MRI Systems I: B0

M219 - Principles and Applications of MRI

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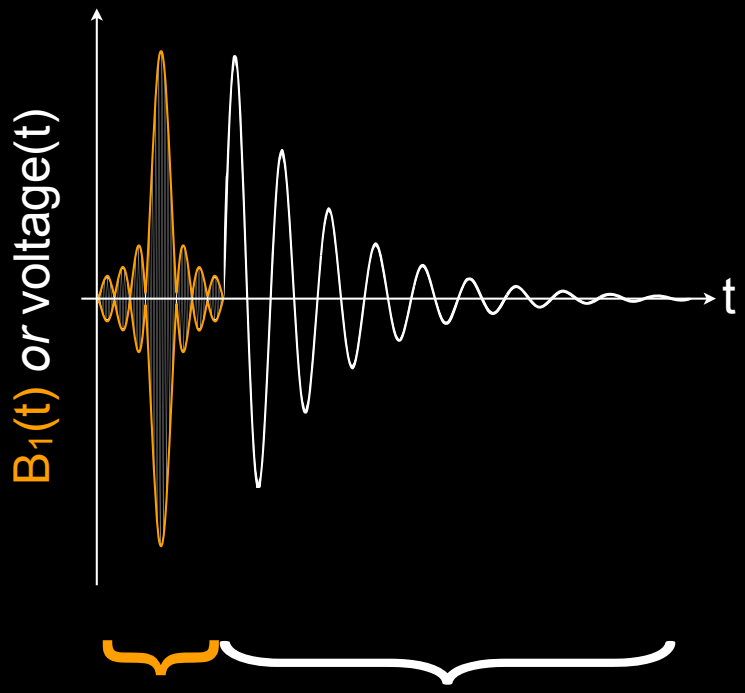
1/5/2022

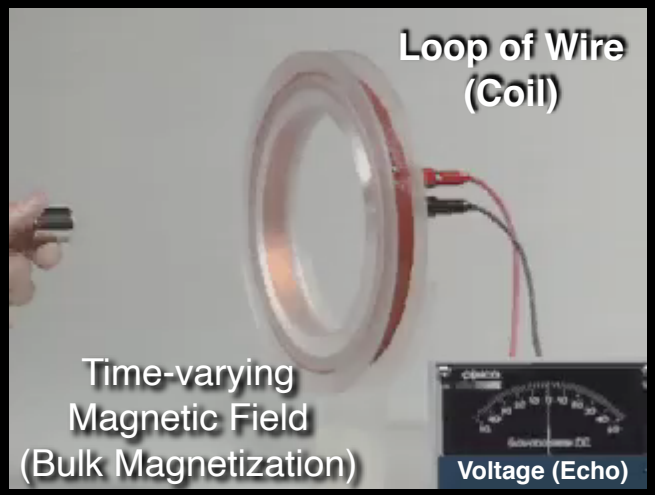
What is MRI?

- Magnetic
  - We need a big magnet
- Resonance
  - Excitation energy has to be on-resonance
- Imaging
  - We can make pretty pictures

What is MRI?

MRI follows a classic excitation-reception paradigm.





Faraday's Law of Induction

MRI encodes spatial information and image contrast in the echo.

Requirements for MRI

- NMR Active Nuclei
  - e.g. ^{1}H in H_20
- Magnetic Field (B_0): Polarizer
- RF System (B_1): Exciter
- Coil: Receiver
- Gradients (G_X, G_Y, G_Z): Spatial Encoding

MRI Hardware

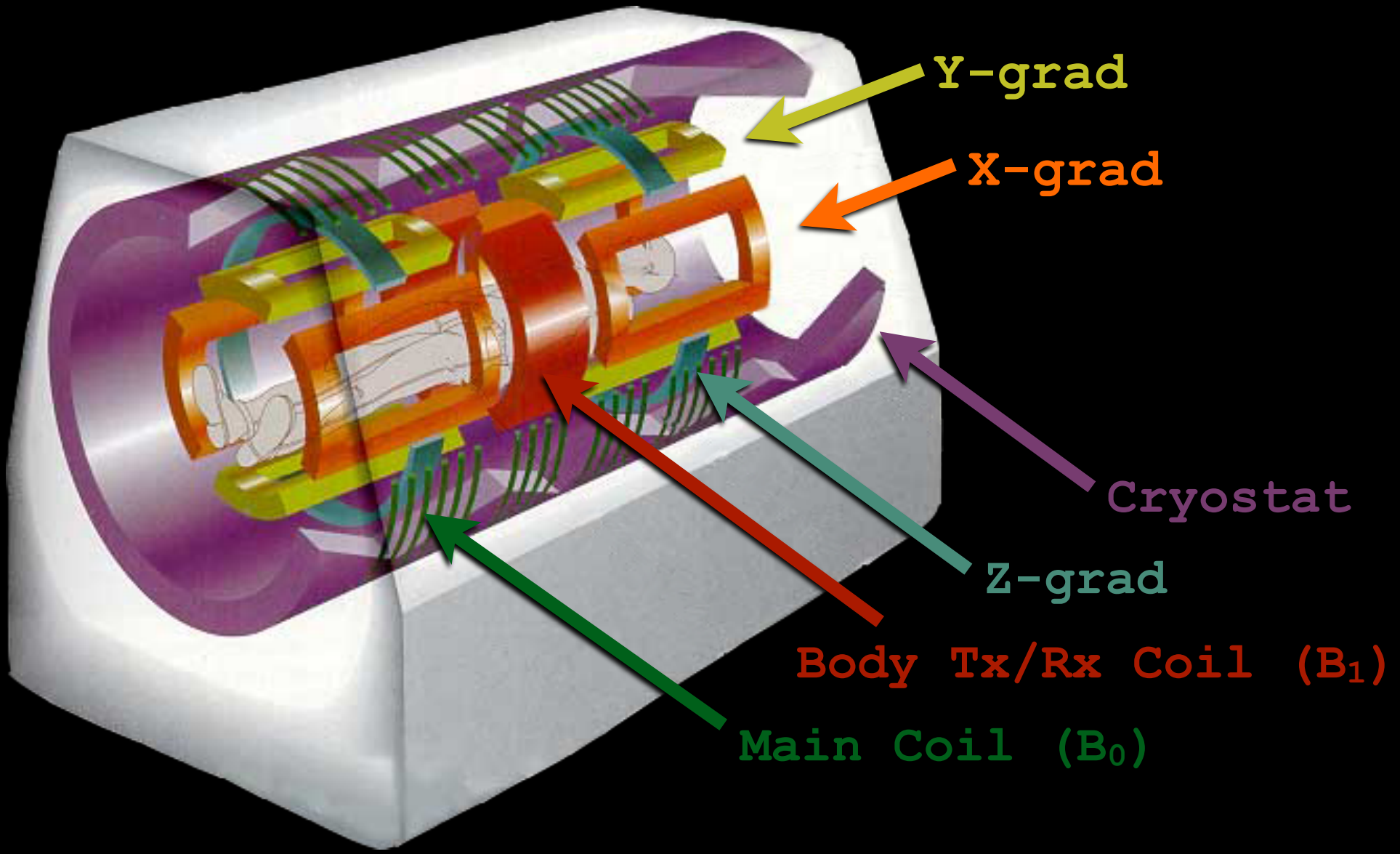
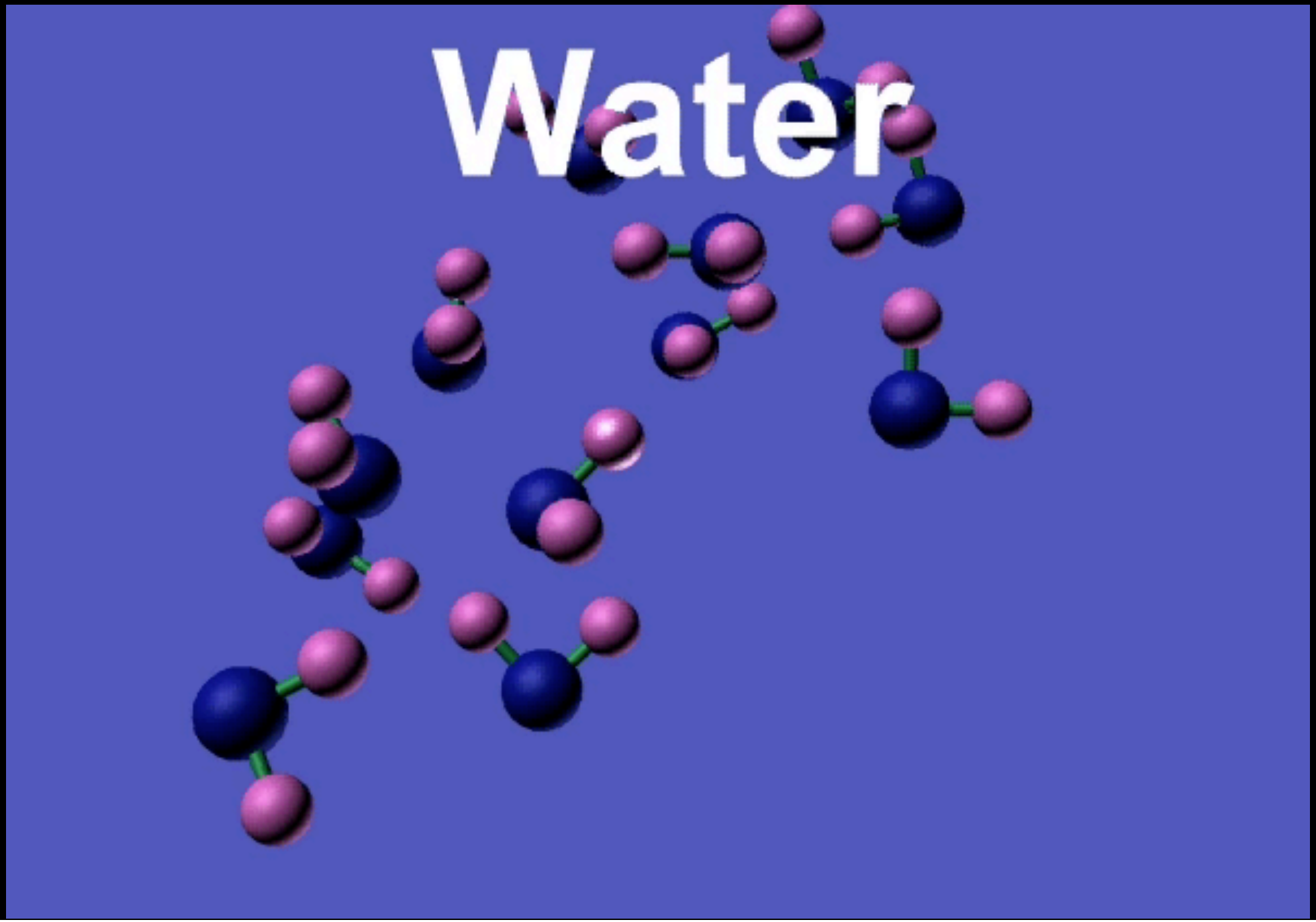


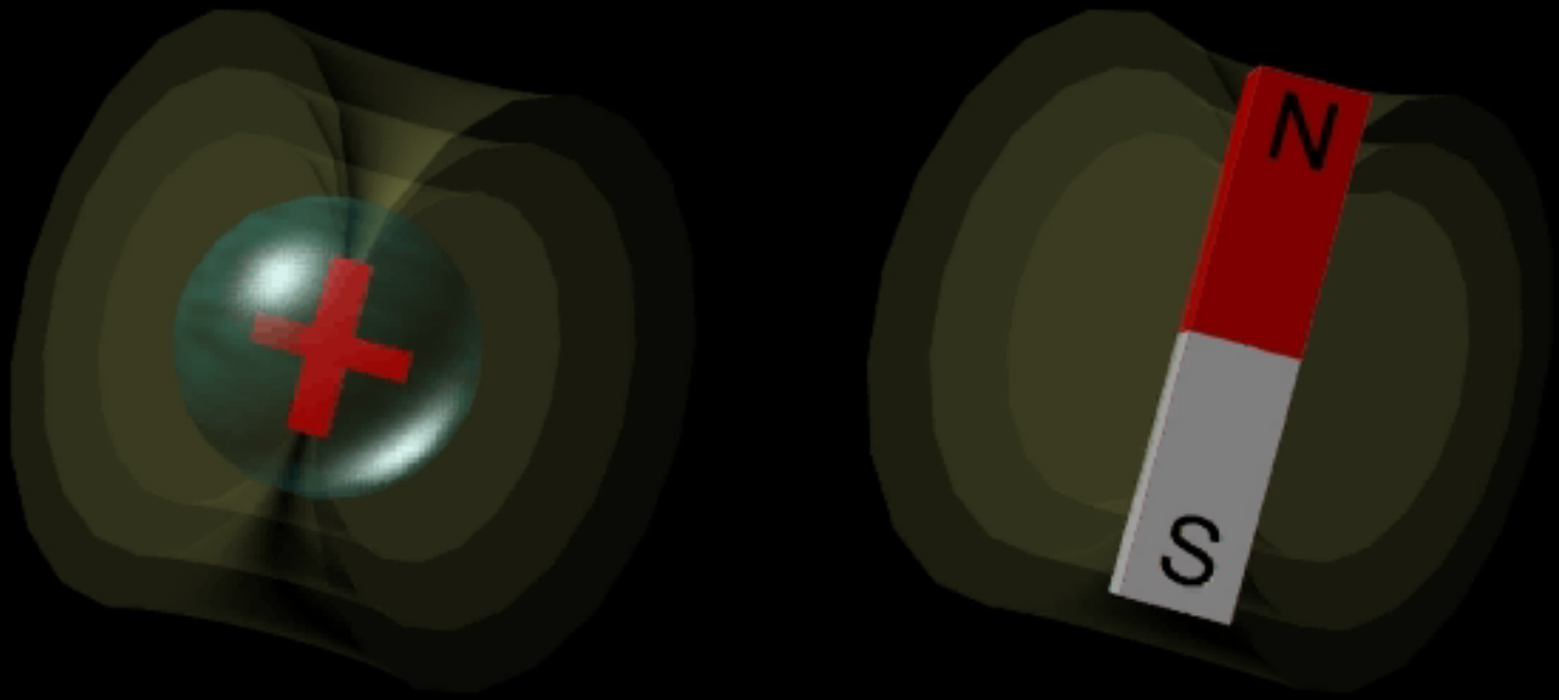
Image Adapted From: http://www.ee.duke.edu/~jshorey

Nuclear Magnetic Resonance

NMR Phenomena



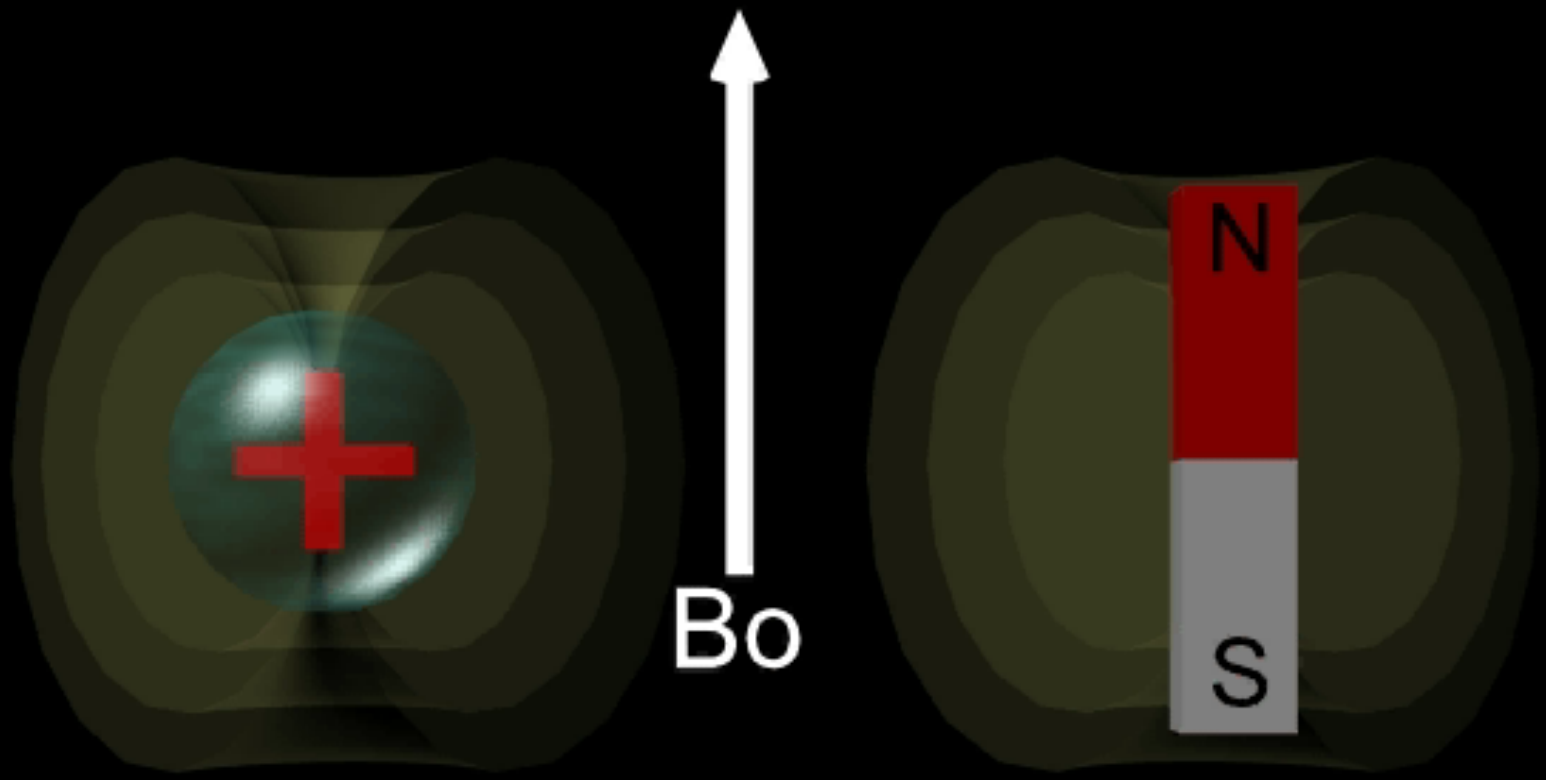
Magnetic Moment



Charge
Spin
} Magnetic Moment

Protons behave like small magnets because of spin and charge.

