# RF Aspects of Magnetic Resonance Imaging

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# Various Commercial Whole Body Human MRI Systems – what is on the other side of the casing?


MRI – excellent medical diagnostic tool with excellent soft tissue contrast

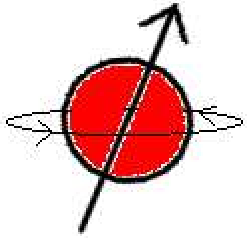
# Outline

- MRI – the atomic viewpoint
- Atomic response to magnetic field
  - Gyromagnetic ratio
  - Net Magnetization Vector
    - Excitation, Recovery, Decay
  - RF excitation, B field gradients
  - Frequency/phase encoding
  - Simple pulse sequence
- MRI Systems Overview
- Transceivers
- PIN Diodes, RF Coils, and switching/protection
- Conclusion

***Understanding MRI physics helps to understand the RF design choices***

# An Introduction to MRI

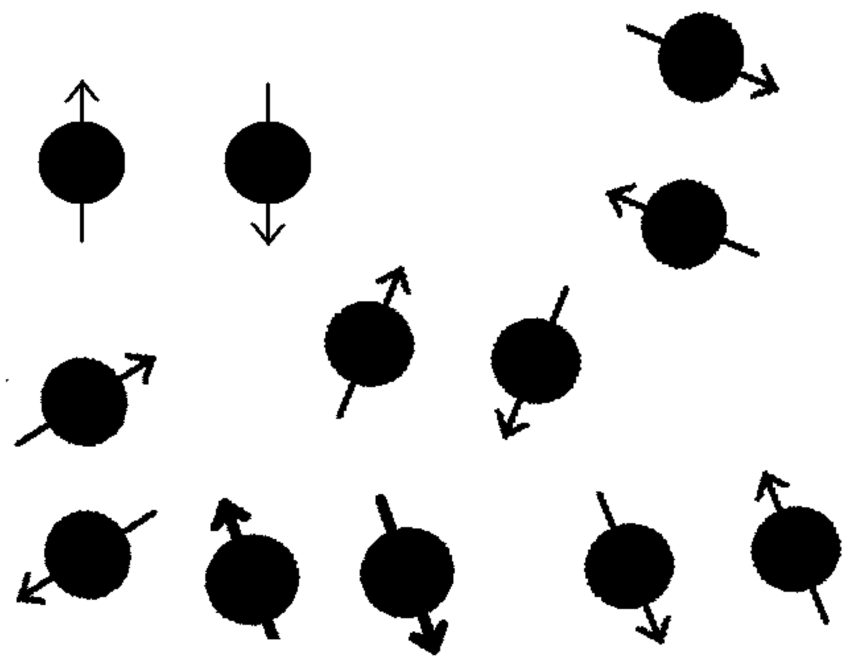
- For MRI, the important term is the atomic mass number AMN…sum of protons/neutrons or nucleons
- Important atomic motion for MRI is the rotation or spin of protons on their own axis
  - Even AMN – ½ spin up, ½ spin down – no net spin
  - Odd AMN – neutron spin more/less than proton spin
    - A net spin
    - Nuclear angular momentum
    - Resulting magnetic moment of nucleus



# An Introduction to MRI

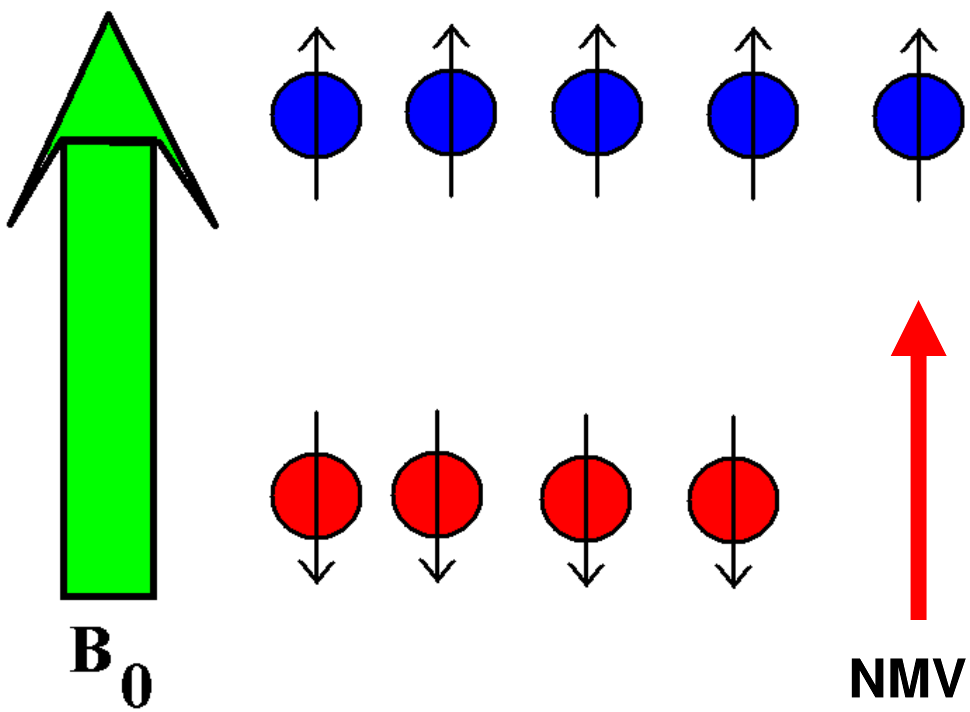
- Important MRI elements

| Element | H | C | O | F | Na | P | Xe |
|---|---|---|---|---|---|---|---|
| AMN | 1 | 13 | 17 | 19 | 23 | 31 | 129 |



With no external magnetic field applied, the MM of the protons are randomly oriented – no net magnetization.

