Slew rate} = \frac{\text{Max gradient strength}}{\text{Rise time}}$$

Gradient echo



Ideal (rectangular) waveform

Trapezoid waveform of gradients



Ascending/descending with certain slope (slew rate)

Rise time and slew rate

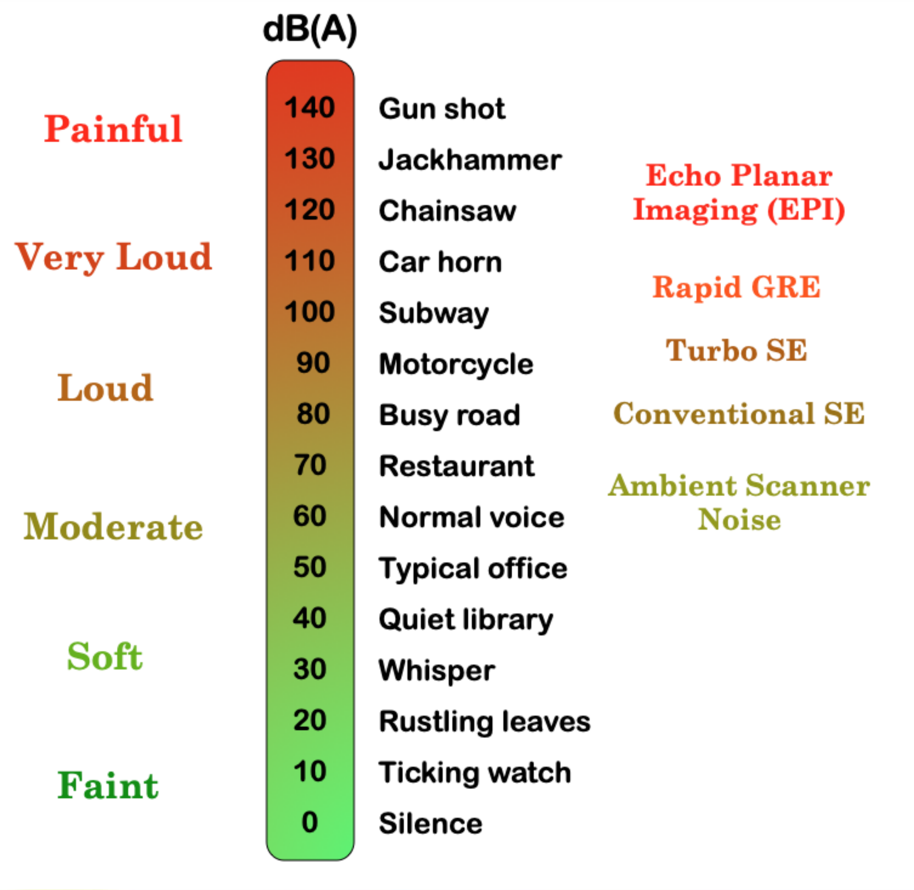
- For modern MRI scanners (2020's)
  - Gradient strength: max at 40-60 mT/m
  - Slew rate: max at 150-200 T/m/s (or mT/m/ms)
- Rise time: around 0.1-0.3 ms
  - Not a big deal except for rapid imaging
- But the switching of gradients also causes acoustic noise and eddy currents.

Switching of gradients: acoustic noise

- Lorentz force is applied on the gradient coil driven by currents in strong magnetic field (B_0).
- Switching on and off the gradient causes vibration of the gradient coil
- Acoustic noise could reach 100 dB and higher!

Acoustic noise

- Fast sequences cause louder noise
  - EPI, fast GRE, FSE (TSE)
- Protection for patients
  - Ear plug or ear mug

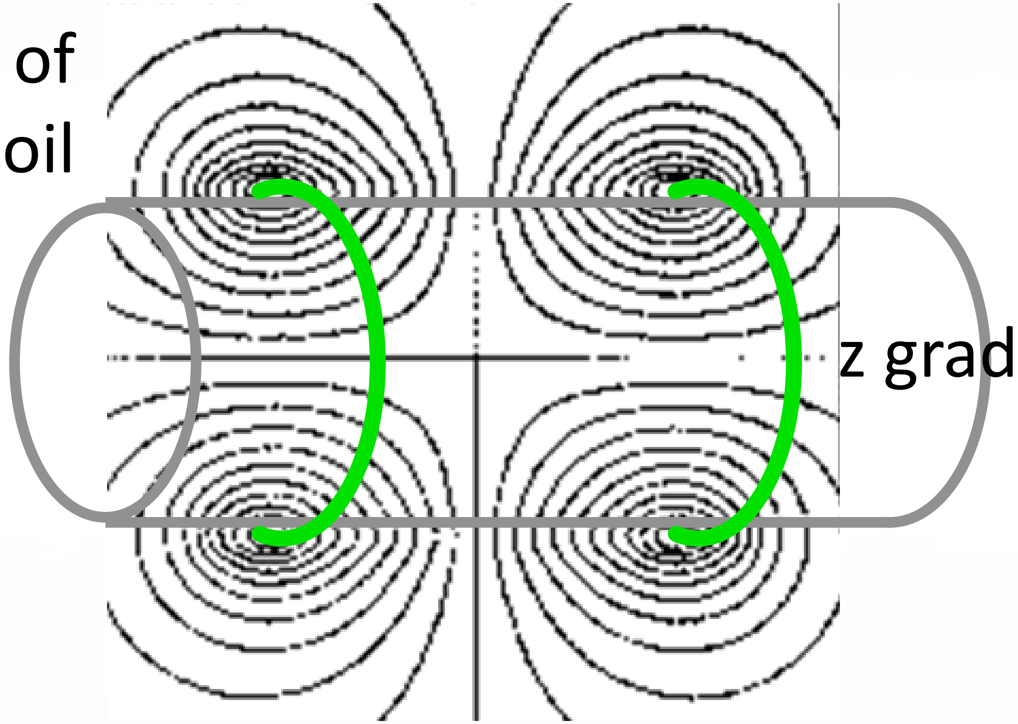


Courtesy: Questions and Answers in MRI
https://mriquestions.com/acoustic-noise.html