Magnetic Moment



Charge
Spin
} Magnetic Moment

Protons (small magnets) align with an external magnetic field (B_0).

Angular Momentum

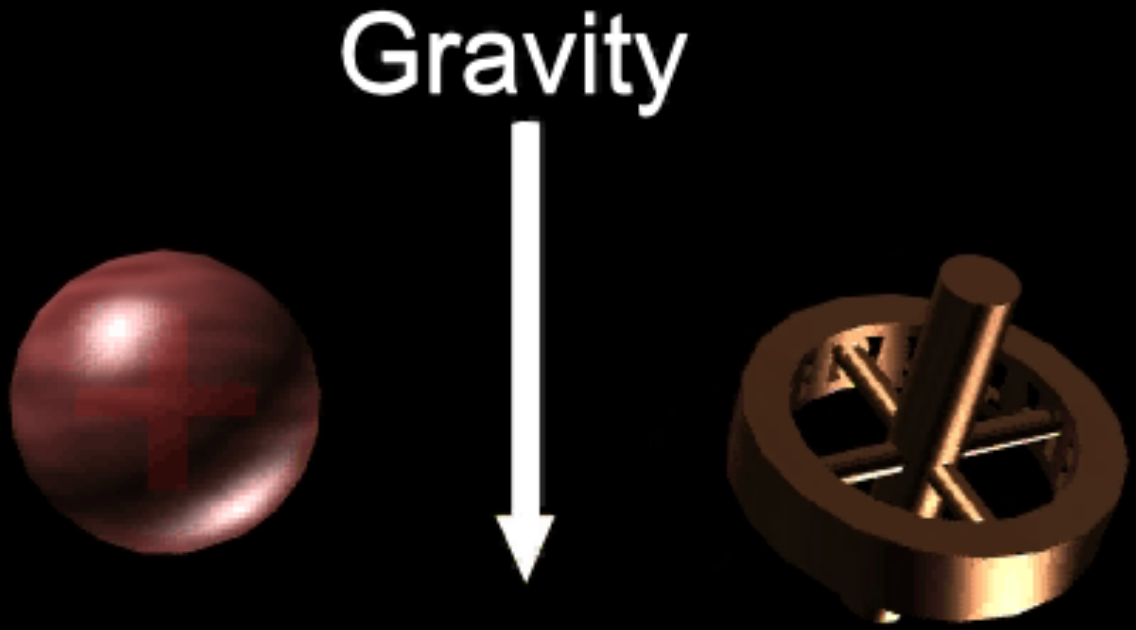
Spin

Mass

} Angular Momentum

Protons have angular momentum because of spin and mass.

Precession (Top Analogy)



Precession

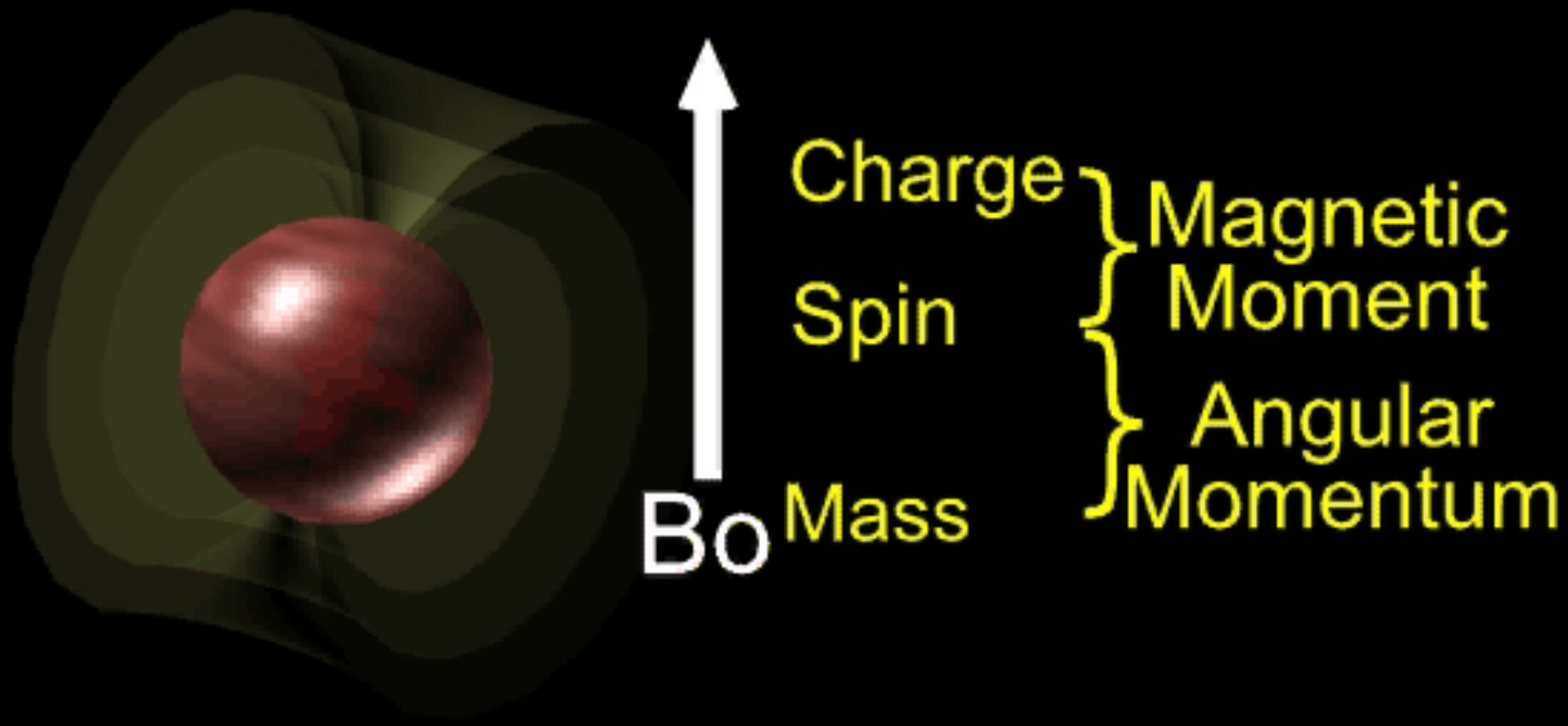
Spin

Mass

} Angular Momentum

A spinning tops precesses in a gravitational field.
A spinning proton precesses in a magnetic (B_0) field.

Larmor Frequency



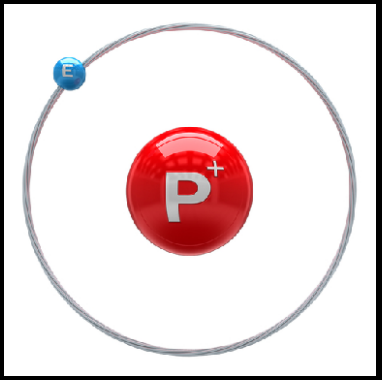
$$\text{Larmor Frequency} = \omega = \gamma B_o$$

The frequency of precession is the Larmor frequency.

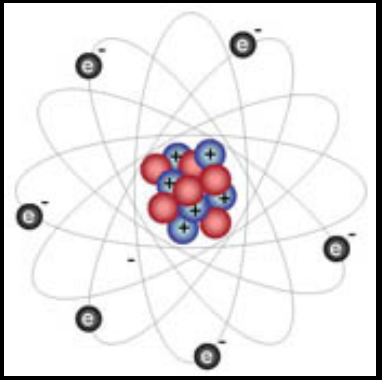
NMR Active Nuclei

- Spin + Charge + Mass $\Longrightarrow$ NMR Active
  - Spin? ***Intrinsic*** form of angular momentum.
- Nuclei have spin angular momentum if:
  - Odd atomic mass (# protons+neutrons)

    And/Or
  - Odd atomic number (# of protons)
- Spin angular momentum
  - Leads to precession
  - Spin ≠ precession (a top spins *and* precesses)
- Frequency of precession (Larmor Frequency)
  - Gyromagnetic Ratio (γ)
    - Physical constant
    - Unique for each NMR active nuclei



Hydrogen


Carbon-13

What is so special about ^{1}H? Spin, charge, and mass!

Larmor Equation

- Spin≠Precession
  - Protons *intrinsically* have spin
  - Protons *precess* in the presence of a B-field
- Larmor frequency increases with:
  - Larger B_0
  - Higher gyromagnetic ratio
  - Higher frequencies produce stronger signals...

$$\omega = \gamma B_0$$

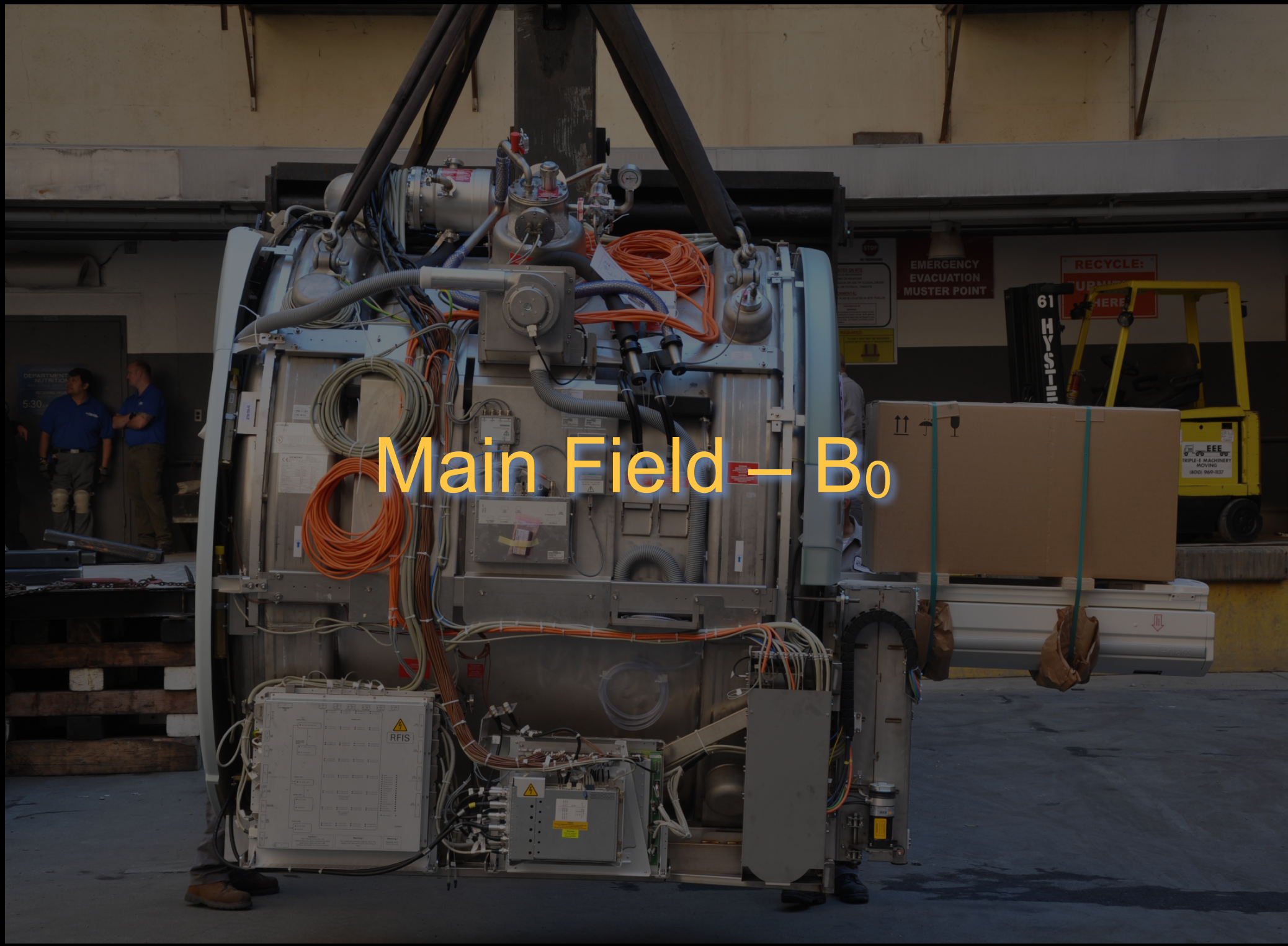
NMR Active Nuclei

Isotope	*Spin [I]*	Gyromagnetic Ratio [MHz/T]	Relative Sensitivity	Natural Abundance	Absolute Sensitivity
^{1}H	**1/2**	**42.57**	**1**	**0.9980**	**9.98E-01**
^{2}H	1	6.54	9.65E-06	0.0002	1.93E-09
^{12}C	0	---	---	0.9890	---
^{13}C	**1/2**	**10.71**	**0.016**	**0.0110**	**1.76E-04**
^{14}N	1	3.08	0.001	0.9960	9.96E-04
^{15}N	**1/2**	**-4.32**	**0.001**	**0.0040**	**4.00E-06**
^{16}O	0	---	---	0.9890	---
^{17}O	5/2	-5.77	0.029	0.0004	1.16E-05
^{19}F	**1/2**	**40.05**	**0.83**	**1.0000**	**8.30E-01**
^{23}Na	**3/2**	**11.26**	**0.093**	**1.0000**	**9.30E-02**
^{31}P	**1/2**	**17.24**	**0.066**	**1.0000**	**6.60E-02**

The ***relative sensitivity*** is at constant magnetic field and equal number of nuclei
The ***absolute sensitivity*** is the relative sensitivity multiplied by natural abundance

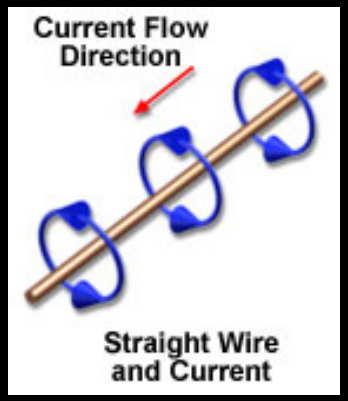
MRI Signal

- **Signal from:**
  - Soft tissues
    - Muscle, organs, fat, etc.
  - Fluids
    - CSF, Blood, Synovial, etc.
- **Signal *not* from:**
  - Hard Tissues
    - Cortical Bone
    - Ligament/Tendon
    - Teeth
  - Gases
    - Lung air space
    - Sinuses
    - Bowel

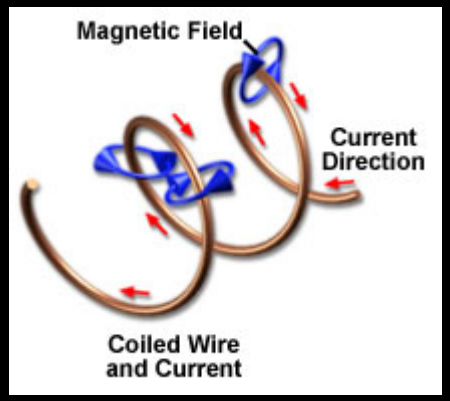


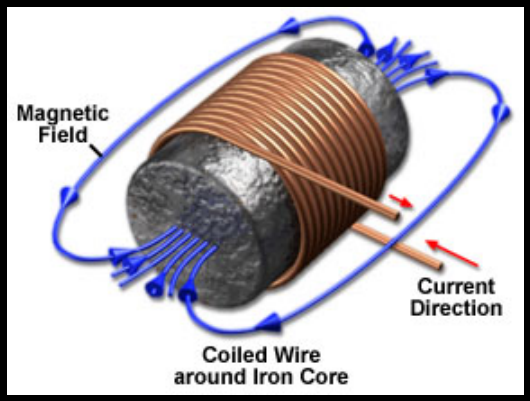
Main Field – B_0

Currents & Magnetic Fields



Left-hand Rule

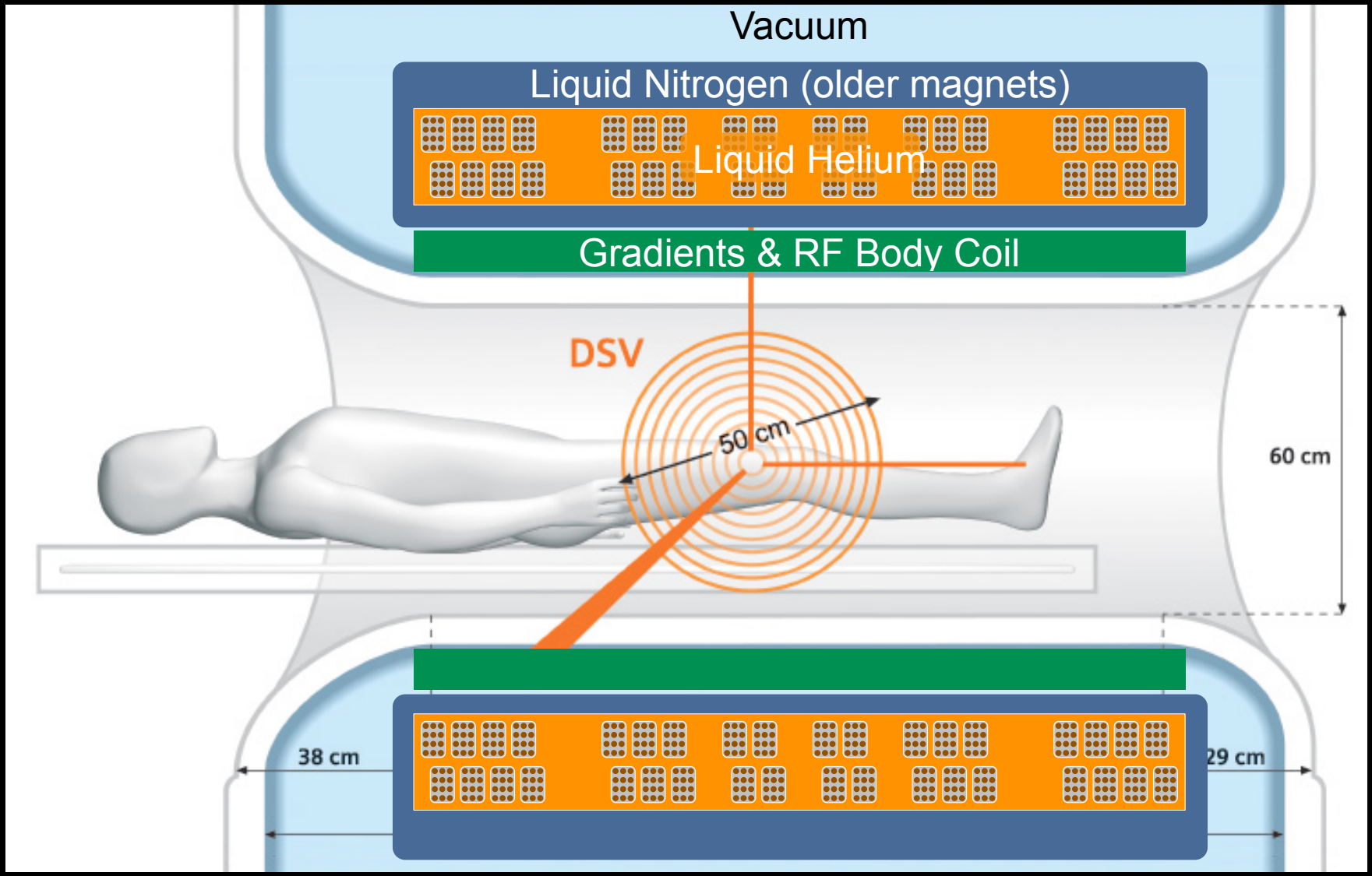




Electromagnet – A current in a wire generates a magnetic field.

http://www.magnet.fsu.edu/education/tutorials/magnetacademy/

Superconducting Electromagnet



MRI scanners are superconducting electromagnets.

