MRI Hardware (Magnet)

- Safety
  - The forces on ferromagnetic object varies as the inverse fourth power of distance from the magnet ($1/r^4$) which means that they can change from being negligible and unfelt to overpowering in just a few steps.
  - Fields greater than 1 mT can affect heart pacemakers and erase credit cards.

- Specifications of a Magnet
  - Strength and size
  - Stability and homogeneity (Uniformity of field over a specified volume)
- Types of magnets
  - Permanent
  - Resistive
  - Superconducting

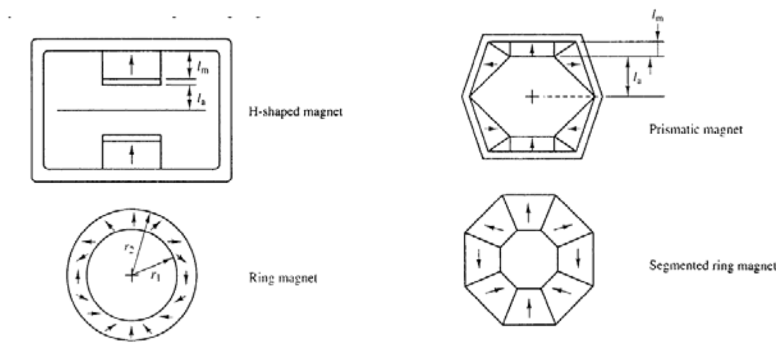
Magnet Types

- Permanent magnet ~ 2 T
- MRI magnet (meter-sized bore) ~ 9.4 T
- Superconducting magnet (NMR) ~ 23 T
- Resistive DC magnet ~ 35 T
- Hybrid DC magnet (resistive+superconducting) ~ 45 T
- “Long-pulse” magnet (100 ms) ~ 60 T
- “Short-pulse” magnet (few ms) ~ 100 T
- Explosive short-pulse magnet ~ 2,800 T

Permanent Magnet

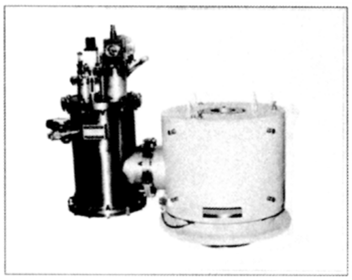
- Built of blocks of magnetic material (Samarium cobalt compounds, ferrites, Neodymium-Iron-Boron (Nd-Fe-B)) that are magnetized in the appropriate direction before being forced into position in the assembly and glued in place.
- Not common in medical use:
  - to insure stability, temperature control to 1 mdegree is needed.
  - Local changes of magnetization due to field gradients being turned on/off can be difficult to control

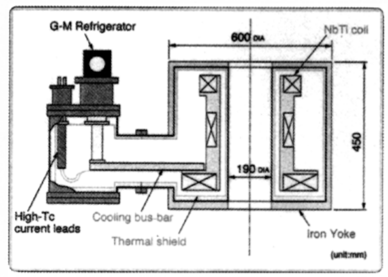
Schematic cross section of permanent magnet structure



- Advantages
  - Their fringe field is small
  - The magnetic field lies perpendicular to the main axis which compensates for their low field (geometry for the coils used for receiving the signal is different).
  - Requires negligible power

Neodymium-Iron-Boron





Resistive Magnets

- Consume high electrical power dissipated in the form of heat which requires and efficient cooling system.
- Stability of the magnetic field is determined by the power supply and the temperature.

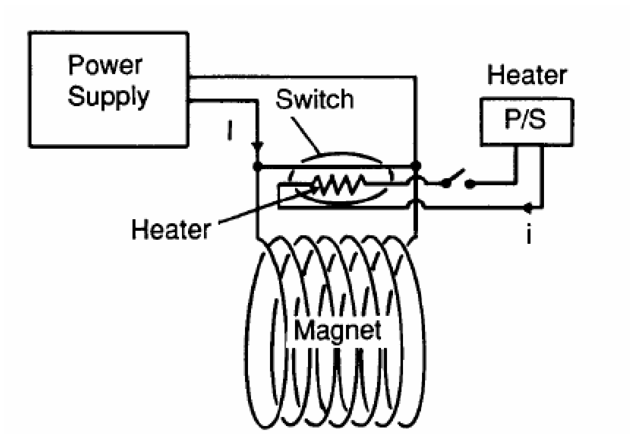
Cryogenic Magnets

- High fields and excellent stability
- At room temperature all known metals and alloys posses resistance (generate heat when an electric current is passed through them)
- At low temperature, superconductors (e.g., niobium-titanium (NbTi) and niobium-tin) completely lose their resistance.
- Superconductors behave as if they have no measurable DC electrical resistivity when they are cooled below their critical temperature (Tc for NbTi = 10K)

Manufacturing of a superconducting magnet

  - Coils are made by a group of coaxial coils, the coils are electrically connected together in series, and a complete circuit is formed with a superconducting switch immersed in liquid helium (4.2 K)
  - The switch consists of a short length of superconducting wire which is in close contact with a heating element.
  - When the heater is on, the switch is warmed above its critical temperature and there is no longer a continuous superconducting circuit and the current can run through the winding using a DC power supply.
  - Upon reaching the desired field, the switch heater is turned off, cools down forming a continuous superconducting circuit.
  - The power supply is removed, leaving the current flowing in the magnet
- The establishment of the magnetic field requires a large amount of energy (Megajoules) stored in the field ($E=1/2\ LI^2$ where L is the inductance and I is the current)