Switching of gradients: eddy currents

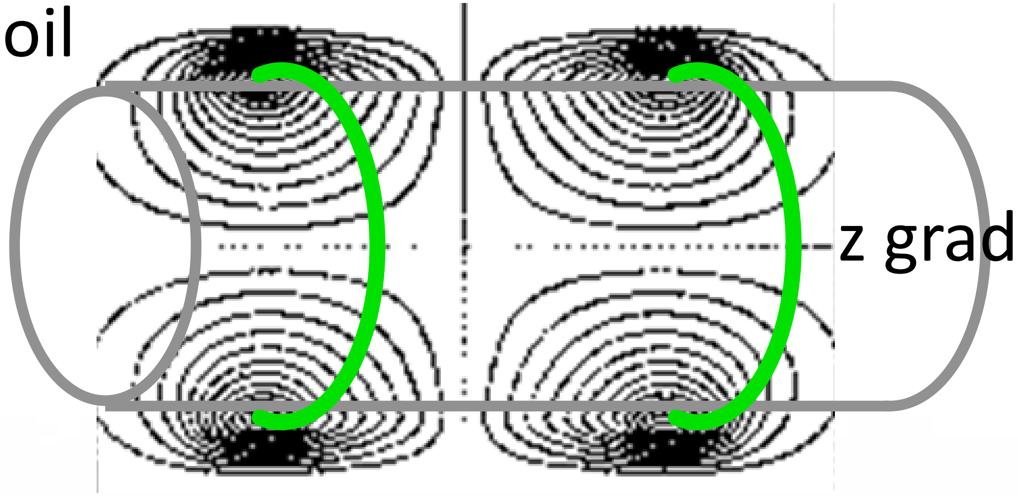
- The rapidly changing magnetic field may induce **currents** on any **conductor** nearby
  - Faraday's law of conduction
  - Conductors: e.g. Gradient coils, RF coils, …
  - Eddy current
- Unwanted gradients, time-varying (false) signals

Eddy currents induced by changing fields



Changing magnetic flux may cause inductive currents

Shielding of gradient coils



The distribution of magnetic flux is constrained by shielding

RF coils

- Excitation and detection of MR signals
  - Transmission and reception of radio-frequency EM waves
  - Larmor frequency

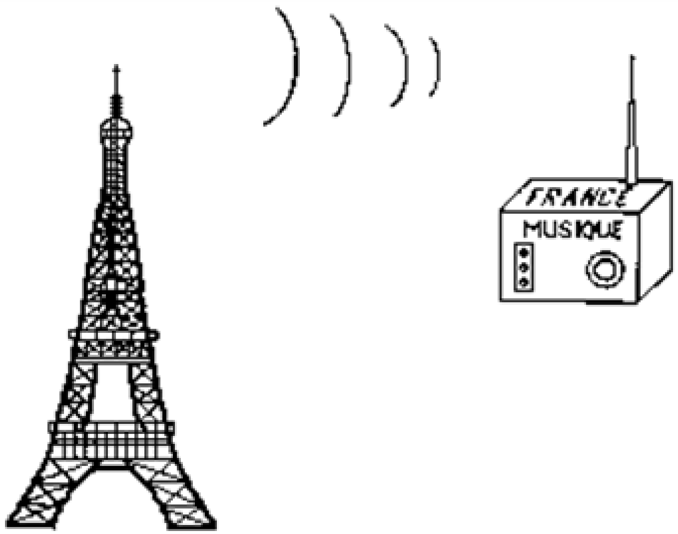
Hardware for signal excitation

- To generate a excitation field (B_1) at Larmor frequency
- Requirement
  - High efficiency/gain at Larmor frequency
  - B_1 must be perpendicular to B_0

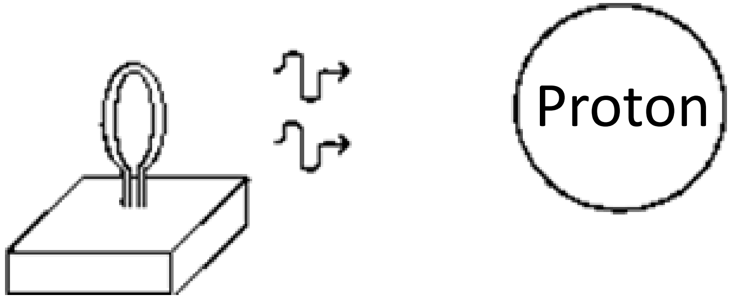
Hardware for signal detection

- To receive the induced currents at Larmor frequency
- Requirement
  - High efficiency/gain at Larmor frequency
  - Aiming at the oscillating magnetic flux, which is perpendicular to B_0

Analog to RF antenna



Radio transmission and reception



RF excitation of magnetization

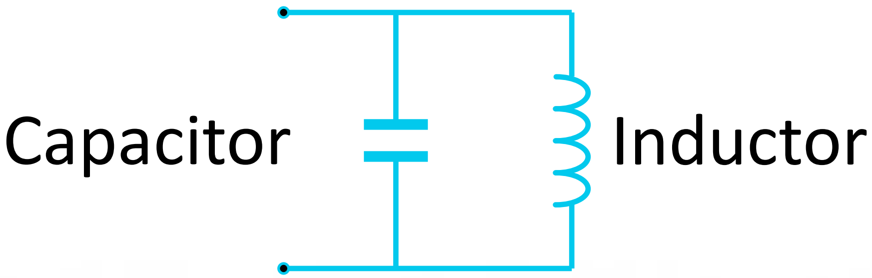
Oscillator circuit

- An electrical circuit that produces a periodic signal
  - For example, LC circuit
- High gain (or low attenuation) at specific frequency
- Covering on the region of interest