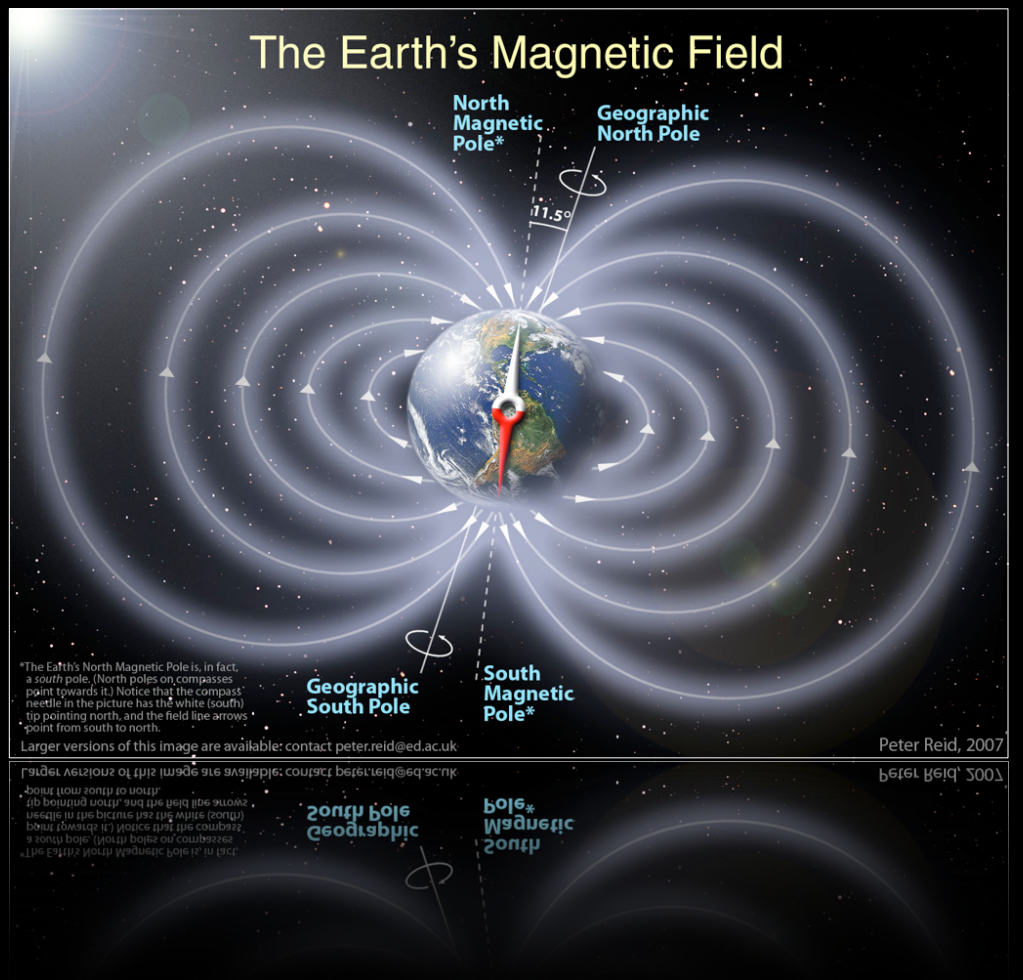
B_0 Field

- B_0 field is:
  - Spatially uniform (over a volume of interest)
    - ~50cm @ isocenter
  - Temporally stable
    - $B_0(t)=B_0(t=0)e^{-(R/L)/t}$
    - Decays <1ppm/hour
  - Oriented along the z-axis ($\vec{k}$)
    - Long axis of the scanner.

$$\vec{B}_0 = B_0\vec{k}$$

Main Field (B_0) – Strength

- Earth's magnetic field
  - 0.5 Gauss
- Refrigerator magnet
  - 10-100 Gauss
- B_0 Field
  - 0.5T = 5000 Gauss
  - 1.5T = 15000 Gauss
  - 3.0T = 30000 Gauss



B_0 Strength - Advantages

- ⬆ $B_0 \Longrightarrow$ ⬆ Polarization ($|\vec{M}|$) = ⬆ SNR
  - ⬆Polarization, therefore more $\vec{M}$ for imaging.
  - SNR $\propto B_0^{7/4}$ (⬆Polarization + ⬆Larmor Frequency)
    - ⬆ Spatial resolution
    - ⬆ Temporal resolution
    - ⬇ Scan time

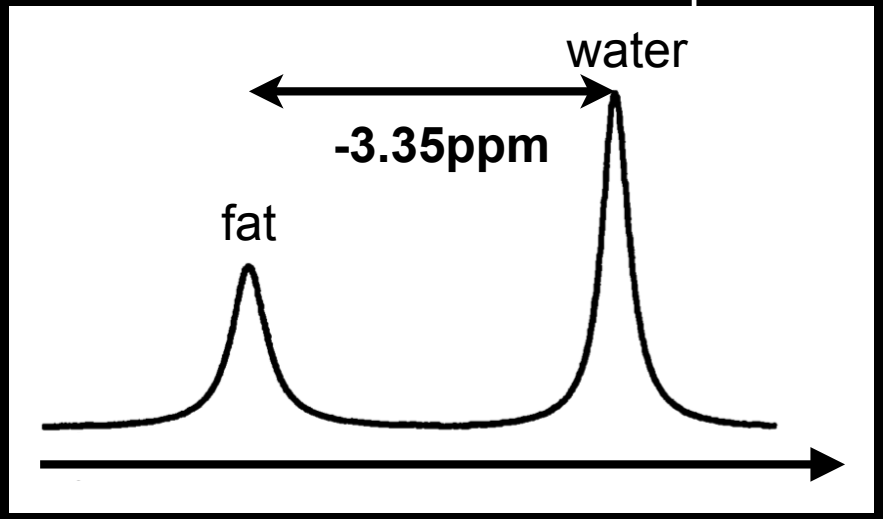
B_0 Strength - Disadvantages

- ⬆ $B_0 \Longrightarrow$ ⬆ Specific Absorption Ratio (SAR)
  - Energy absorbed by body [W/kg]
  - $SAR \propto B_0^2$
- ⬆ $B_0 \Longrightarrow$ ⬆ Cost
  - ~$1,000,000 per Tesla
  - More shielding

Higher B_0 leads to higher SAR for patients and higher costs.

B_0 Strength - Disadvantages

- ⬆ $B_0 \Longrightarrow$ ⬆ Chemical shift (Δf)
  - ⬆ Δf between fat and water
    - Fat and water have different Larmor frequencies
      - ~220Hz different at 1.5T
      - ~440Hz different at 3.0T
    - Fat is *more* spatially mis-registered @ 3T
  - Good for spectroscopy…



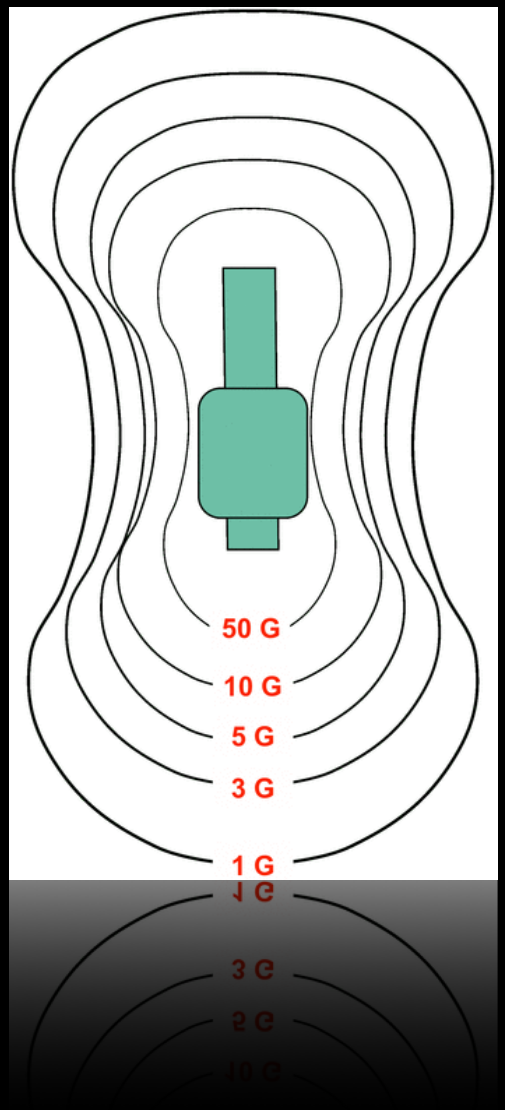
$$B = B_0 (1 - \delta)$$

$$\delta_{-CH_2} = 3.35 ppm$$

Chemical Shift – Fat (–CH_2) is ~220Hz *lower* at 1.5T

Main Field (B_0) – Shielding

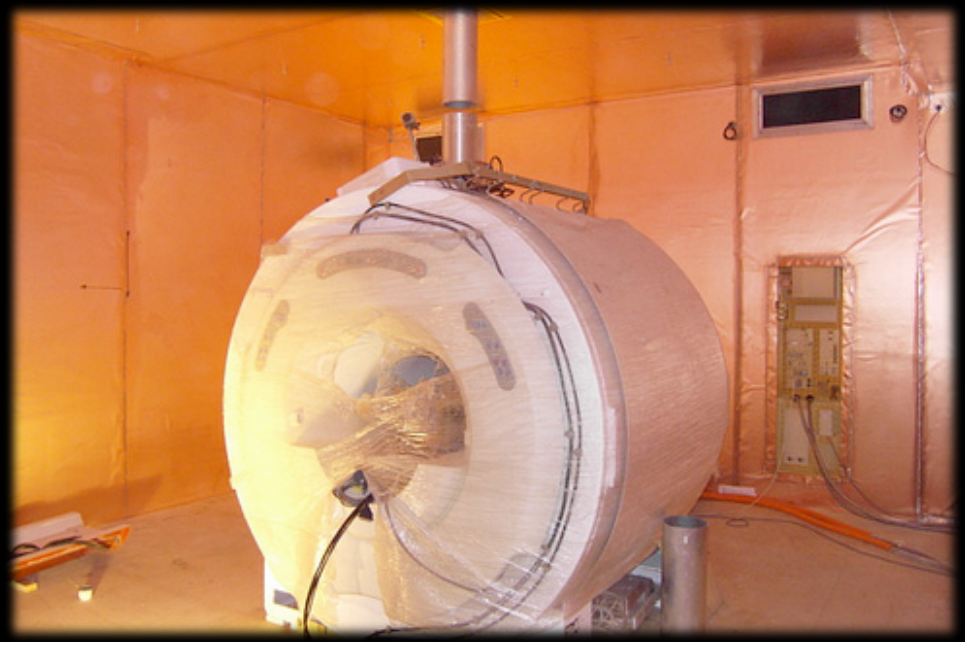
- **Problem**: The B_0 field extends well beyond the scanner.
- **Shielding** reduces B_0 foot print
  - Reduces install cost
  - Reduces interference
- **Passive Shielding**
  - Iron room shielding
  - Heavy, not cheap
- **Active Shielding**
  - Super-conducting coils that oppose (shield) B_0 fringe field
- "**Five Gauss Line**"
  - Threshold beyond which ferromagnetic objects are strictly prohibited
  - 5G=0.5mT



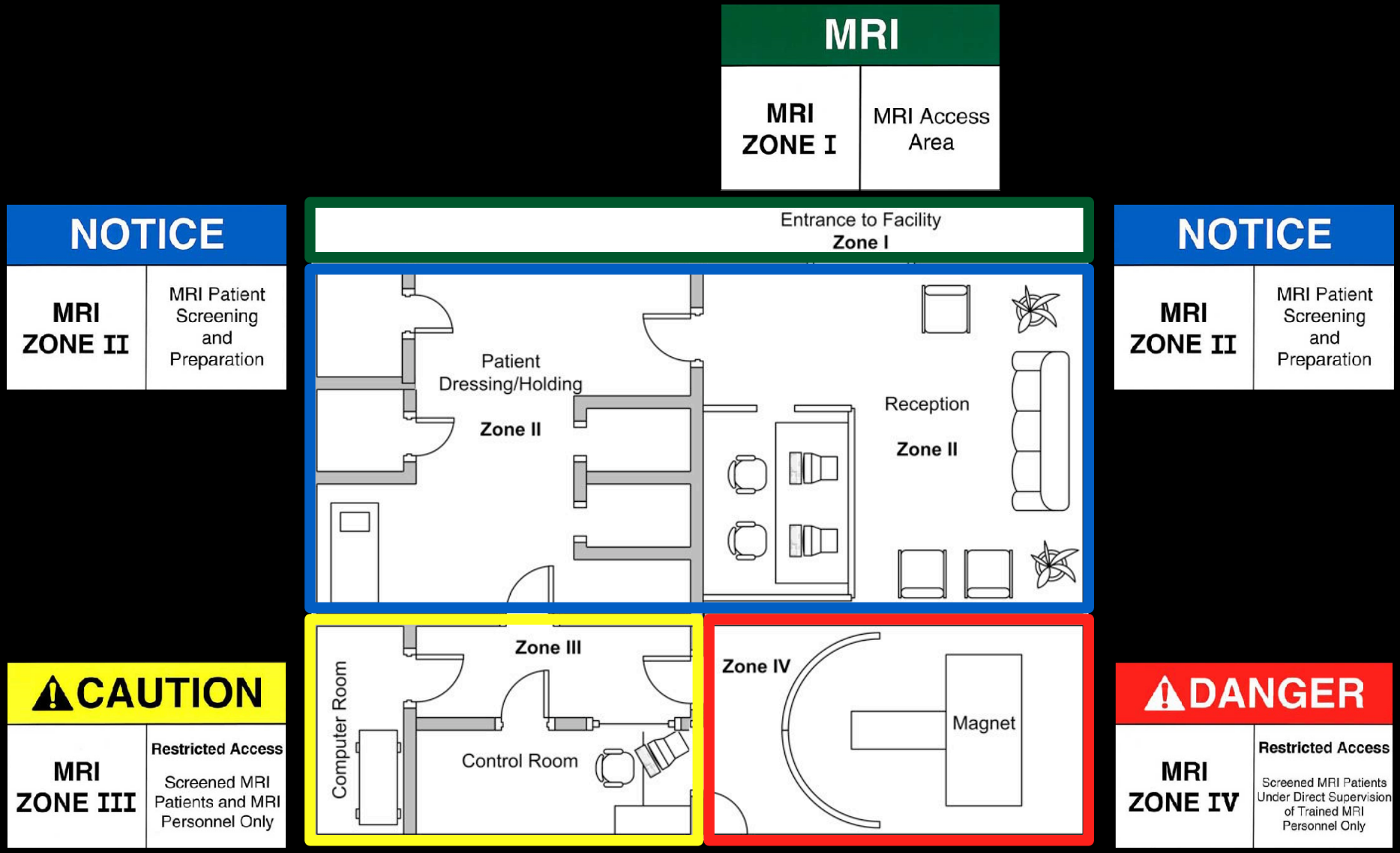
ACR Guidance Document on MR Safe Practices: 2013; *JMRI* 37:501–530 (2013)

RF Shielding

- RF fields are close to FM radio
  - ^{1}H @ 1.5T ⇒ 63.85 MHz
  - ^{1}H @ 3.0T ⇒ 127.71 MHz
  - KROQ ⇒ 106.7 MHz
- Need to shield local sources from interfering
- Copper room shielding required



MRI Zones



ACR Guidance Document on MR Safe Practices: 2013; *JMRI* 37:501–530 (2013)

B_0 Hardware Anatomy

Superconducting Electromagnets

- MRI scanners are superconducting electromagnets
  - B-field is generated by flowing electricity
  - Permanent magnet MRI are uncommon