Schematic drawing a superconducting magnet



- Perturbation of the conductors (accident) may cause a small piece to be resistive, which heats the area causing adjacent areas to be resistive and soon the effect may propagate through the magnet causing a ***quench*** to occur.
- To control the quenching process, the niobium-titanium wire is often in the form of multiple filaments embedded in a copper matrix.
- The copper acts as an alternative low resistance path when a piece of superconductor goes normal, thereby slowing or stopping the quenching propagation

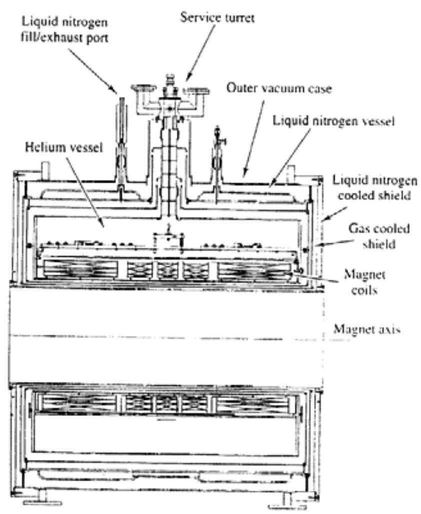
- Emergency run down unit (ERDU): During a quench the heaters warm parts of the magnet windings above their critical temperature and thus out of the superconducting state.
- Once part of the magnet winding is resistive, the current quickly decays.

Cryostat

- Croyostat: the boiler that holds the liquid helium and the wire.
- The use of liquid nitrogen reservoir (77K) a low-temperature heated shield between the helium and the outside.

Cryostat Design

- The liquid helium vessel containing the windings needs to be thermally isolated from room temperature, i.e. convection, conduction, and radiation need to be minimized.
- Heat transfer via convection is almost completely eliminated by evacuating the cryostat.
- The external structure of the cryostat which contains the vacuum is referred to as the outer vacuum container (OVC).



Homogeneity

- Field inhomogenity due to :
  - tiny errors in magnet fabrication
  - Distortion of the magnet due to magnetic and gravitational forces
  - Iron impurities in the cryostat
  - Gradient coil assembly and the probe
  - Iron in the environment about the magnet
  - Magnetic susceptibility variations in tissue and bulk susceptibility effects.
- We correct for field inhomogenity by a process known as shimming

Field Shimming

- Small magnetic fields generated to provide a homogeneous field.
- Shimming can be achieved by:
  - Passive shimming: small pieces of iron
  - Active shimming: small coils or called shim coils *(x, y, z, $2xy$, x^2-y^2, etc)*
  - Combination of both.
- Shim coils can be wound from conventional conductor and operated at room temperature in the warm bore of the magnet , and driven continuously from a high stability power supply

Stray Field and Shielding

- Most health and safety guidelines require that people with pacemakers or other mechanically active implants be excluded from area in which the magnetic fields exceeds 5G (0.5mT).
- Certain equipments can be particularly sensitive to magnetic field

Guideline to maximum field levels for certain equipments

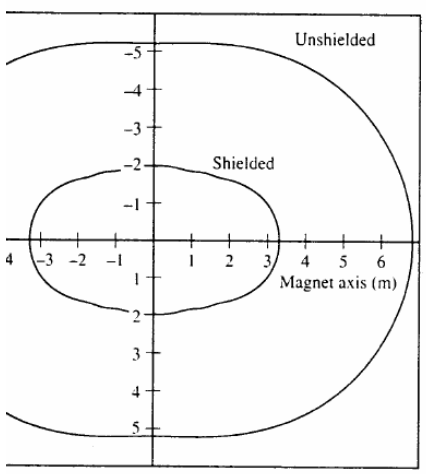
Equipment[a]	Maximum Exposure (mT)
PET scanners	0.1
Nuclear medicine instruments	0.1
CT scanners	0.1
Ultrasound instruments	0.1
Linear accelerators	0.1
Lithotriptors	0.1
Image intensifiers	0.1
Televisions and video monitors	0.1
Computer screens and terminals	0.1
Electron microscopes	0.1
High precision measuring scales	0.1
Cyclotrons	0.1
Cardiac pacemakers	0.5
Neurostimulators	0.5
Biostimulators	0.5
Magnetic media (floppy disks, etc.)	1.0
Video recorders	1.0
X-ray tubes	1.0
Radiography equipment	1.0
Analog watches and clocks	1.0

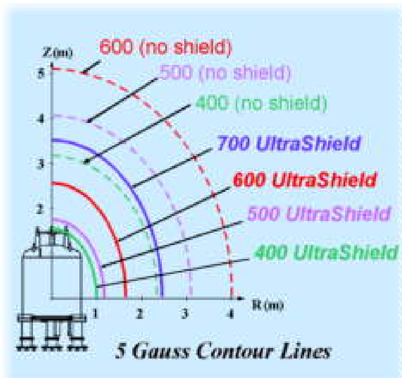
[a] CT, computed tomography.

Shielding

- The fringe field of a magnet can be reduced either by
  - Passive shielding: the use of mild steel, the steel can be placed within closed proximity to the cryostat, such that it provides a return path for the magnetic field outside the windings
    - The field should not distort the central field homogeneity
  - Active shielding: Additional superconducting coils located outside the main coils windings. These coils are connected in series with the main coil windings and have their current flow direction reversed

Comparison of the stray fields (actively shielded and unshielded)





Eddy Currents

- Due to field gradients, currents are induced in the metal of the magnet cryostat creating eddy currents.
- These eddy currents create an array of spherically harmonic fields.