Basic concept of the oscillator circuit

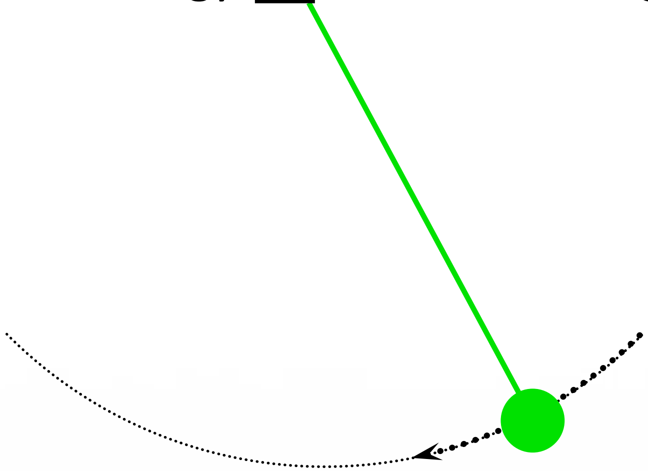
LC circuit

Electrical energy ↔ Magnetic energy



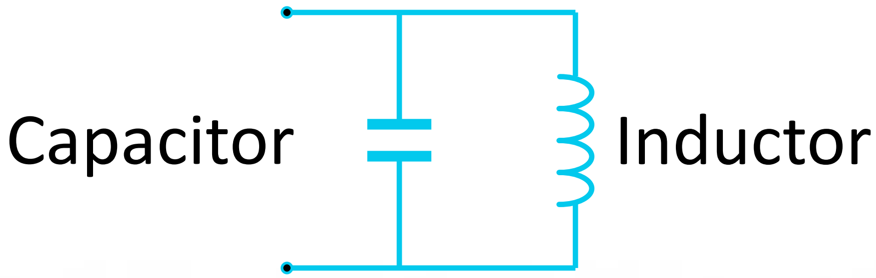
Harmonic motion

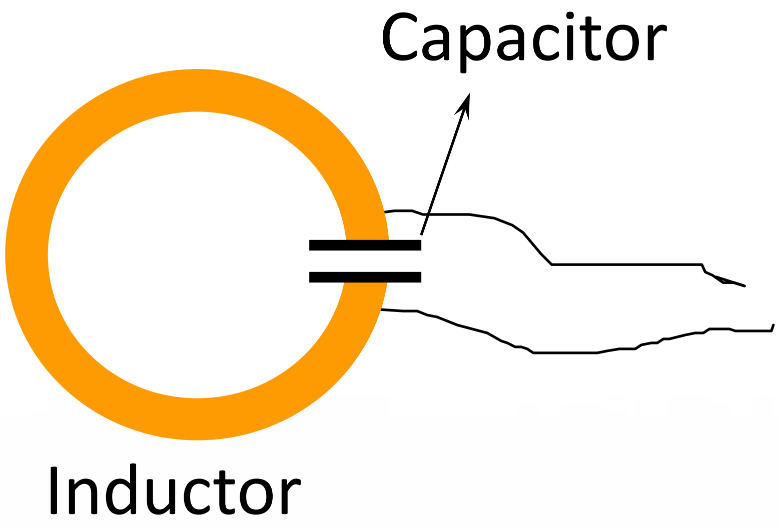
Kinetic energy ↔ Potential energy



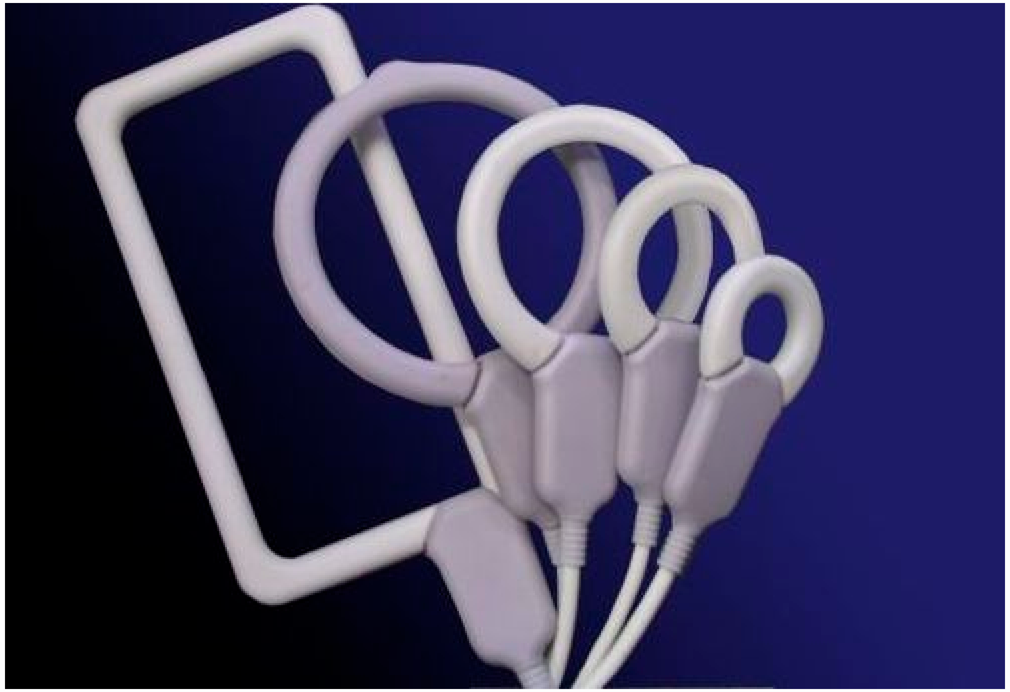
Conservation of energy

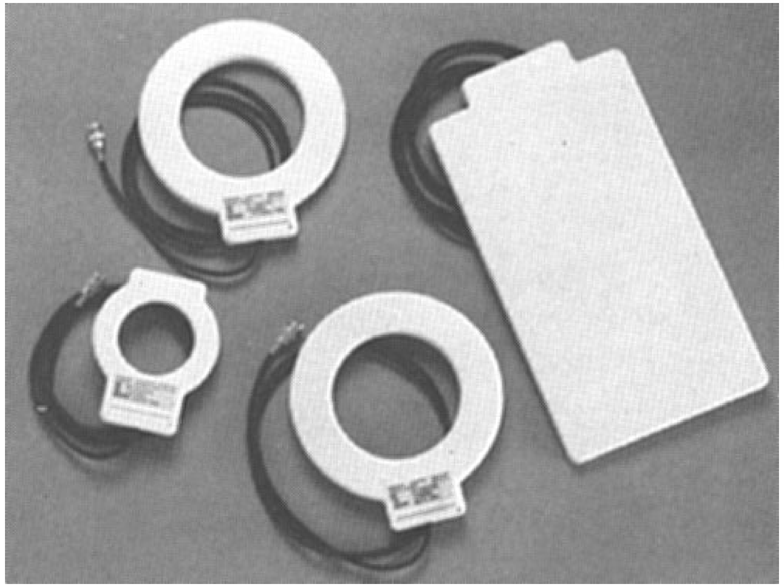
Oscillator circuit: LC circuit



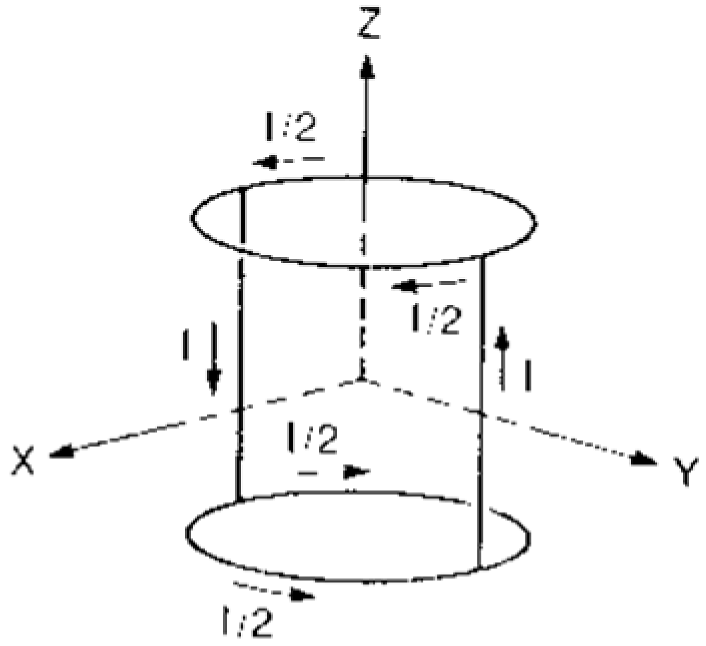