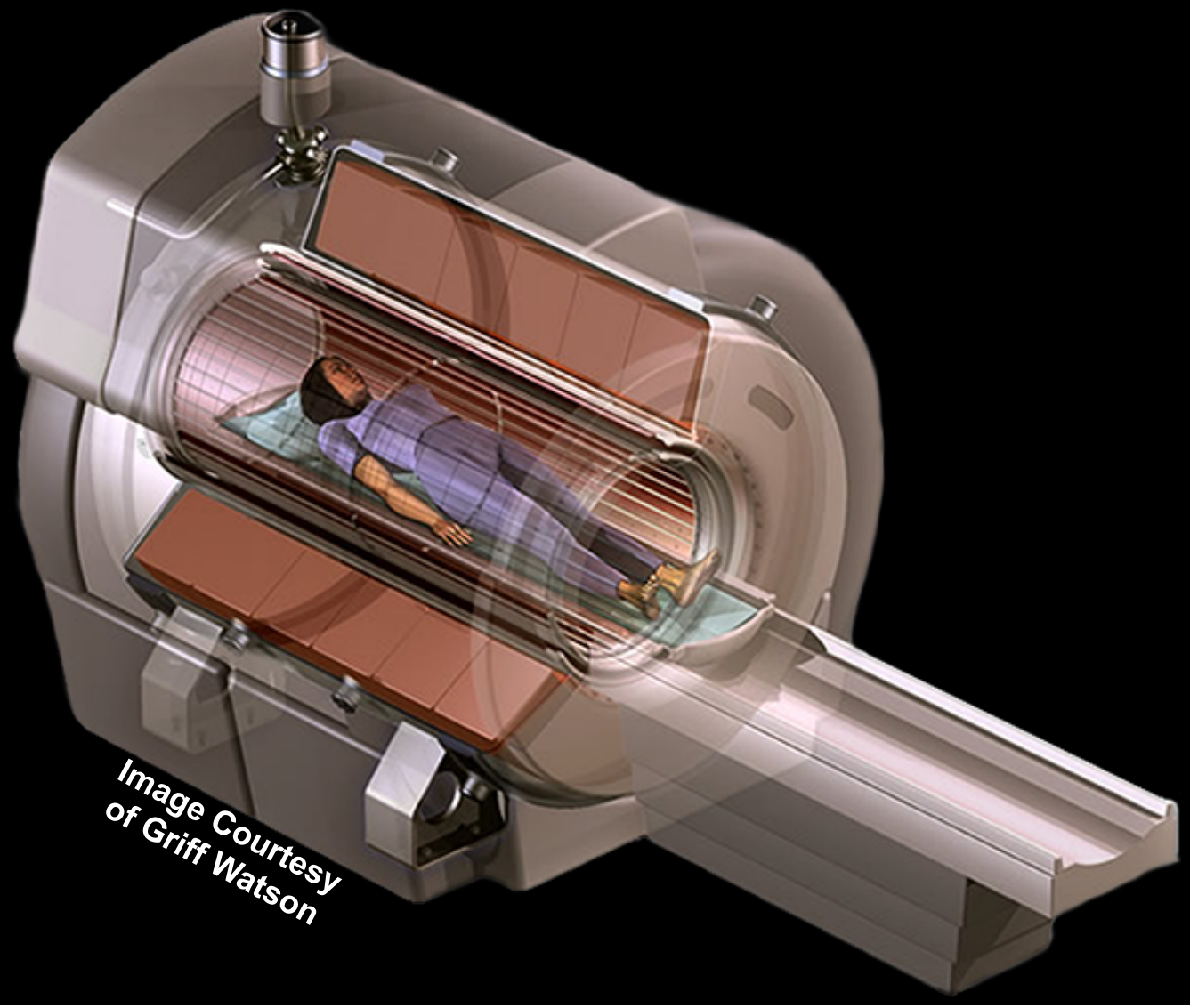
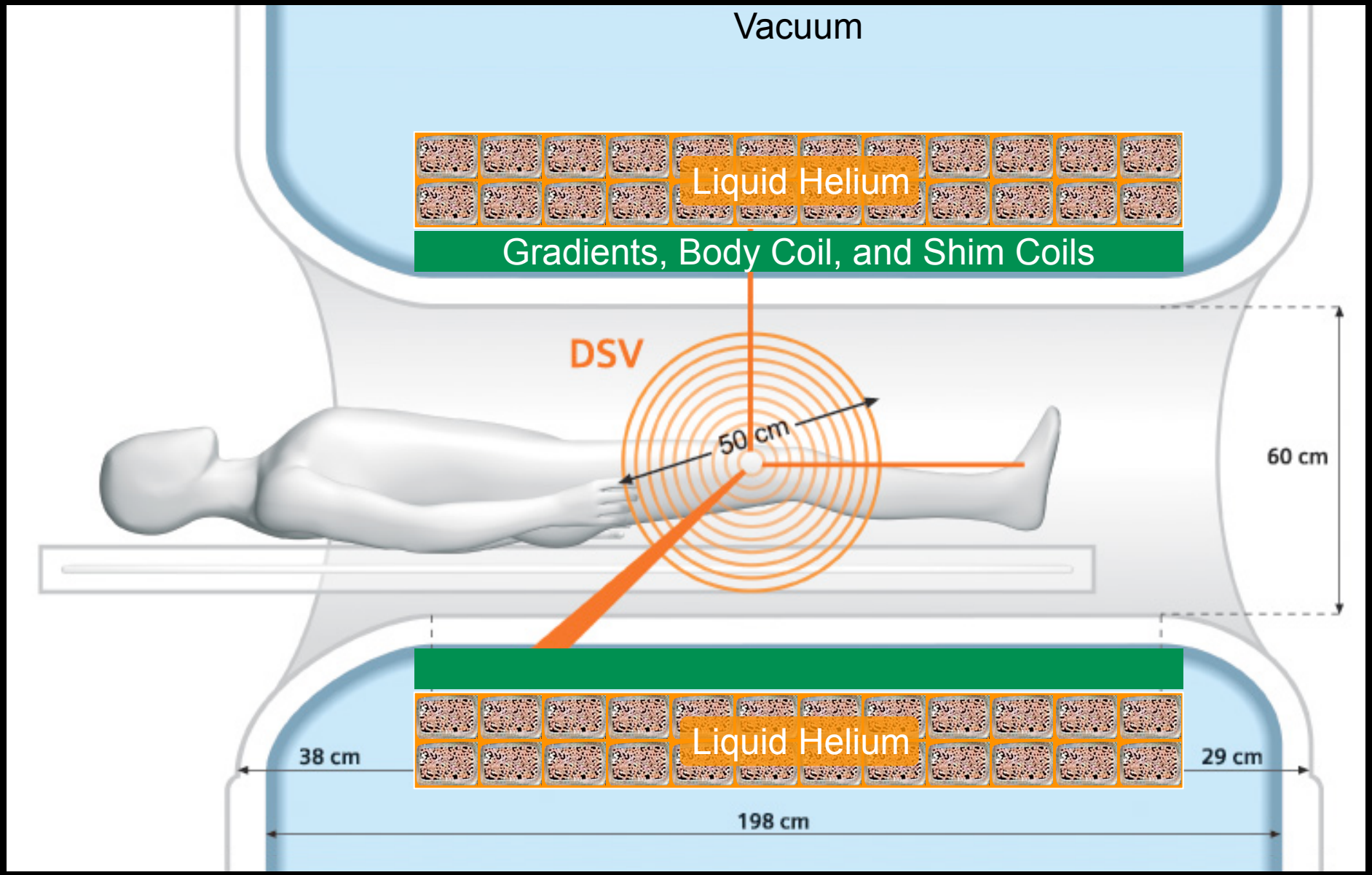
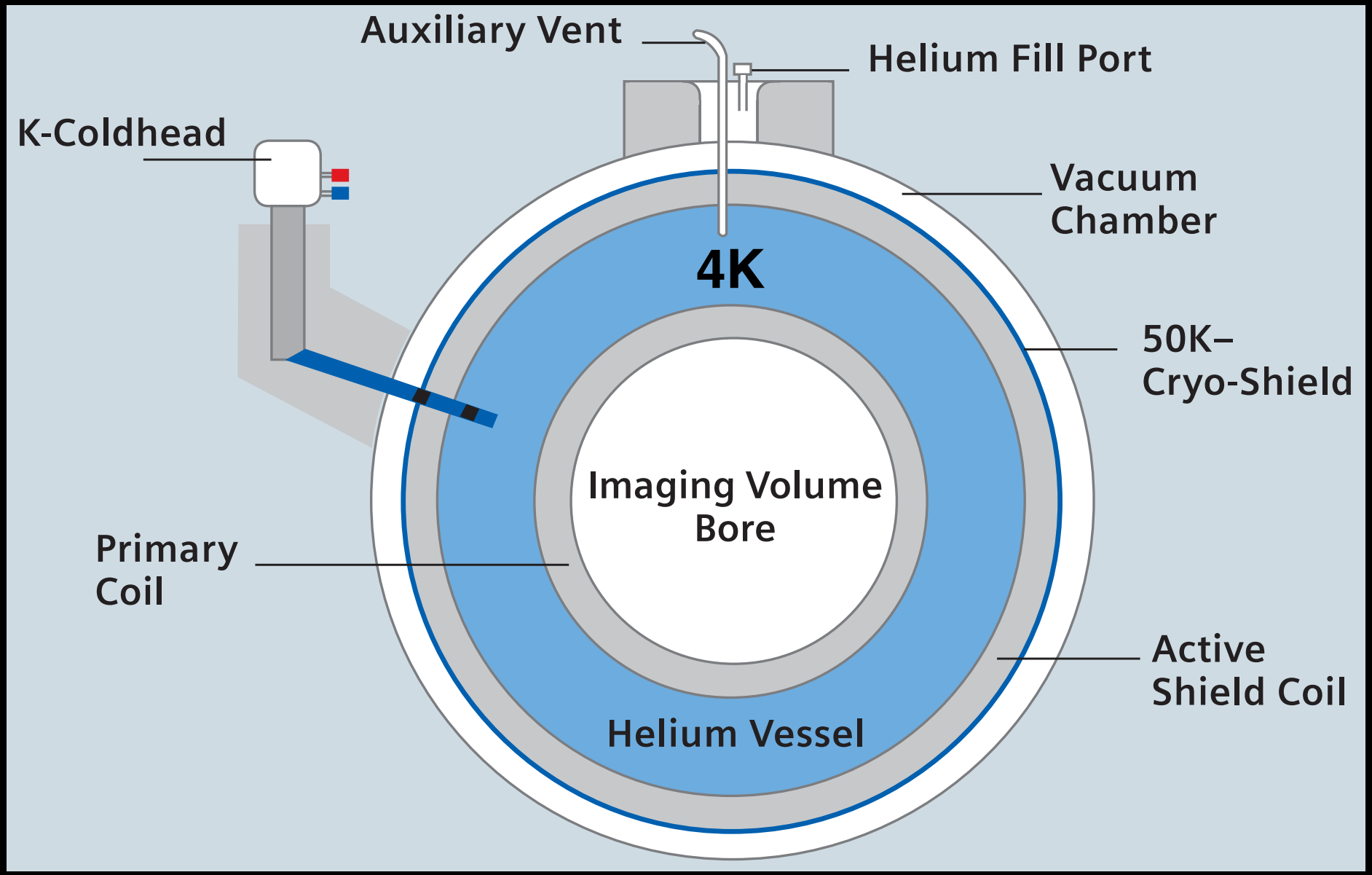


Image Courtesy of Griff Watson

Superconducting Magnet

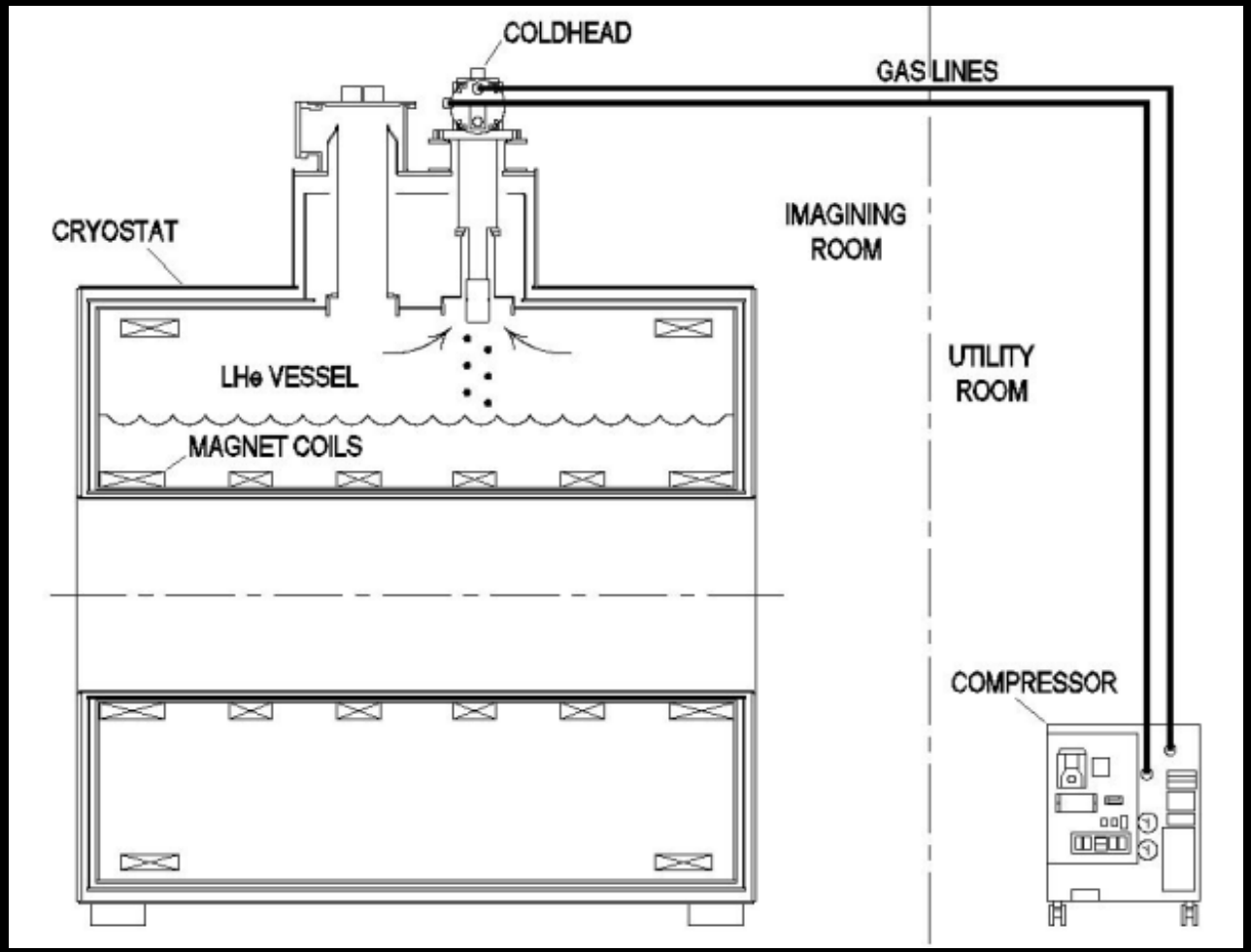


Superconducting Electromagnets



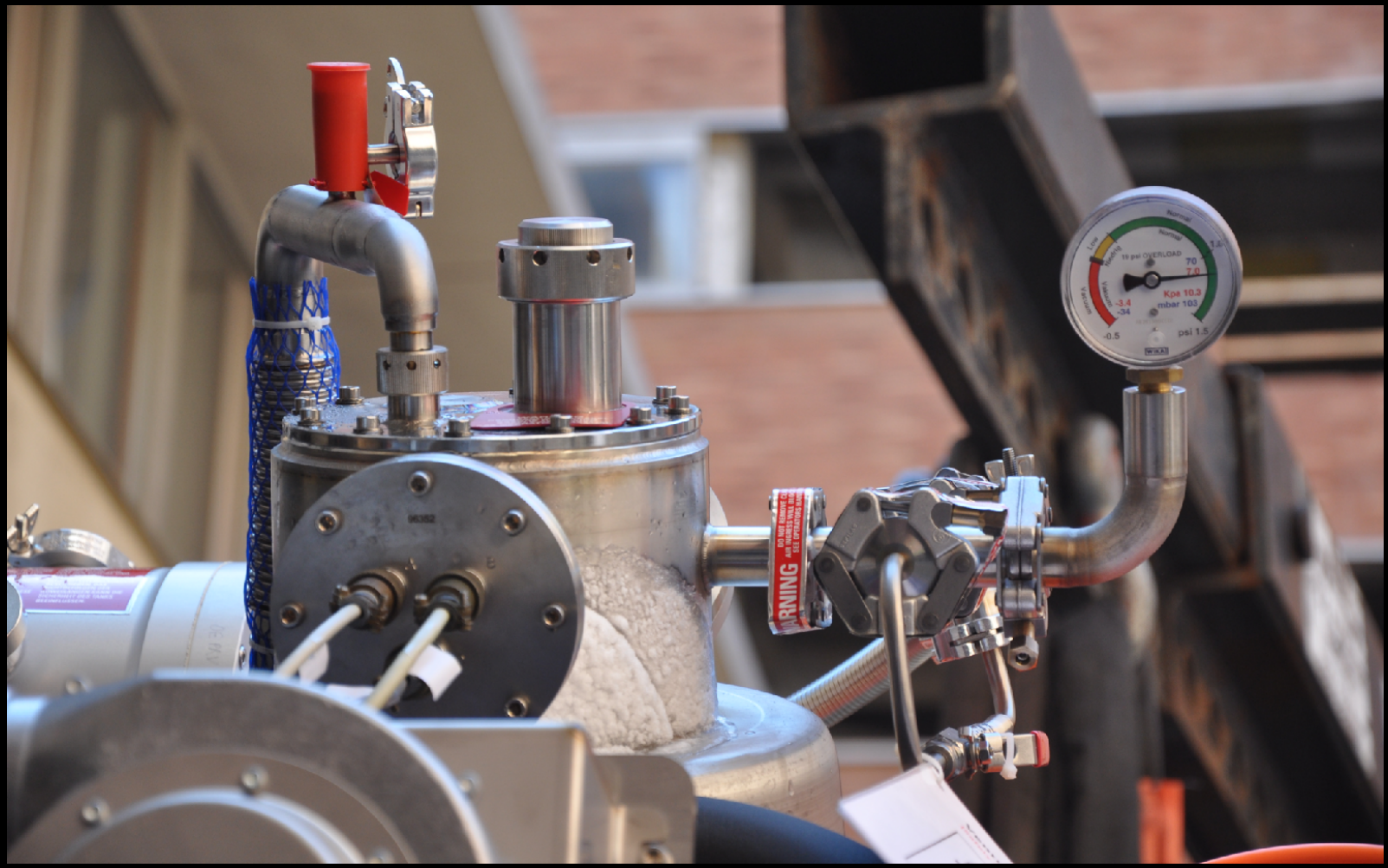
www.siemens.com/magnetom-world (Magnetom Flash 2/2008)

Coldhead (Cryocooler)



Re-condenses helium vapor and returns liquid helium to vessel.

Helium Fill Port

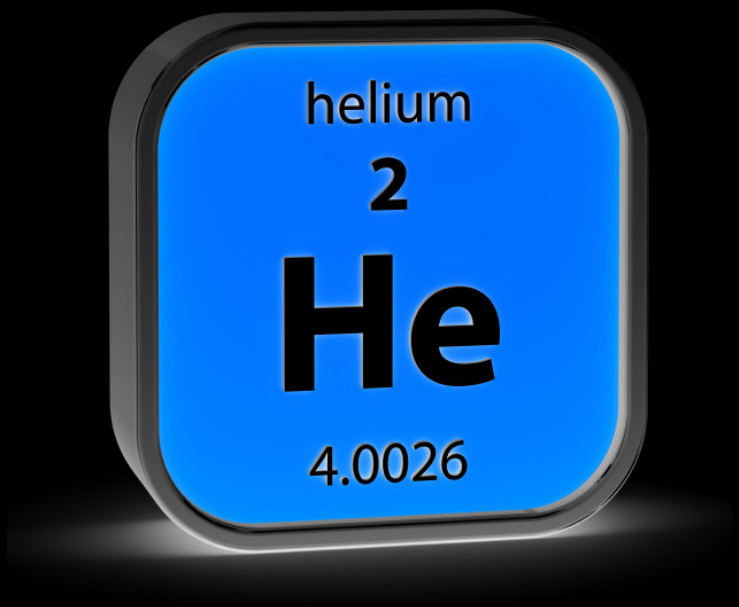


Helium boils off at 0 to 0.03 L/hour.
$10-$25 per liter of liquid Helium.

Zero Boil-off and Low Volume (~20L vs 2000L) systems are emerging.

Liquid Helium

- **Where does helium come from?**
  - **Extracted from natural gas**
  - **Strategic helium reserve**
  - **Helium that escapes to atmosphere is lost *forever*.**
- **Zero boil-off design**
  - **Captures and re-compresses cryogen**
  - **Saves 700-1300L per year**

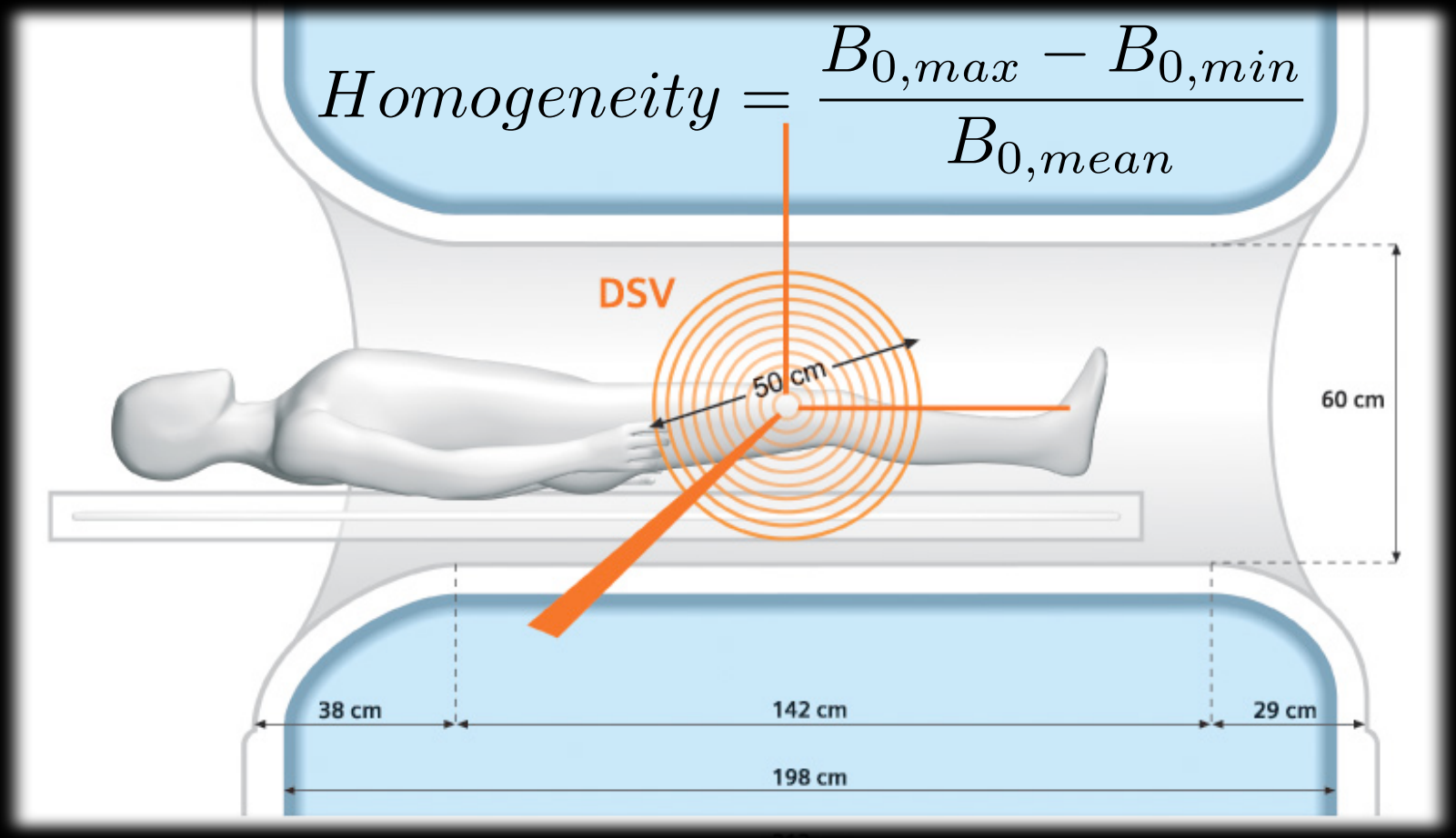


B_0 Field Inhomogeneity

B_0 Field Inhomogeneity

- **Problem**: Magnets aren't perfect
  - 100s ppm for best bare magnets
- B_0 field inhomogeneity induces image and phase artifacts
  - geometric distortion, image shifts, decreased SNR, and off-resonance errors
- B_0 Homogeneity improved by:
  - **Passive Shimming**
    - Placement of ferromagnetic structures within the bore to improve field uniformity
  - **Active Shimming**
    - Small "always on" currents in the gradient coils improve the field
    - Fine-tuned during pre-scan

B_0 Field Inhomogeneity

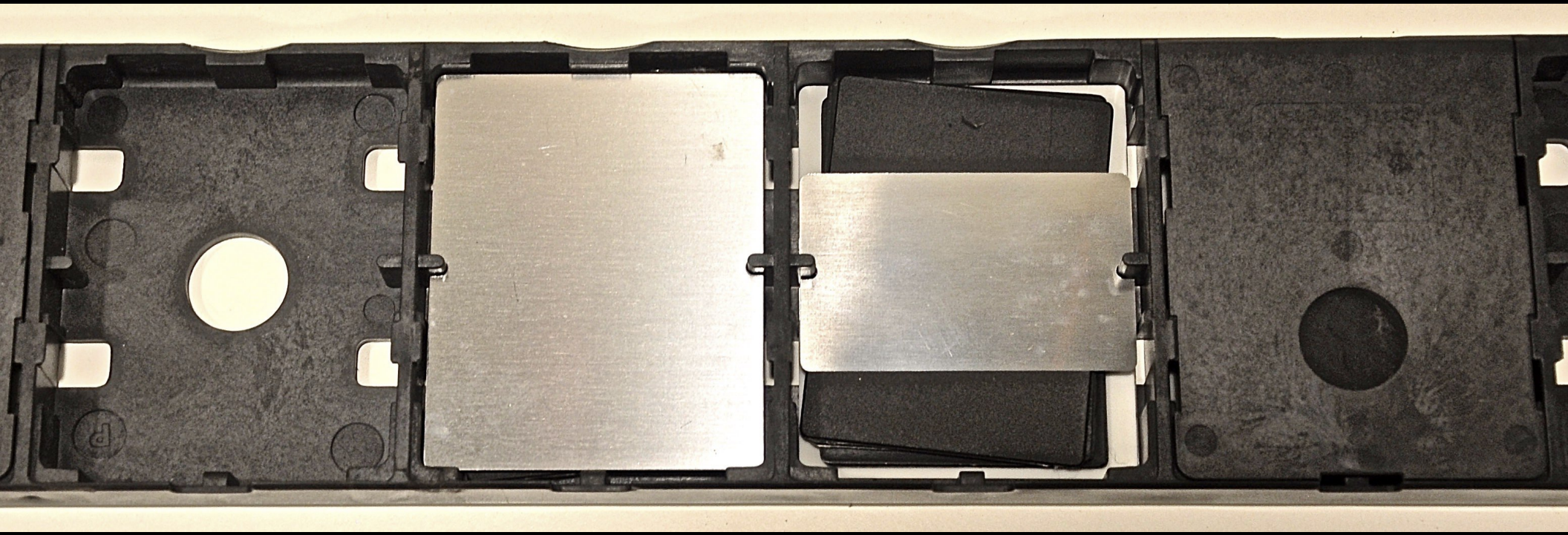


Homogeneity

- 0.25 ppm VRMS* for a 40 cm (16 inch) DSV†
- 1.00 ppm VRMS for a 50 cm (20 inch) DSV
  - <4ppm peak-peak variation

Passive B_0 Field Shims

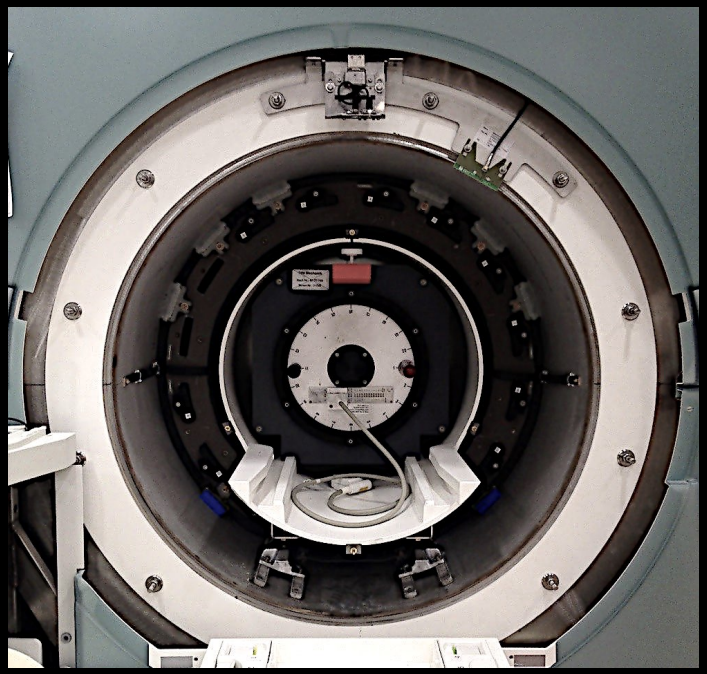
Passive Shim Tray

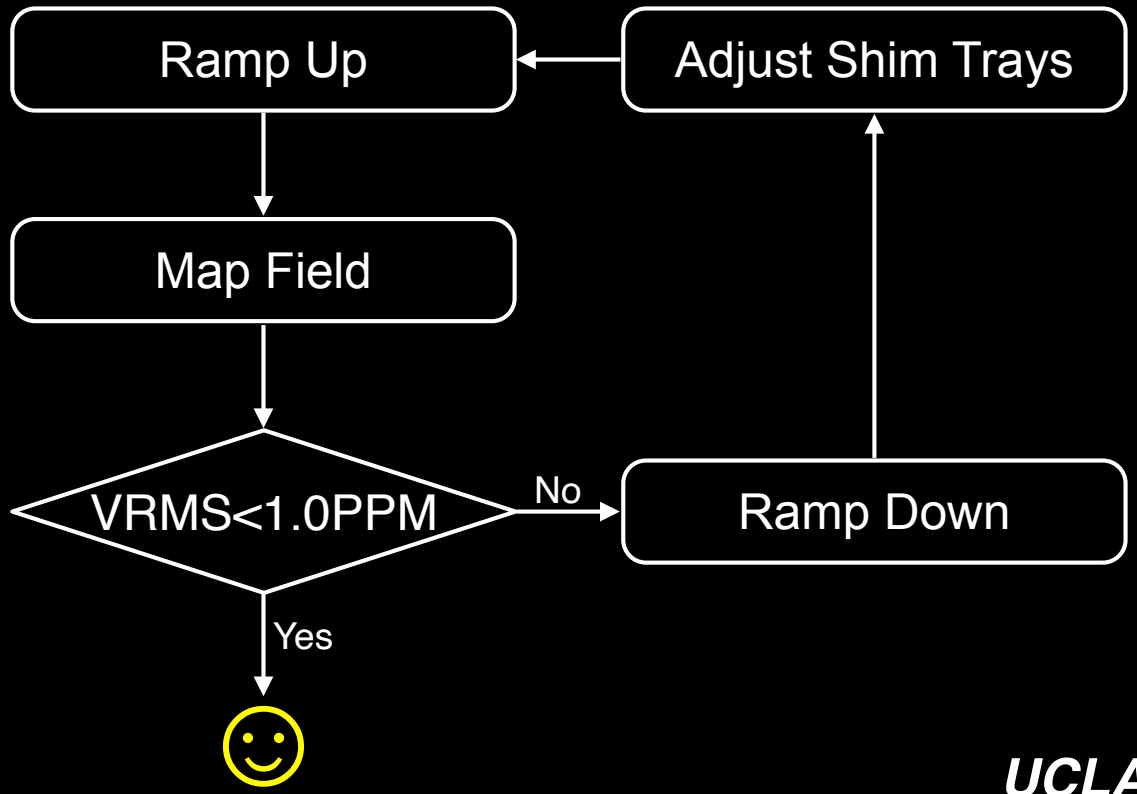


No Shim Card | Large Shim Card | Small Shim Card | Sealed Shim Deck

Passive B_0 Field Shims

- Small ferromagnetic cards are slotted into trays to shape the magnetic field and off-set field inhomogeneities.
- First order compensation for:
  - Manufacturer tolerances
  - Local conditions





Active B_0 Field Shims

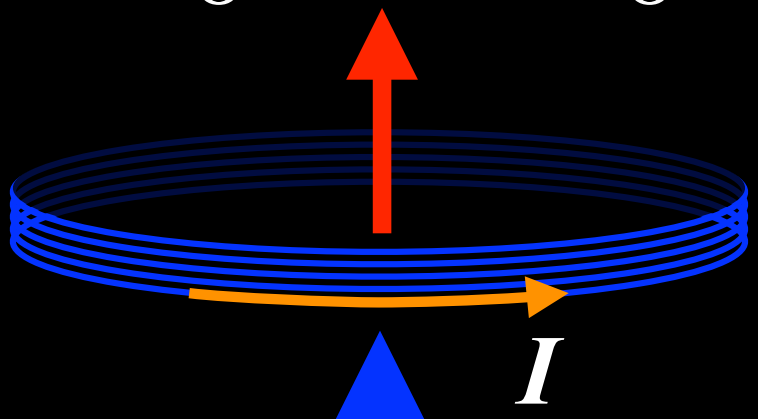
- Several ***active shim coils*** within the magnet
  - Small constant +/- currents tune the shim.
  - The small magnetic fields compensate for inhomogeneities.

- Second order compensation for
  - Coil effects
  - Patient effects

- Passive+Active shimming still results in an imperfect magnetic field.