Surface coils

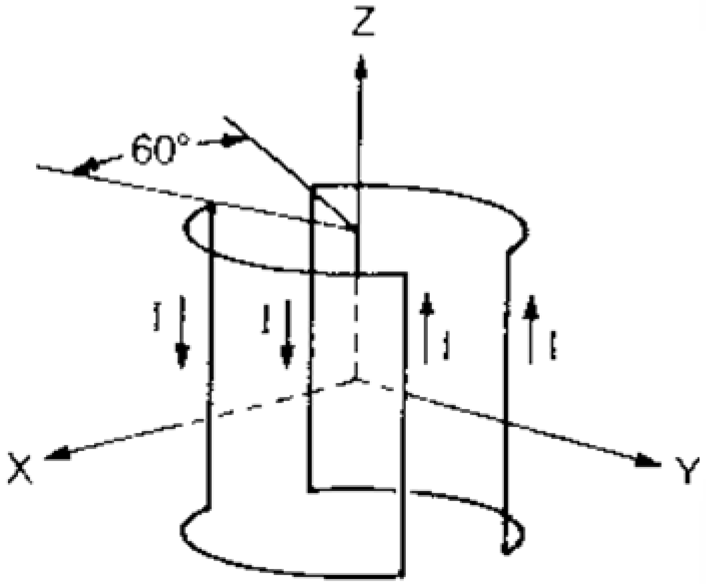




Saddle coil and Helmholtz coil

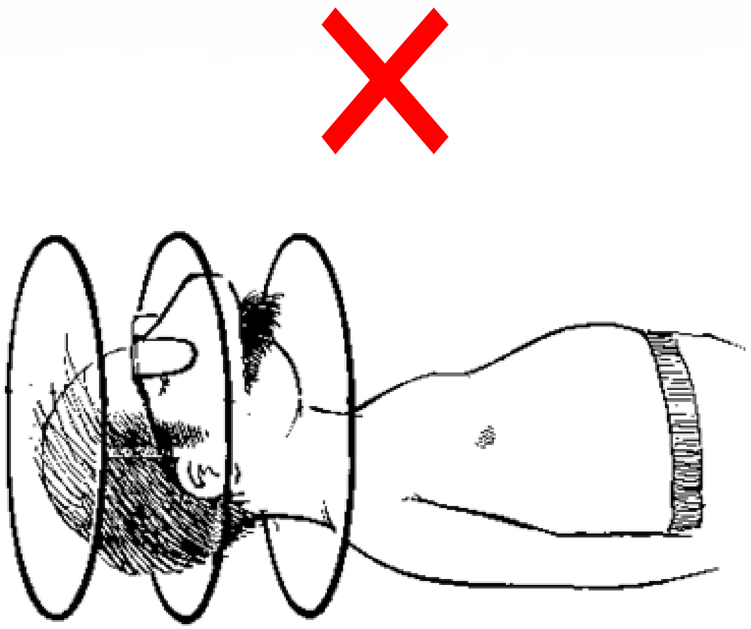


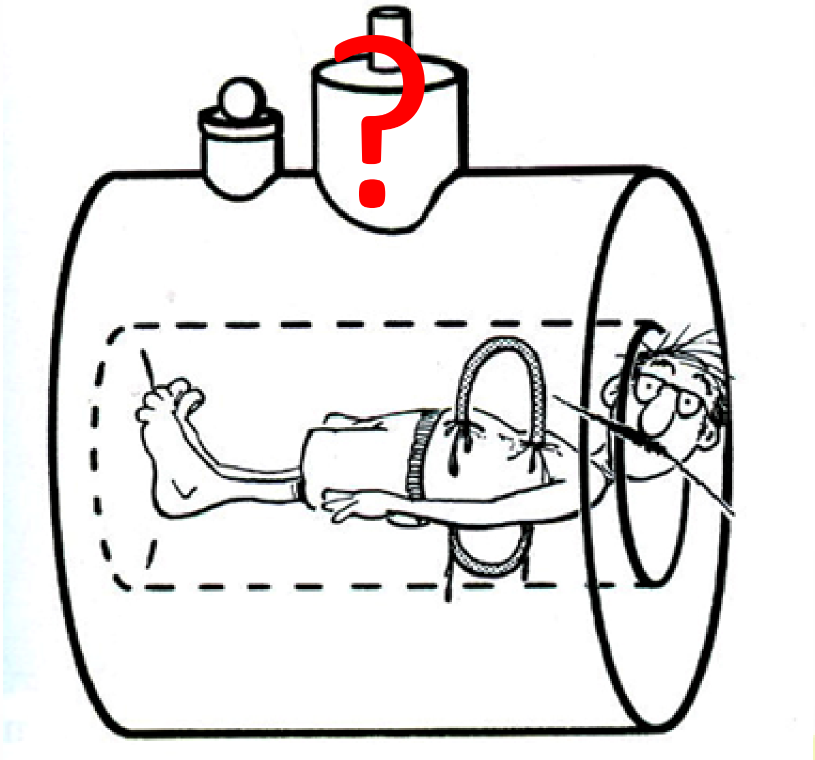
Saddle coil



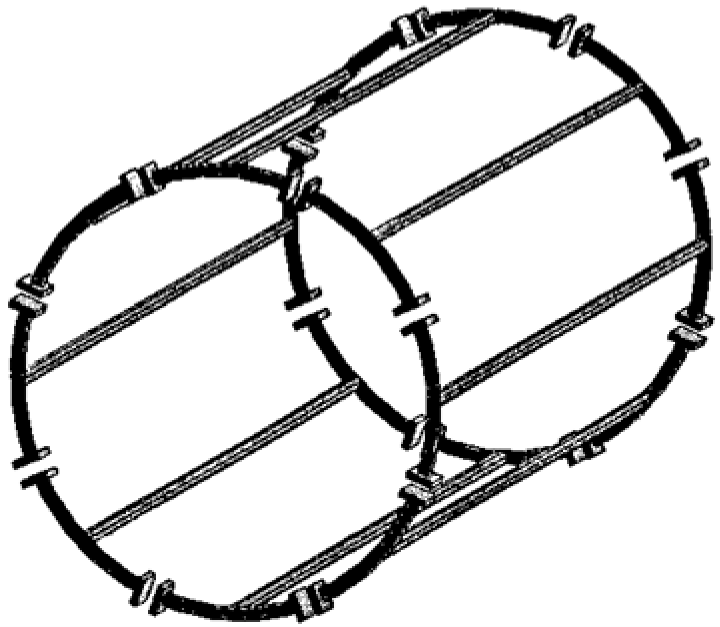
Helmholtz coil

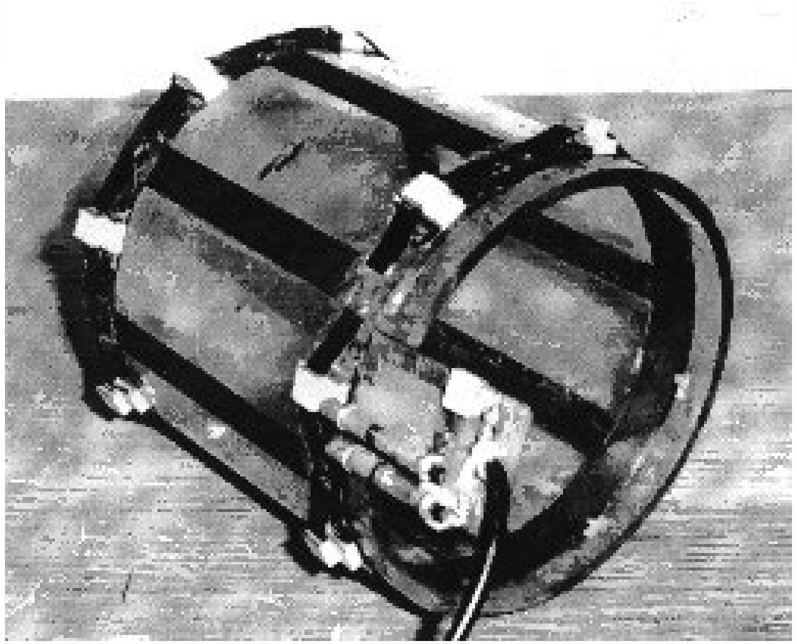
Helix coil can’t be used as a RF coil





Birdcage coil





Head coil

Comparison of different coils


Body coil


Head coil


3” Surface coil

Purposes of the RF coils