Z-Axis Active Shim

$$B_0 + \delta B_0$$



$$B = \mu I N L^{-1}$$

Maxwell Pair Coil

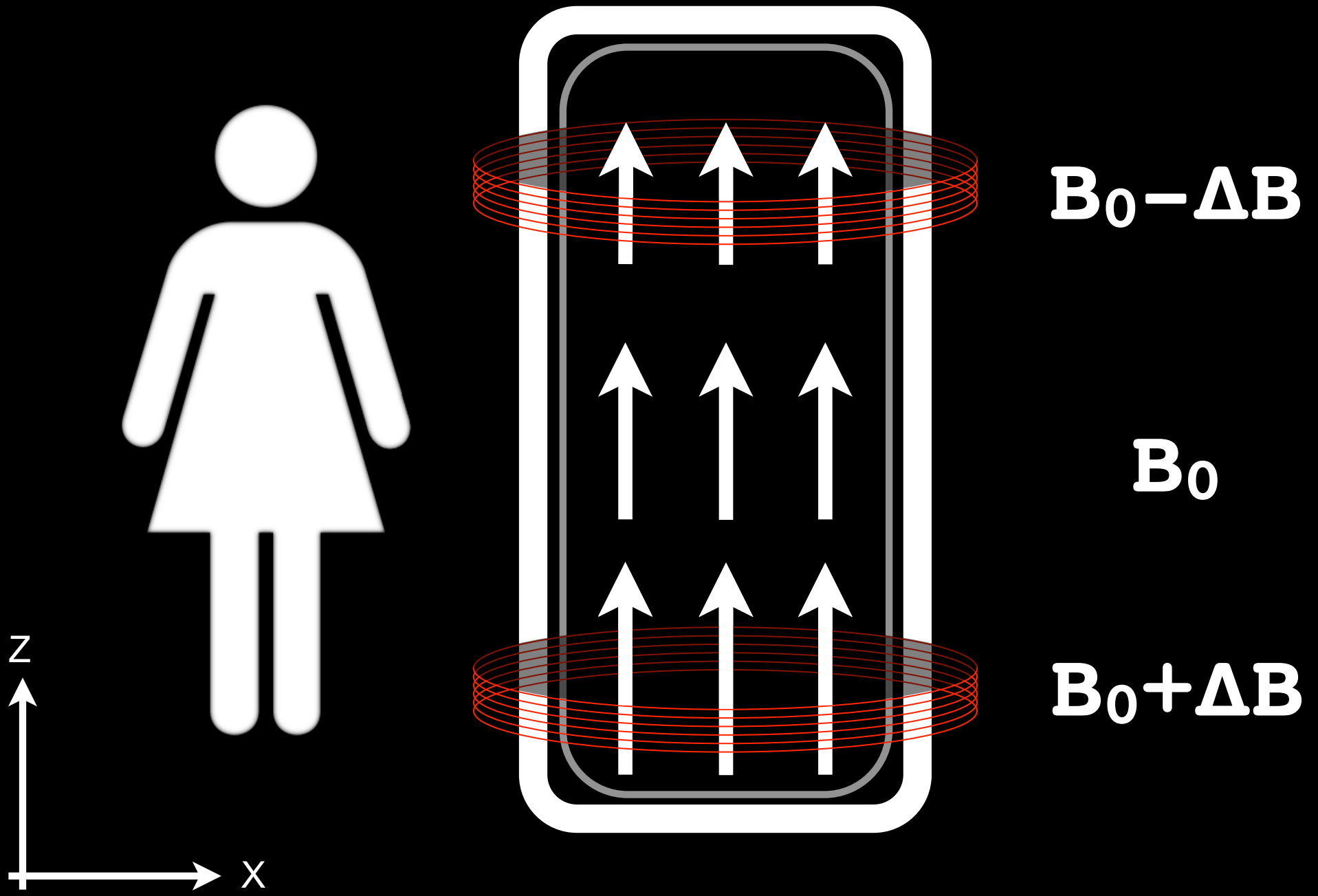
I

B_0

I

$$B_0 - \delta B_0$$

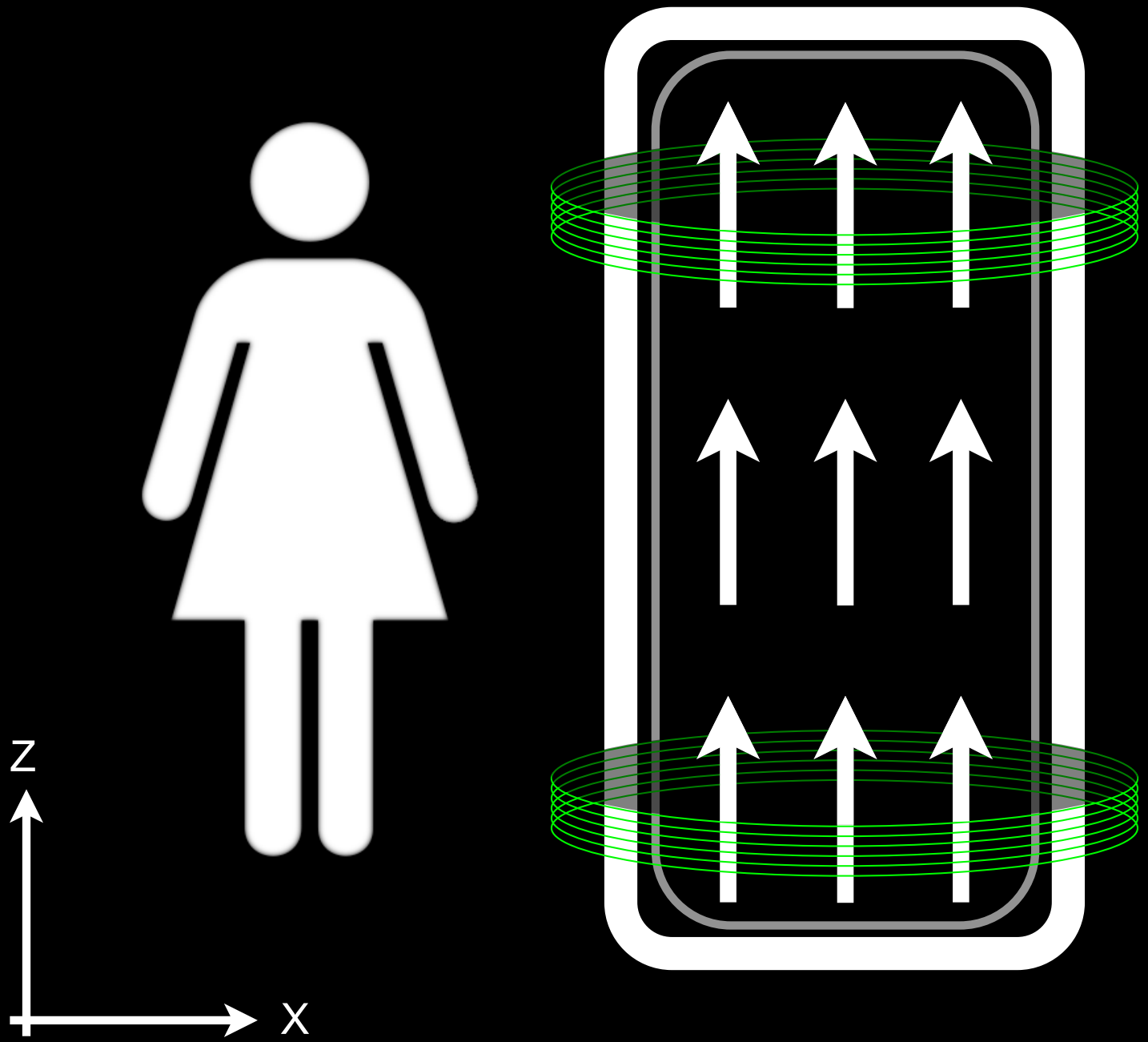
Z-Axis Active Shim - **Off**



B_0 is imperfect with the active shim coil turned off or poorly tuned.

David Geffen School of Medicine
UCLA Radiology

Z-Axis Active Shim - **On**

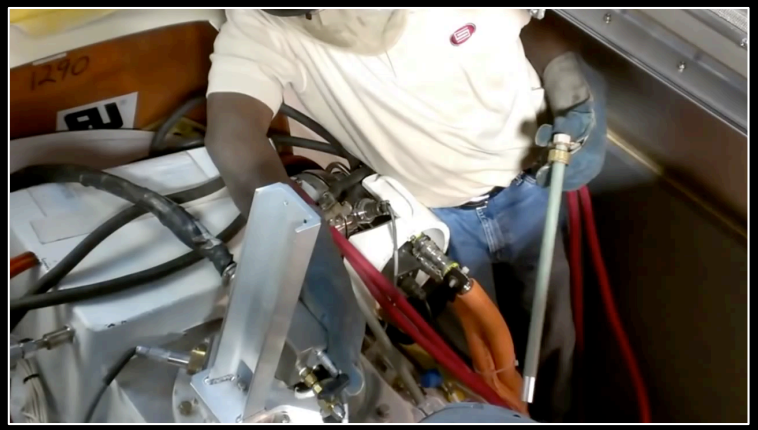


B_0 is more homogeneous with the active shim coil turned on.

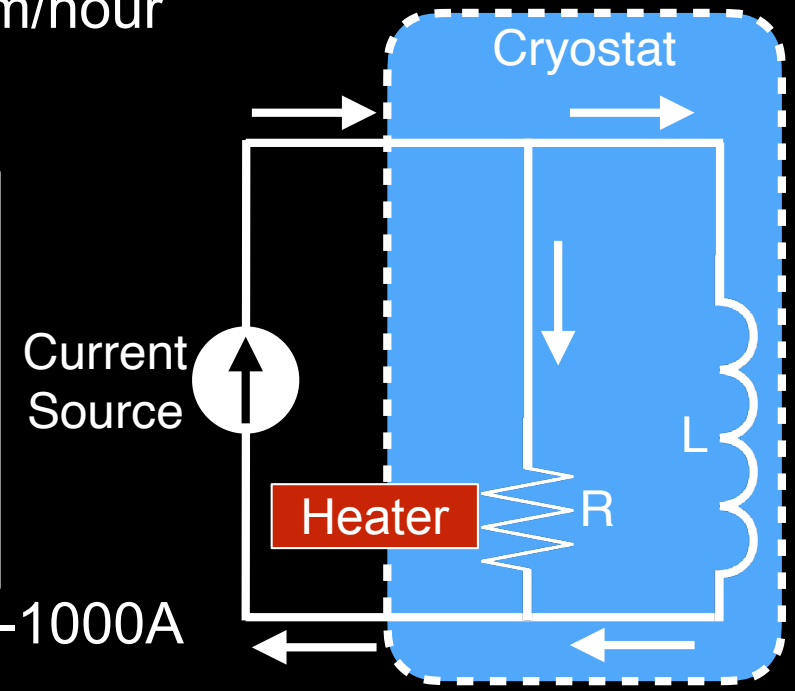
B_0 Ramping & Quenching

Ramping Up the Field

- Pumping in current energizes the field
  - Requires some resistive wires
- Short circuit main windings with superconductor
  - "***persistent switch***"
- Turn off power supply
- Magnet now in ***Persistent Mode***
  - Magnetic field stability persists for many months
  - $B=B_0e^{-(R/L)/t}$ or <1ppm/hour

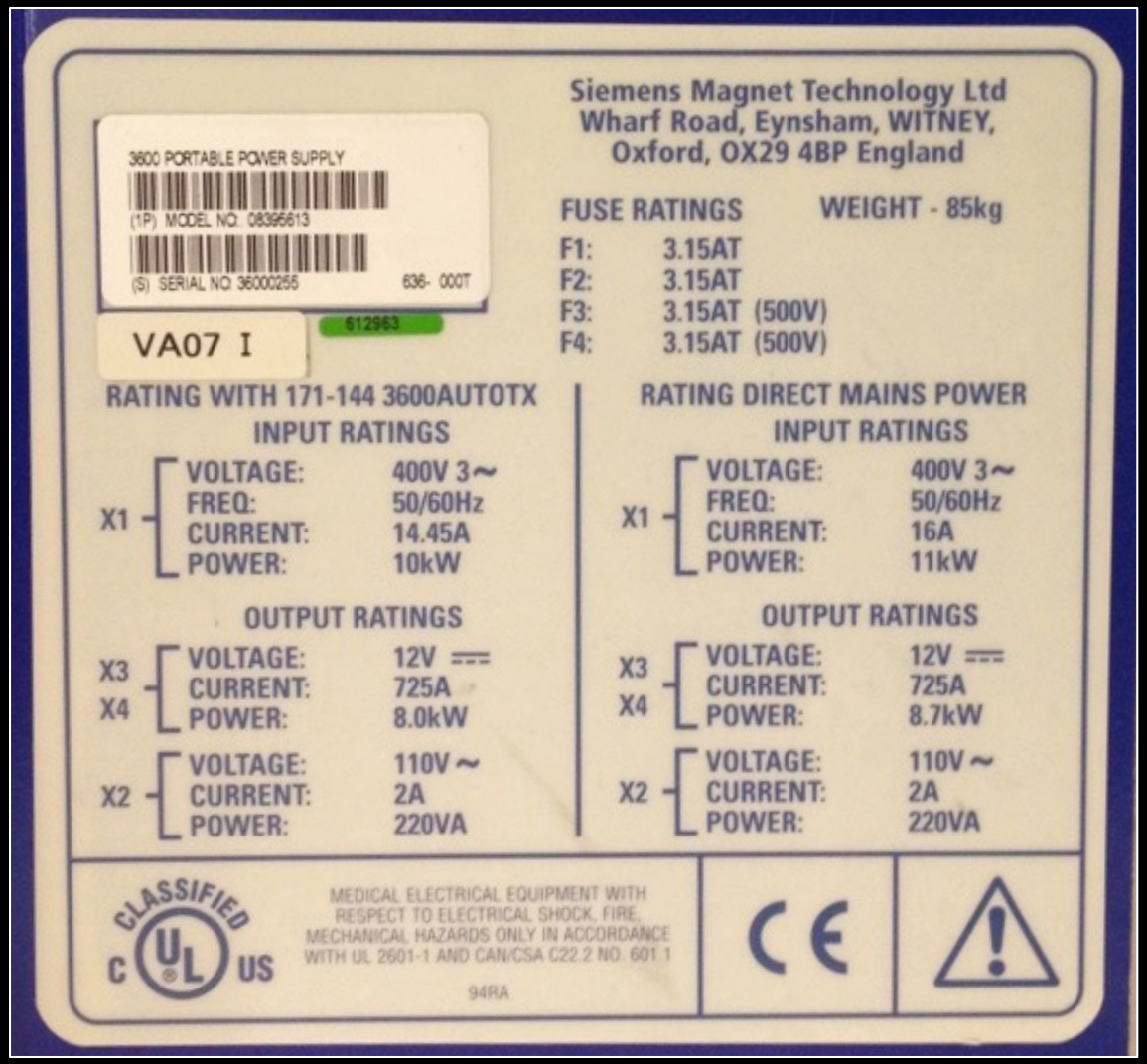


- steady state current 500-1000A



http://mri-q.com/how-to-ramp.html

Ramping Up the Field

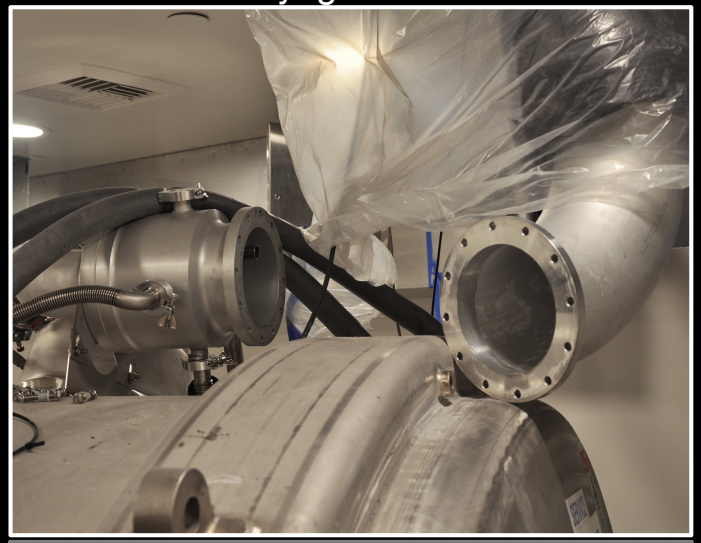


Quenching the Field

- Only performed under life threatening circumstances
  - May occur spontaneously (e.g. unmonitored cryogen leak)
- Loss of superconductivity is positive-feedback cycle
- Huge energy dissipation (MJ)
  - Loud bang
  - Electrical arcing (kV)
  - Cryogen boil-off