- Excitation coil: producing homogeneous B_1 field
- Receive coil: close to patient's body for better signal intensity

- Usually, separate coils are utilized for RF excitation and reception.

Classification: volume coil vs surface coil

- Volume coil
  - Coverage of a large volume
  - Good homogeneity
- Surface coil
  - Flexible size and shape
  - Closer to the body for high sensitivity

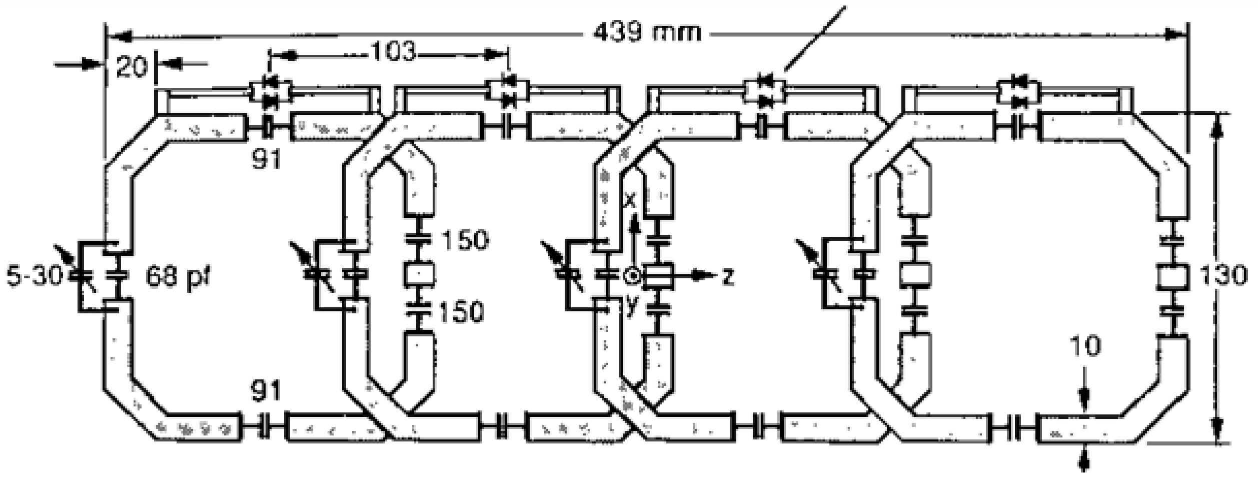
How to choose?

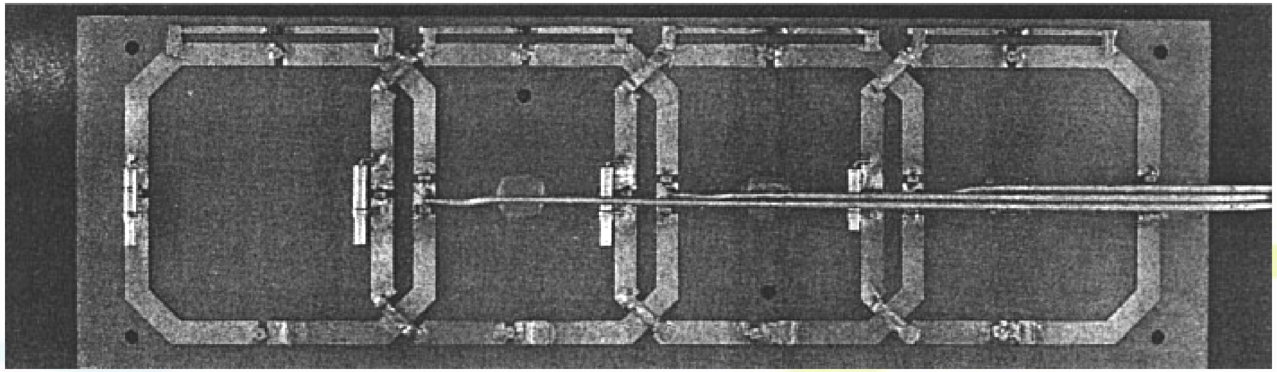
- Depending on the region to be imaged
- Large area: use the minimal volume coil for excitation and detection
- Small area: use the volume coil for excitation and a surface coil for detection

Phased-array coil

- Combination of multiple small surface coils into large arrays
  - Each element collects MR signals independently
  - Coupling between nearest elements minimized
  - Similar to the phased array from antenna theory
- High SNR and large FOV!