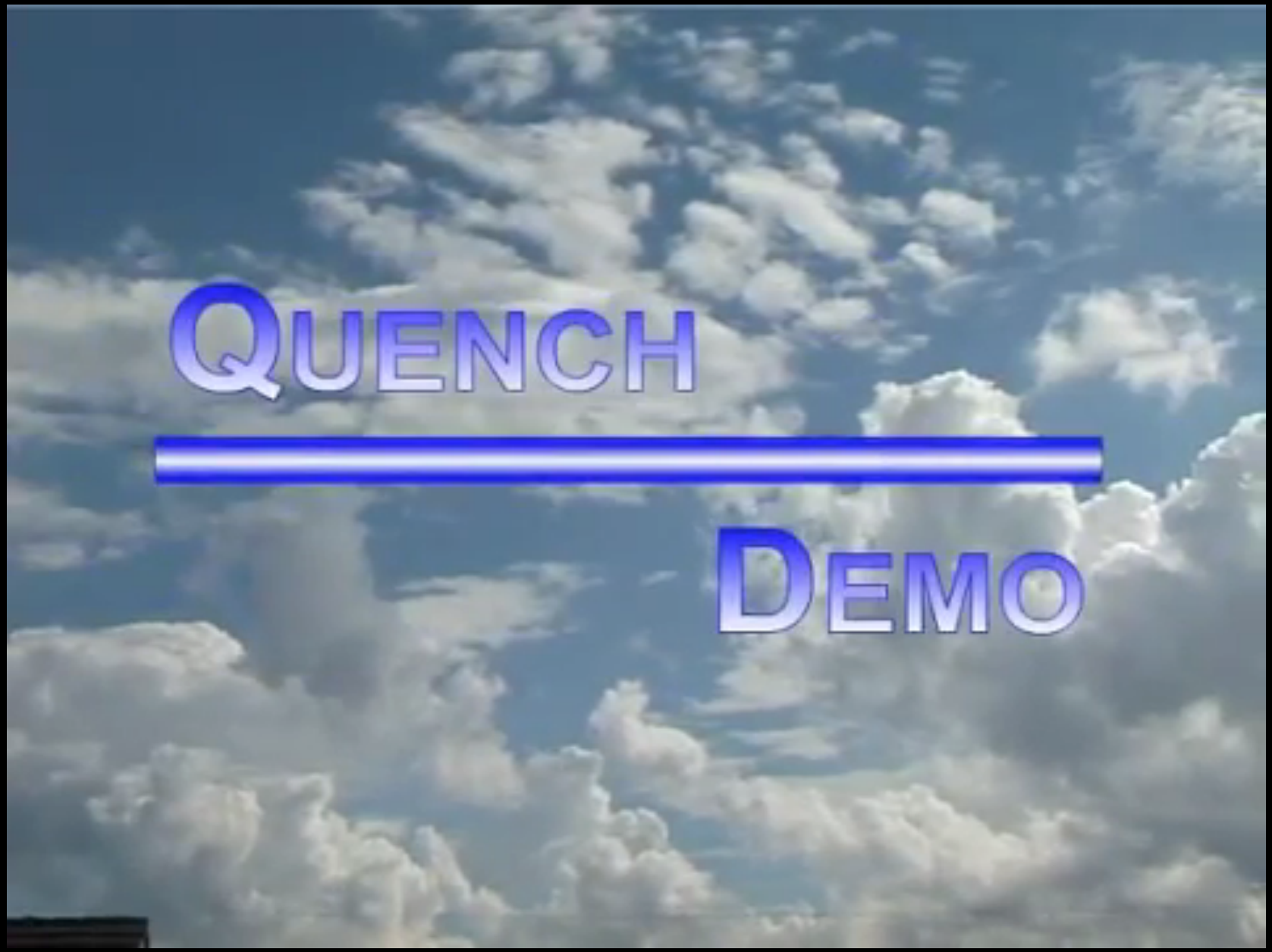
Quench Button

Cryogen Vent



Active Quench & Cryogen Venting

MRI Quench

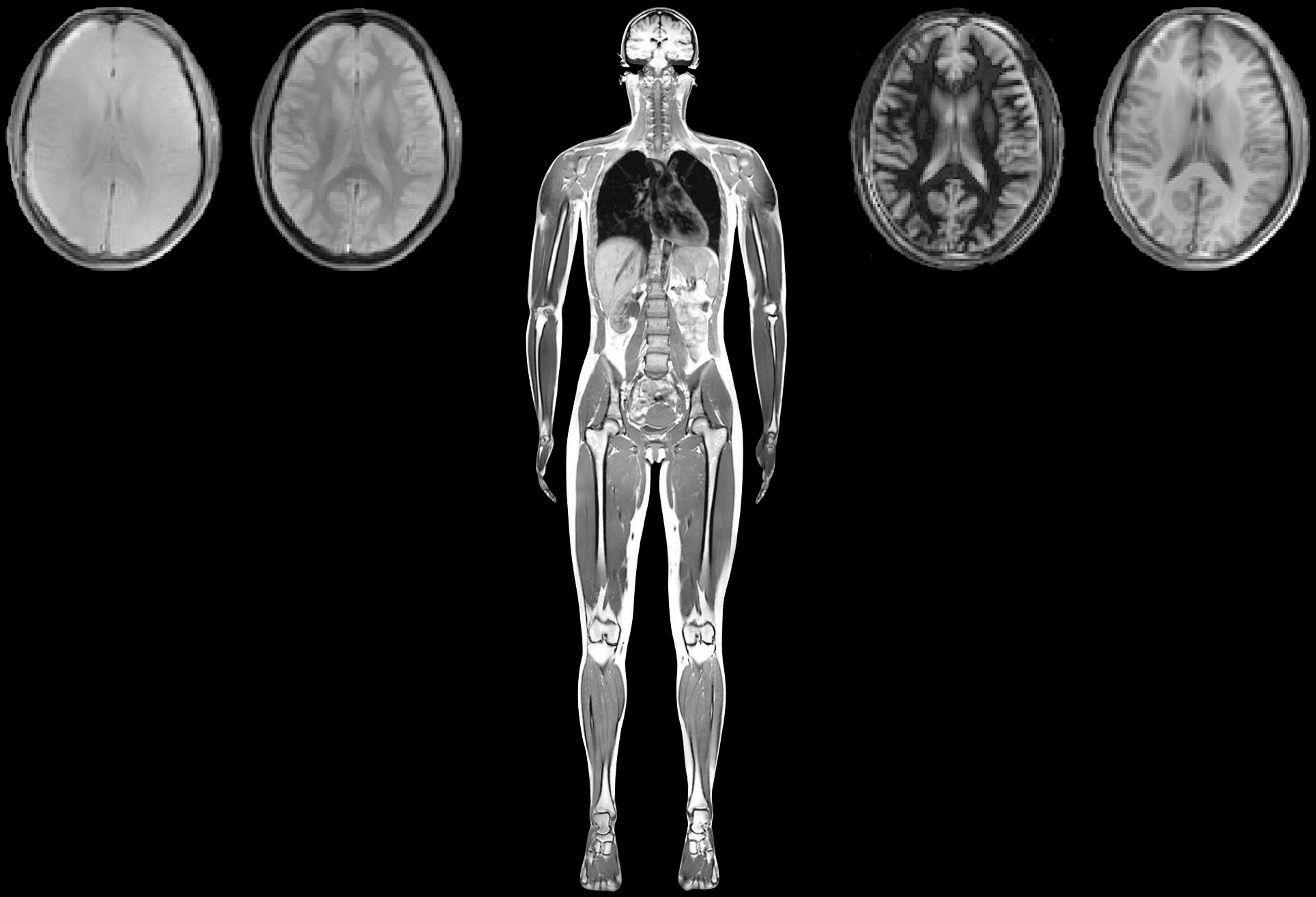


Cost of a Quench

- Hardware replacement if damaged
- ~2000 L of Helium @ $10/liter
- 2-4 days of down time
- Engineer's time
- Cost of electricity to ramp field

MRI Advantages

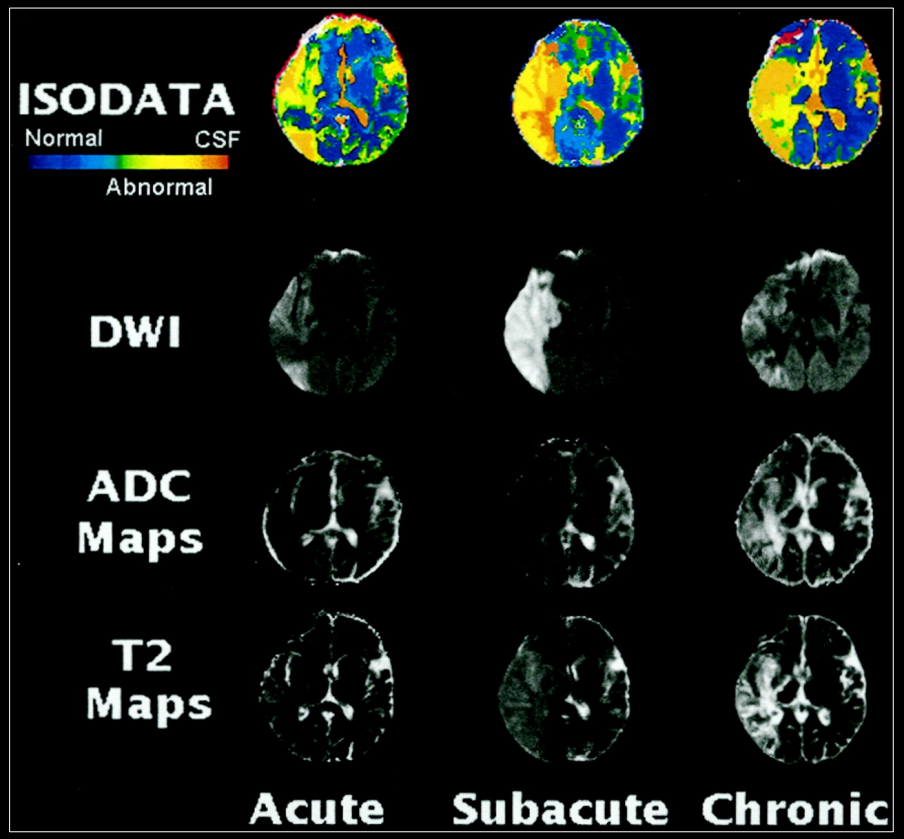
Soft Tissue Contrast



Tissue Characterization

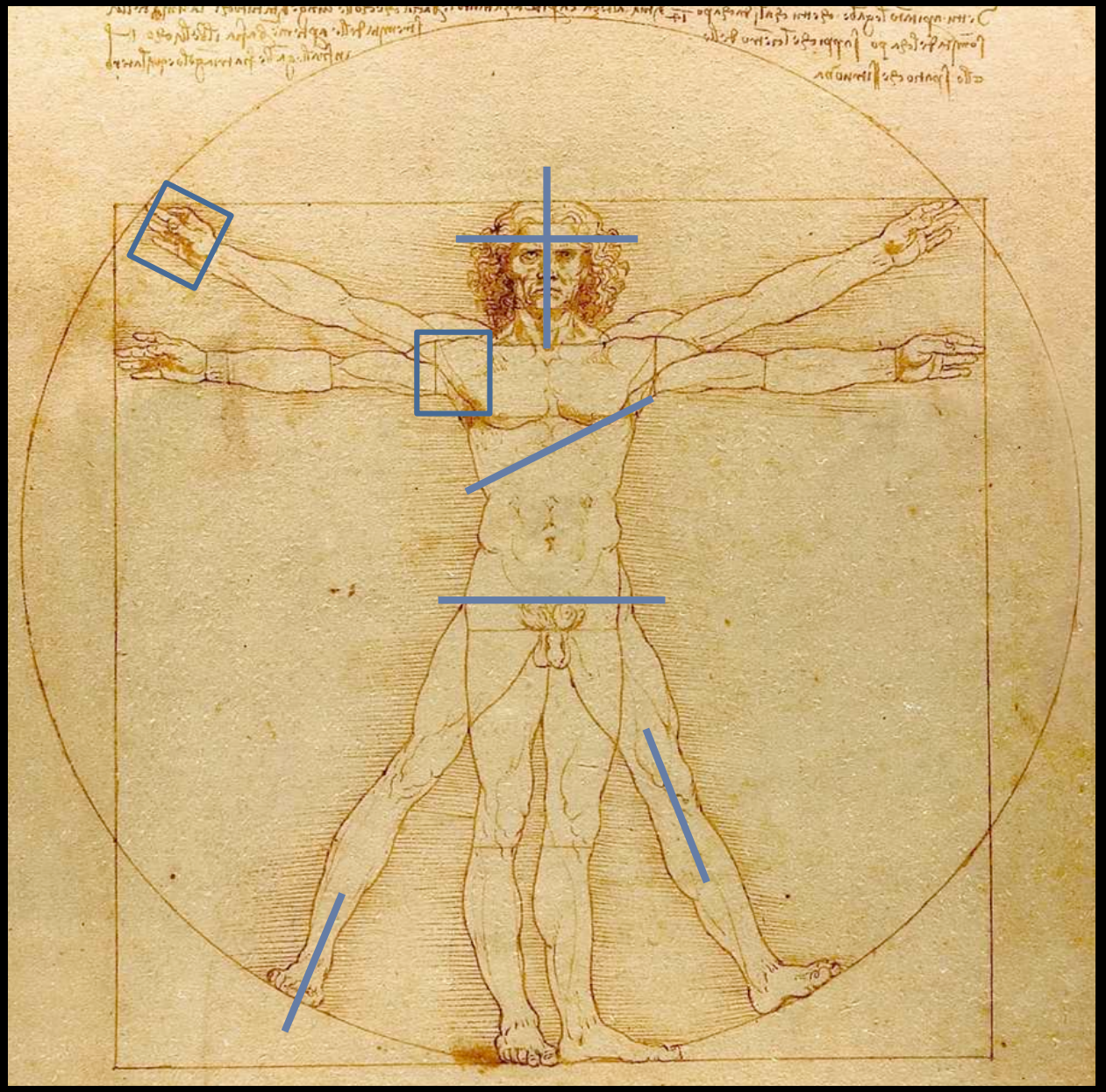
- **Routine**
  - T_1, T_2, T_2^*, proton weighted
  - Perfusion
  - Diffusion
  - Contrast enhancement
    - Tumor evaluation

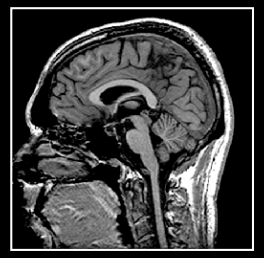
- **Advanced**
  - T1- and T2-mapping
  - Fat/Water & Iron quantification
  - Spectroscopy (molecular)
  - Susceptibility weighted imaging (SWI) for blood products and calcium
  - Non-contrast angiography

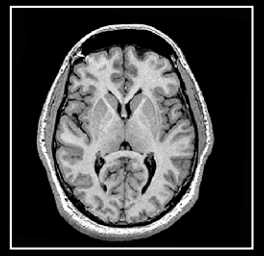


Demonstration of the multiparametric ISODATA segmentation methodology and corresponding DWI (b=1000 s/mm2), ADC map, and T2 map at different times after stroke. *Jacobs M A et al. Stroke. 2001;32:950-957*

Arbitrary Imaging Planes







No Ionizing Radiation

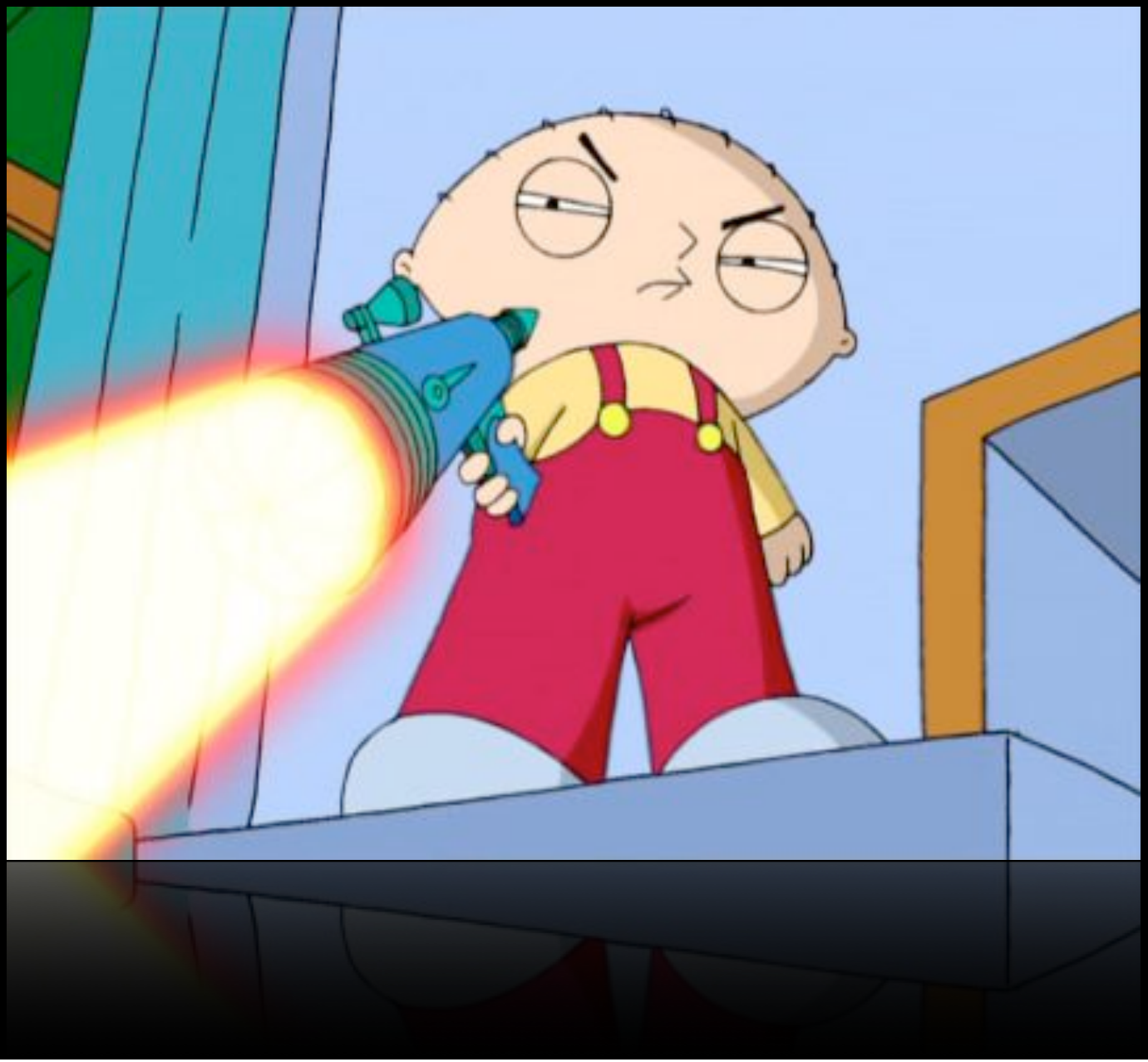


Image Physiologic Motion

MRI Disadvantages

MRI - Disadvantages

- **Safety**
  - Main Field (B_0)
  - Radiofrequency Field (B_1)
  - Gradients (G_x, G_y, and G_z)
- **Slow**
- **Expensive**
- **Technically challenging**

Patient Screening Forms

MAGNETIC RESONANCE (MR) PROCEDURE SCREENING FORM FOR PATIENTS

Date _____/_____/_____ Patient Number _____

Name _____ Age _____ Height _____ Weight _____
Last name First name Middle Initial

Date of Birth _____/_____/_____ Male ❒ Female ❒ Body Part to be Examined _____
month day year

Address _____ Telephone (home) (_____) _____-_____

City _____ Telephone (work) (_____) _____-_____

State _____ Zip Code _____

Reason for MRI and/or Symptoms _____

Referring Physician _____ Telephone (_____) _____-_____

1. Have you had prior surgery or an operation (e.g., arthroscopy, endoscopy, etc.) of any kind? ❒ No ❒ Yes
   If yes, please indicate the date and type of surgery:
   Date _____/_____/_____ Type of surgery _____
   Date _____/_____/_____ Type of surgery _____
2. Have you had a prior diagnostic imaging study or examination (MRI, CT, Ultrasound, X-ray, etc.)? ❒No ❒ Yes
   If yes, please list:

	Body part	Date	Facility
MRI	_____	_____/_____/_____	_____
CT/CAT Scan	_____	_____/_____/_____	_____
X-Ray	_____	_____/_____/_____	_____
Ultrasound	_____	_____/_____/_____	_____
Nuclear Medicine	_____	_____/_____/_____	_____
Other_____	_____	_____/_____/_____	_____

3. Have you experienced any problem related to a previous MRI examination or MR procedure? ❒ No ❒ Yes
   If yes, please describe: _____
4. Have you had an injury to the eye involving a metallic object or fragment (e.g., metallic slivers, shavings, foreign body, etc.)? ❒ No ❒ Yes
   If yes, please describe: _____
5. Have you ever been injured by a metallic object or foreign body (e.g., BB, bullet, shrapnel, etc.)? ❒ No ❒ Yes
   If yes, please describe: _____
6. Are you currently taking or have you recently taken any medication or drug? ❒ No ❒ Yes
   If yes, please list:_____
7. Are you allergic to any medication? ❒ No ❒ Yes
   If yes, please list:_____
8. Do you have a history of asthma, allergic reaction, respiratory disease, or reaction to a contrast medium or dye used for an MRI, CT, or X-ray examination? ❒ No ❒ Yes
9. Do you have anemia or any disease(s) that affects your blood, a history of renal (kidney) disease, renal (kidney) failure, renal (kidney) transplant, high blood pressure (hypertension), liver (hepatic) disease or seizures? No ❒ Yes
   If yes, please describe: _____

For female patients:

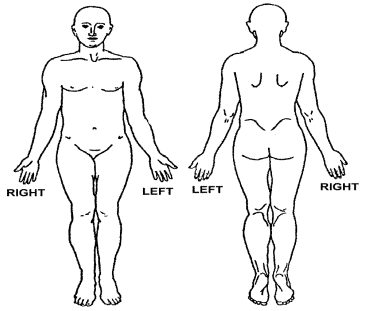
10. Date of last menstrual period:_____/_____/_____ Post menopausal? ❒ No ❒ Yes
11. Are you pregnant or experiencing a late menstrual period? ❒ No ❒ Yes
12. Are you taking oral contraceptives or receiving hormonal treatment? ❒ No ❒ Yes
13. Are you taking any type of fertility medication or having fertility treatments? ❒ No ❒ Yes
    If yes, please describe: _____
14. Are you currently breastfeeding? ❒ No ❒ Yes

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, MR angiography, functional MRI, MR spectroscopy). Do not enter the MR system room or MR environment if you have any question or concern regarding an implant, device, or object. Consult the MRI Technologist or Radiologist BEFORE entering the MR system room. The MR system magnet is ALWAYS on.

Please indicate if you have any of the following:

❒ Yes	❒ No	Aneurysm clip(s)
❒ Yes	❒ No	Cardiac pacemaker
❒ Yes	❒ No	Implanted cardioverter defibrillator (ICD)
❒ Yes	❒ No	Electronic implant or device
❒ Yes	❒ No	Magnetically-activated implant or device
❒ Yes	❒ No	Neurostimulation system
❒ Yes	❒ No	Spinal cord stimulator
❒ Yes	❒ No	Internal electrodes or wires
❒ Yes	❒ No	Bone growth/bone fusion stimulator
❒ Yes	❒ No	Cochlear, otologic, or other ear implant
❒ Yes	❒ No	Insulin or other infusion pump
❒ Yes	❒ No	Implanted drug infusion device
❒ Yes	❒ No	Any type of prosthesis (eye, penile, etc.)
❒ Yes	❒ No	Heart valve prosthesis
❒ Yes	❒ No	Eyelid spring or wire
❒ Yes	❒ No	Artificial or prosthetic limb
❒ Yes	❒ No	Metallic stent, filter, or coil
❒ Yes	❒ No	Shunt (spinal or intraventricular)
❒ Yes	❒ No	Vascular access port and/or catheter
❒ Yes	❒ No	Radiation seeds or implants
❒ Yes	❒ No	Swan-Ganz or thermodilution catheter
❒ Yes	❒ No	Medication patch (Nicotine, Nitroglycerine)
❒ Yes	❒ No	Any metallic fragment or foreign body
❒ Yes	❒ No	Wire mesh implant
❒ Yes	❒ No	Tissue expander (e.g., breast)
❒ Yes	❒ No	Surgical staples, clips, or metallic sutures
❒ Yes	❒ No	Joint replacement (hip, knee, etc.)
❒ Yes	❒ No	Bone/joint pin, screw, nail, wire, plate, etc.
❒ Yes	❒ No	IUD, diaphragm, or pessary
❒ Yes	❒ No	Dentures or partial plates
❒ Yes	❒ No	Tattoo or permanent makeup
❒ Yes	❒ No	Body piercing jewelry
❒ Yes	❒ No	Hearing aid *(Remove before entering MR system room)*
❒ Yes	❒ No	Other implant _____
❒ Yes	❒ No	Breathing problem or motion disorder
❒ Yes	❒ No	Claustrophobia

Please mark on the figure(s) below the location of any implant or metal inside of or on your body.



IMPORTANT INSTRUCTIONS

Before entering the MR environment or MR system room, you must remove all metallic objects including hearing aids, dentures, partial plates, keys, beeper, cell phone, eyeglasses, hair pins, barrettes, jewelry, body piercing jewelry, watch, safety pins, paperclips, money clip, credit cards, bank cards, magnetic strip cards, coins, pens, pocket knife, nail clipper, tools, clothing with metal fasteners, & clothing with metallic threads.

Please consult the MRI Technologist or Radiologist if you have any question or concern BEFORE you enter the MR system room.

NOTE: You may be advised or required to wear earplugs or other hearing protection during the MR procedure to prevent possible problems or hazards related to acoustic noise.

I attest that the above information is correct to the best of my knowledge. I read and understand the contents of this form and had the opportunity to ask questions regarding the information on this form and regarding the MR procedure that I am about to undergo.

Signature of Person Completing Form: _____ Date _____/_____/_____
Signature

Form Completed By: ❒ Patient ❒ Relative ❒ Nurse _____ _____
Print name Relationship to patient

Form Information Reviewed By: _____ _____
Print name Signature

❒ MRI Technologist ❒ Nurse ❒ Radiologist ❒ Other_____

Patient *and* personnel screening before an MRI exam is critical.

MRI - Contraindication?

Box 2 Example of a check list with potential contraindications to an MRI examination

If any of the following is checked, evaluation of the individual risk has to be performed before the MRI examination

- Aneurysm clip(s)
- Any metallic fragment or foreign body
- Coronary and peripheral artery stents
- Aortic stent graft
- Prosthetic heart valves and annuloplasty rings
- Cardiac occluder devices
- Vena cava filters and embolisation coils
- Haemodynamic monitoring and temporary pacing devices, eg, Swan–Ganz catheter
- Haemodynamic support devices
- Cardiac pacemaker
- Implanted cardioverter-defibrillator (ICD)
- Retained transvenous pacemaker and defibrillator leads
- Electronic implant or device, eg, insulin pump or other infusion pump
- Permanent contraceptive devices, diaphragm, or pessary
- Cochlear, otologic, or other ear implant
- Neurostimulation system
- Shunt (spinal or intraventricular)
- Vascular access port and/or catheter
- Tissue expander (eg, breast)
- Joint replacement (eg, hip, knee, etc)
- Any type of prosthesis (eg, eye, penile, etc)
- Tattoo or permanent makeup
- Known claustrophobia
- Body piercing jewellery
- Hearing aid
- Renal insufficiency
- Known/possible pregnancy or breast feeding

Modified from: Shellock FG, Crues JV. MR procedures: biologic effects, safety, and patient care. *Radiology* 2004;**232**:635–52.

Contraindications to Magnetic Resonance Imaging. T Dill. *Heart* 2008;94;943-948.

MRI Safety Designations

MR Safe: “An item that poses no known hazards in all MR environments.” (e.g. a plastic Petri dish)

MR Conditional: “An item that has been demonstrated to pose no known hazards in a specified MR environment with specified conditions of use. Field conditions that define the specified MR environment include field strength, spatial gradient, dB/dt (time rate of change of the magnetic field), radio frequency fields, and specific absorption rate. Additional conditions, including specific configurations of the item, may be required.” (e.g. a Patient Monitor)

MR Unsafe: “An item that is known to pose hazards in all MR environments.” (e.g. Floor Buffer)

“MRI Compatible” is not an FDA term.

B_0 Safety – Room Safety

$2.9 Million Settlement Closes Colombini MRI Death Case

5 Replies

This week the settlement documents were released — closing the chapter on the lawsuit that arose from the seminal event in MRI safety, the 2001 oxygen tank fatality of then-six-year-old Michael Colombini.

Not MRI Compatible

MRI Compatible

B_0 is VERY strong and ALWAYS on.

B_0 Safety – Implanted Devices

B_0 exerts a force or torque on implanted ferromagnetic devices.

RF (B_1) Safety - SAR Limits

- **RF pulses deposit energy in the body.**
- **Specific Absorption Rate [W/kg]**
  - Rate of energy absorption during exposure to RF
- High-field (>1.5T) imaging with high flip angles (>45-90°) can be challenging. $\mathrm{SAR} \propto \omega_0^2 B_1^2 \propto B_0^2 \alpha^2$

Limit	Whole-Body Average
Normal (all patients)	2 W/kg (0.5°C)
First level (supervised)	4 W/kg (1°C)

The scanner (FDA!) limits SAR, which in turn limits the max. flip angle.

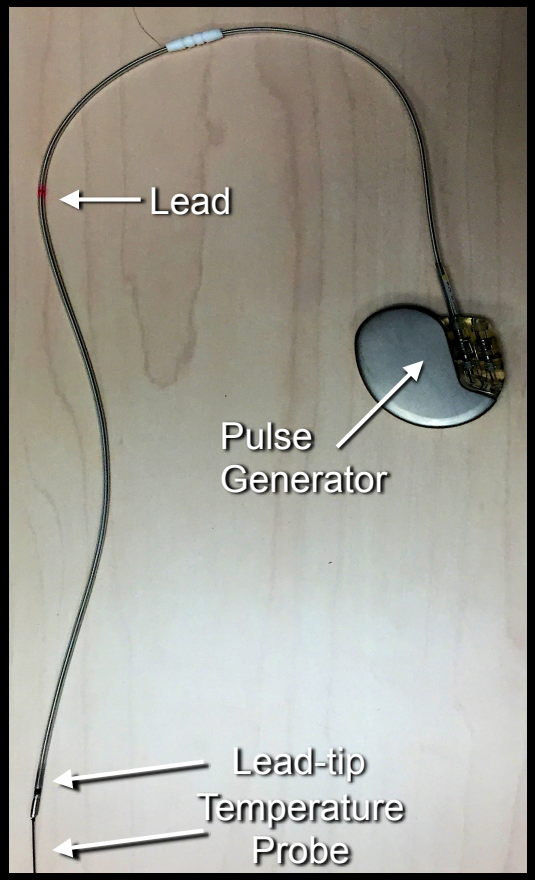
Bottomley PA. Turning up the heat on MRI. J Am Coll Radiol 2008;5(7):853-855.

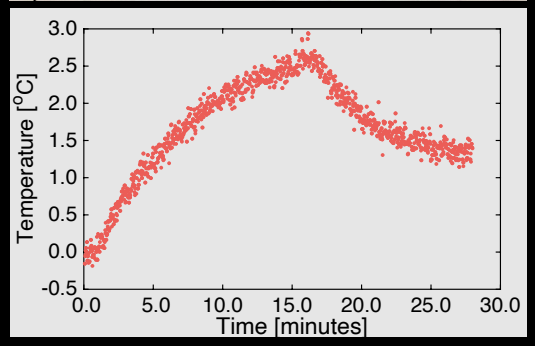
RF (B_1) Safety - Burns & Heating

- **Tissue burns**
- **RF induced heating of implanted devices**

Eising EG et al. J. Clin. Imaging 2010;34(4):293-297.

Solution: Avoid skin-to-skin loops; avoid arms directly touching scanner bore.

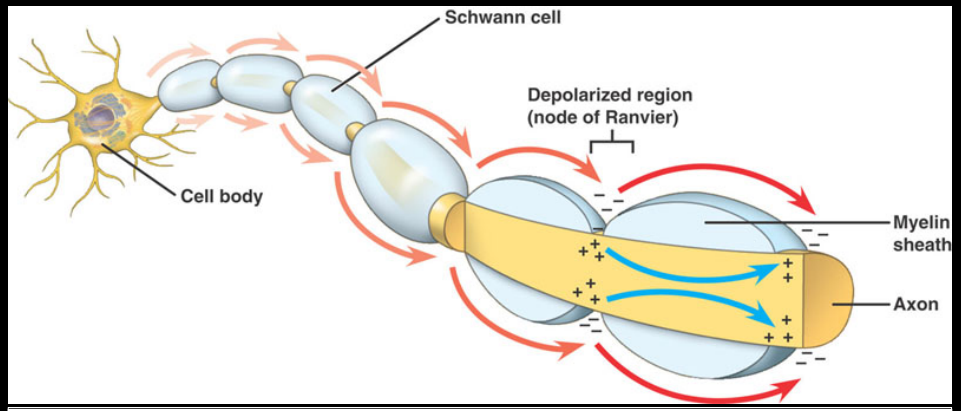


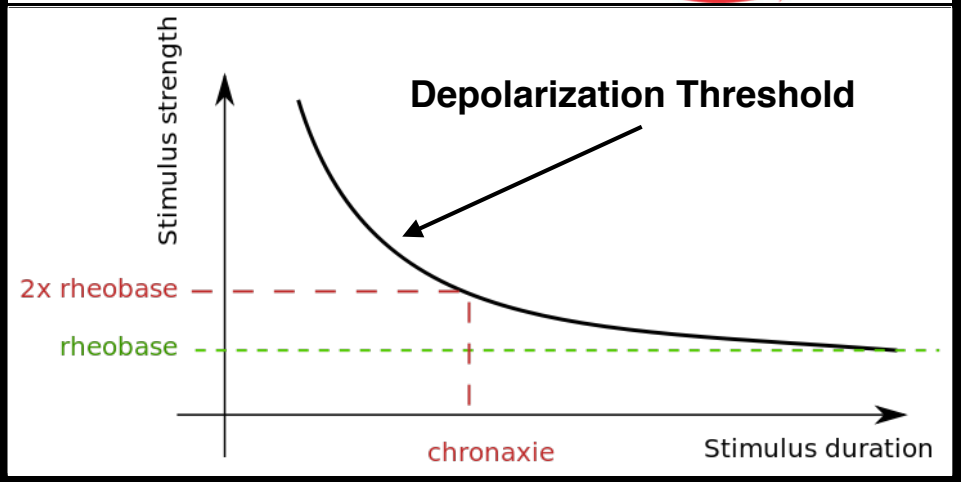


RF energy contributes to patient and device heating (or burns!).

Gradient Safety

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





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

Solution:

Ear plugs

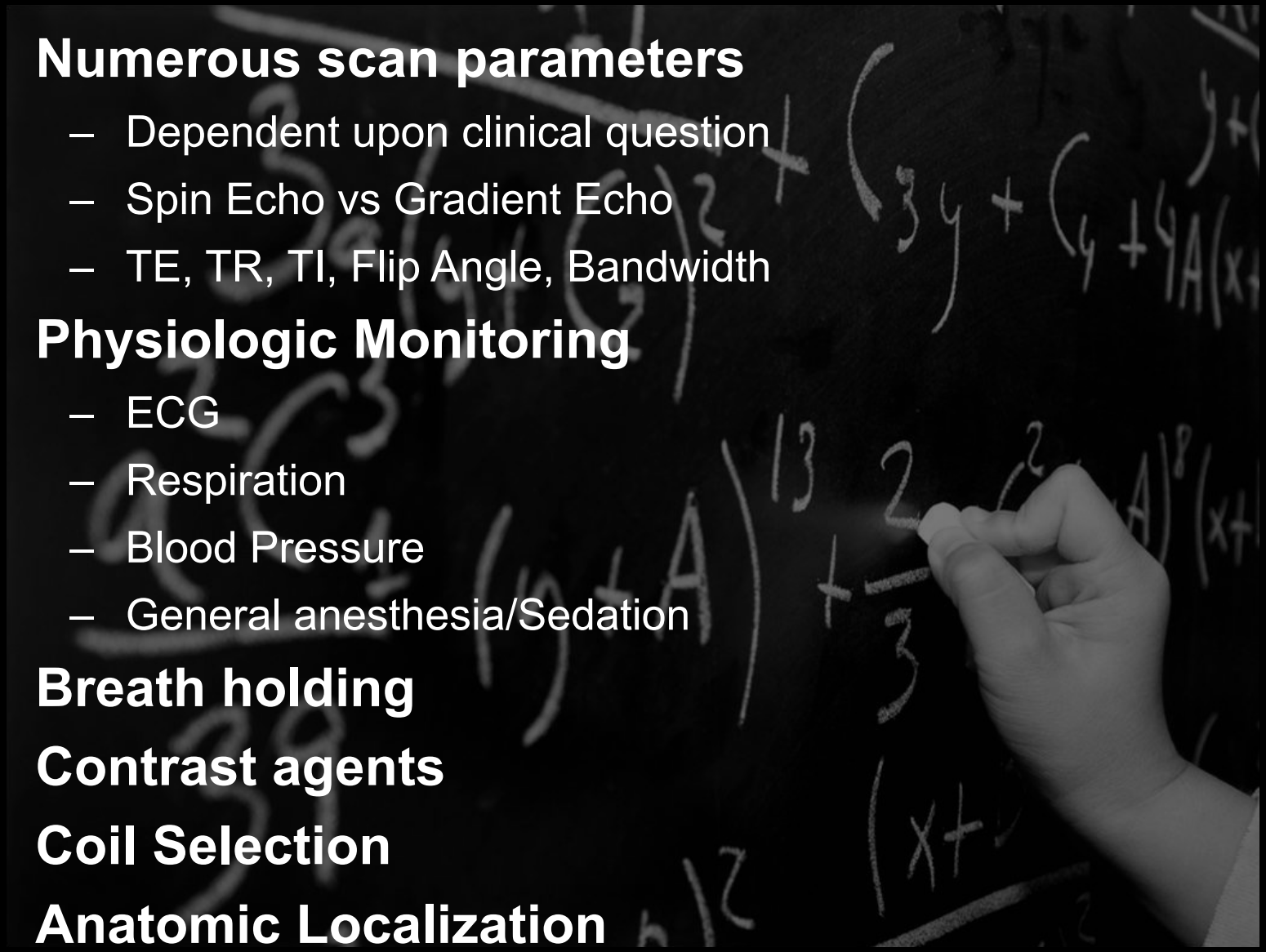
Head phones

Time-varying gradients induce mechanical vibrations and PNS.

MRI is Expensive

- **Purchase**
  - **$1-3 million**
- **Site**
  - **$0.5-1.0 million**
- **Maintain (Service Contract)**
  - **$100,000 per year**
- **Operate**
  - **$500-1000/hour**

Technically Challenging



- **Numerous scan parameters**
  - Dependent upon clinical question
  - Spin Echo vs Gradient Echo
  - TE, TR, TI, Flip Angle, Bandwidth
- **Physiologic Monitoring**
  - ECG
  - Respiration
  - Blood Pressure
  - General anesthesia/Sedation
- **Breath holding**
- **Contrast agents**
- **Coil Selection**
- **Anatomic Localization**

Next time…

Bulk Magnetization and Nuclear Precession

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