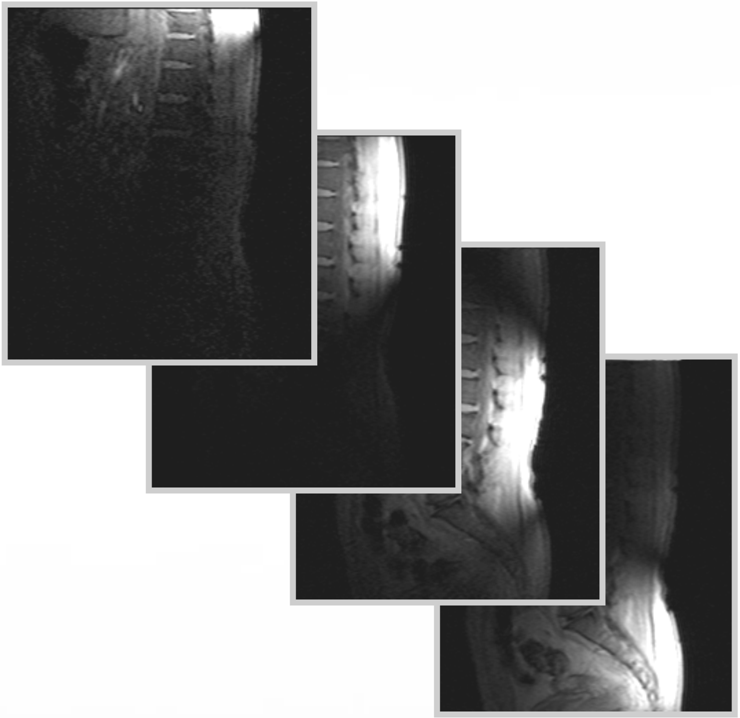
Phased-array coil





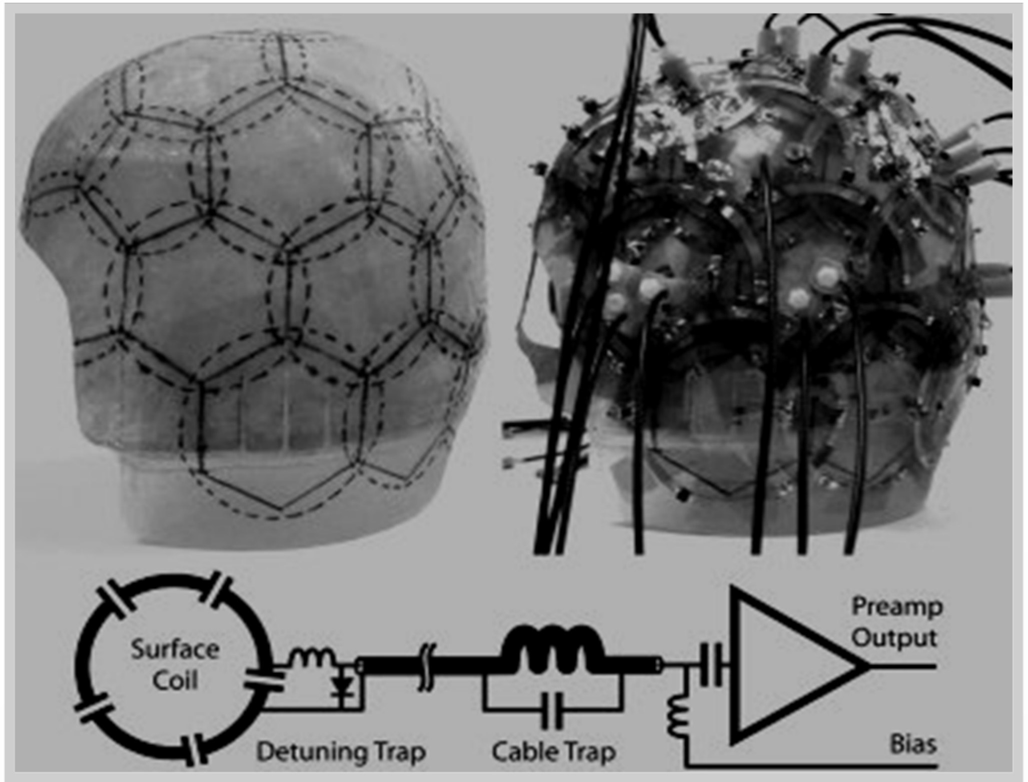
Spine phased-array coil

Spine imaging using a phased-array coil



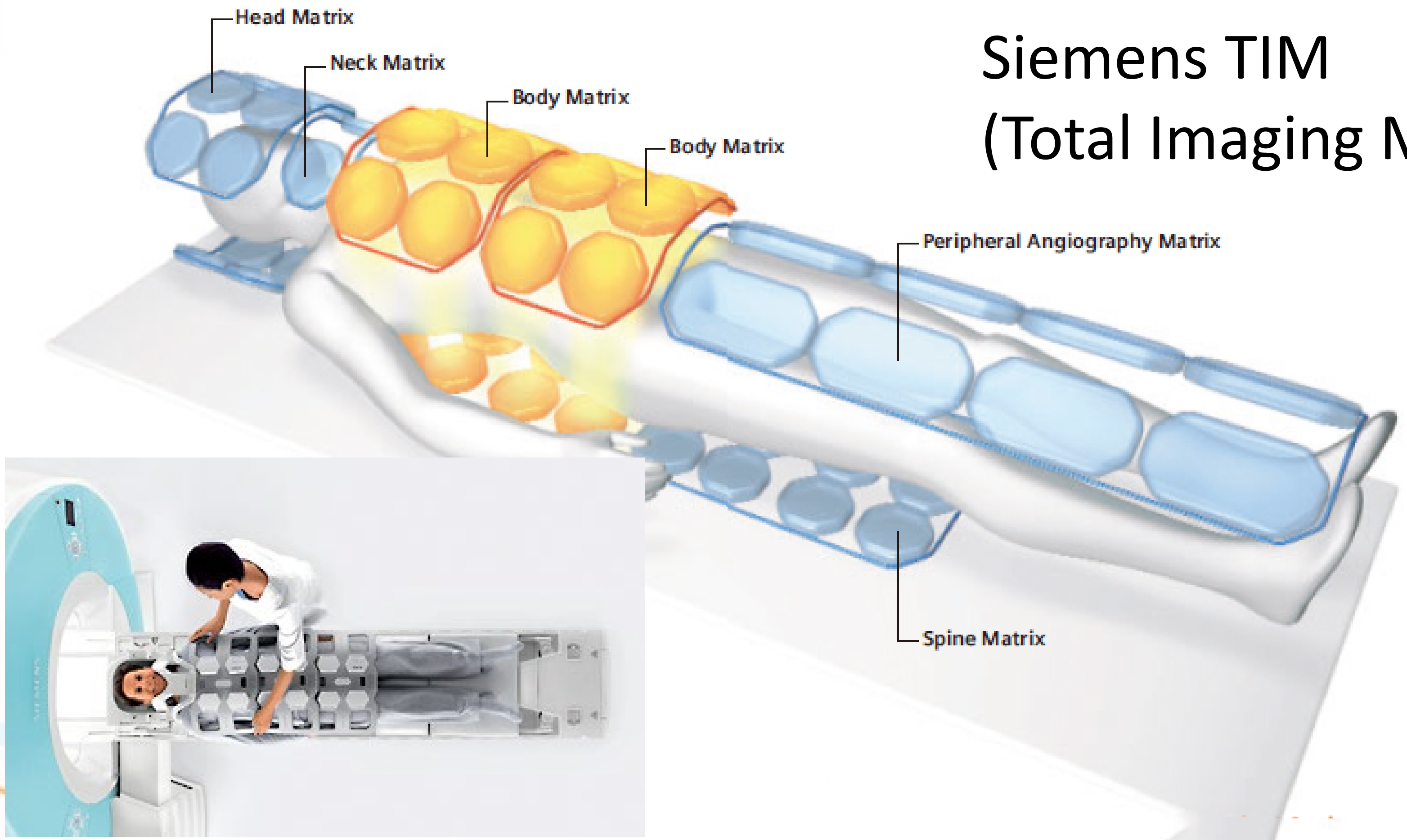
Combination of all elements achieves large coverage.

Advanced phased-array: 32-channel head coil



Each channel equipped with its own amplifier and filter ($$$)

Terracotta Warriors?



Siemens TIM
(Total Imaging Matrix)

Flexible coils: adaptive to body shape

Contour S Coil

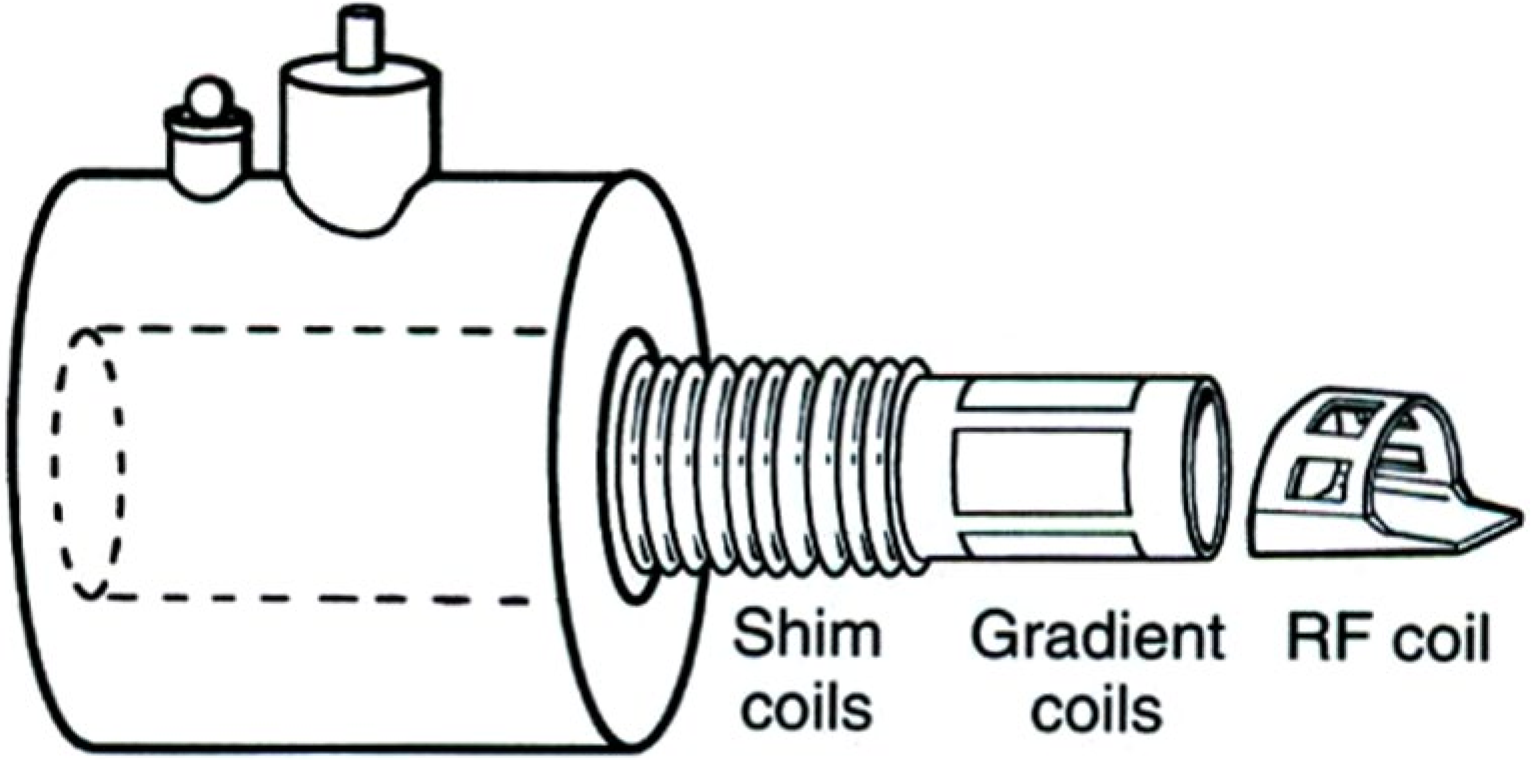
Contour M Coil[1]

Contour L Coil

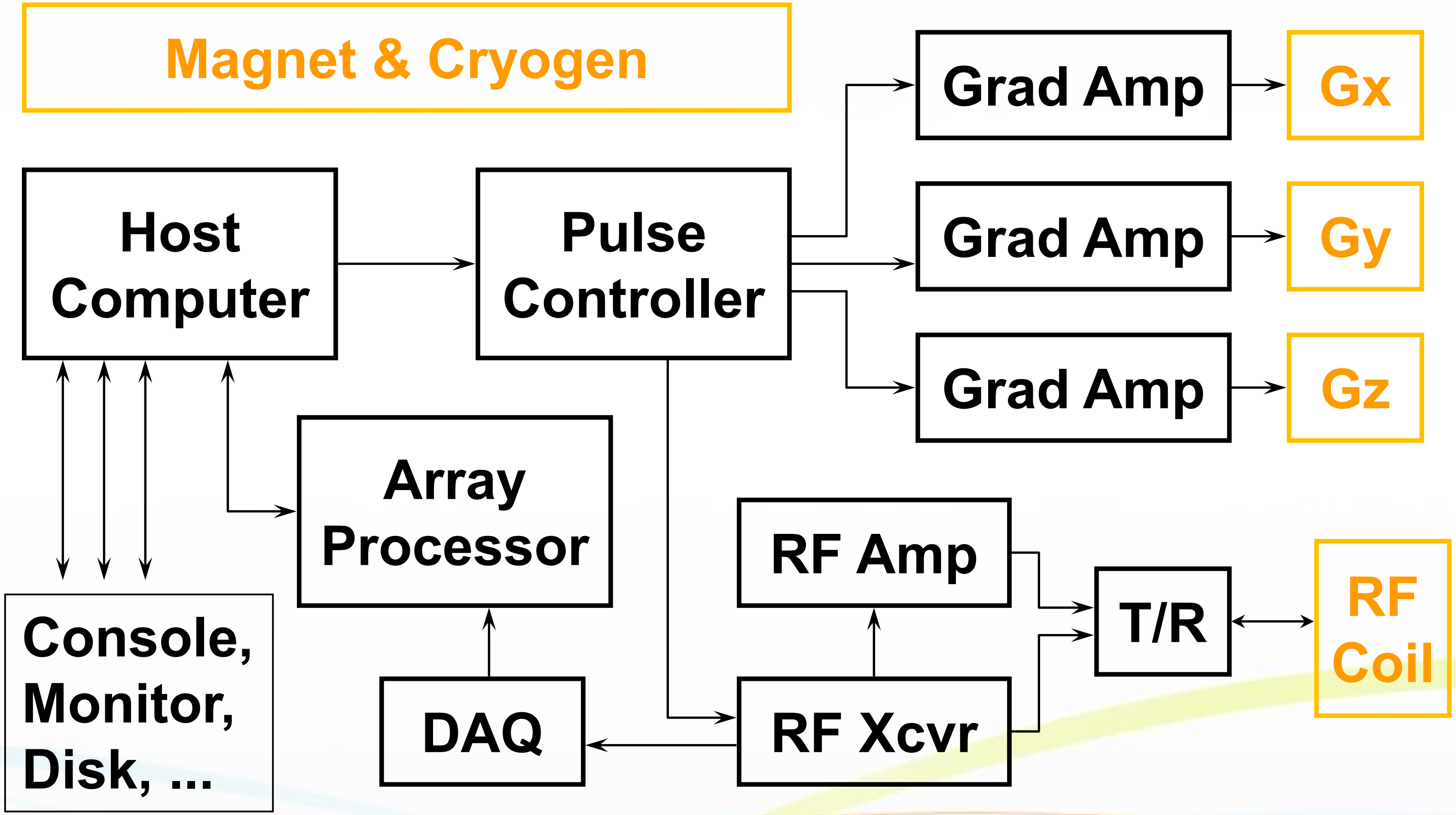
Siemens Contour coil

Courtesy: Siemens Healthcare

So many coils in an MRI scanner…



System chart



MRI Hardware:
Magnet, Gradient coils, and RF coils