# An Introduction to MRI




*NOTE: only MM orient themselves, not the actual protons*

$\gamma$ *- gyromagnetic ratio = q/2m*

Apply a static magnetic field and the MM align either parallel (low energy) or anti-parallel (high energy) to the field line.

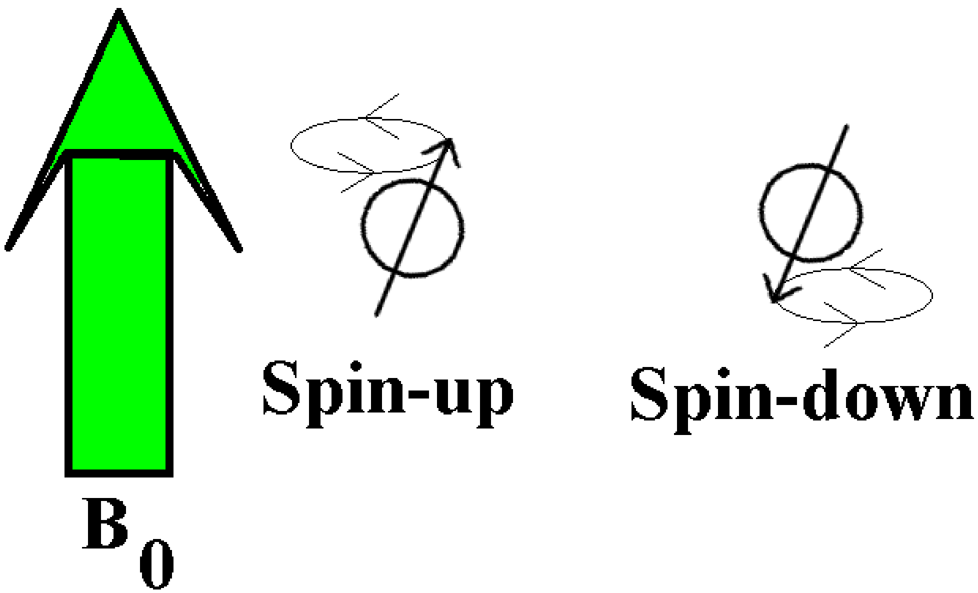
Fewer anti-parallel than parallel

$$\frac{n^-}{n^+} \propto e^{-h\gamma B/kT}$$

Low energy – spin up

High energy – spin down

# An Introduction to MRI




B-field interaction with MM causes a 'wobble' or precession of the MM (so-called spinning top)

$$\frac{\partial \vec{M}}{\partial t} = \vec{\gamma} \times \vec{B}$$

$$\omega = \gamma B = qB/2m$$

M – Magnetization Vector

$\gamma$ - Gyromagnetic Ratio – q/2m

***Larmor Equation***

# Selected elements and their respective Gyromagnetic Ratios

| Element | H | C | F | Na | P | Xe |
|---|---|---|---|---|---|---|
| $\gamma$ MHz/T | 42.57 | 10.7 | 40.05 | 11.26 | 17.25 | 11.78 |

$$n^{-}/n^{+} \propto e^{-h\gamma B/kT}$$

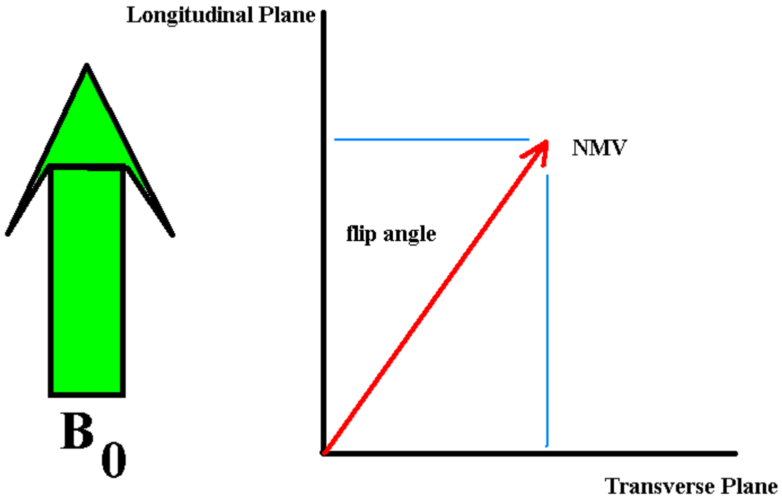
For Hydrogen:

| B field | 0.2 | 0.5 | 1.0 | 2.0 | 3.0 | 7.0 |
|---|---|---|---|---|---|---|
| F (MHz) | 8.51 | 21.29 | 42.57 | 85.14 | 127.72 | 298 |

# An Introduction to MRI

If we hit this proton with an RF field that resonates with the Larmor precession frequency, RF energy is absorbed and two processes occur

1. causes the NMV to move out of alignment with B
2. causes precession of MMs to be coherent

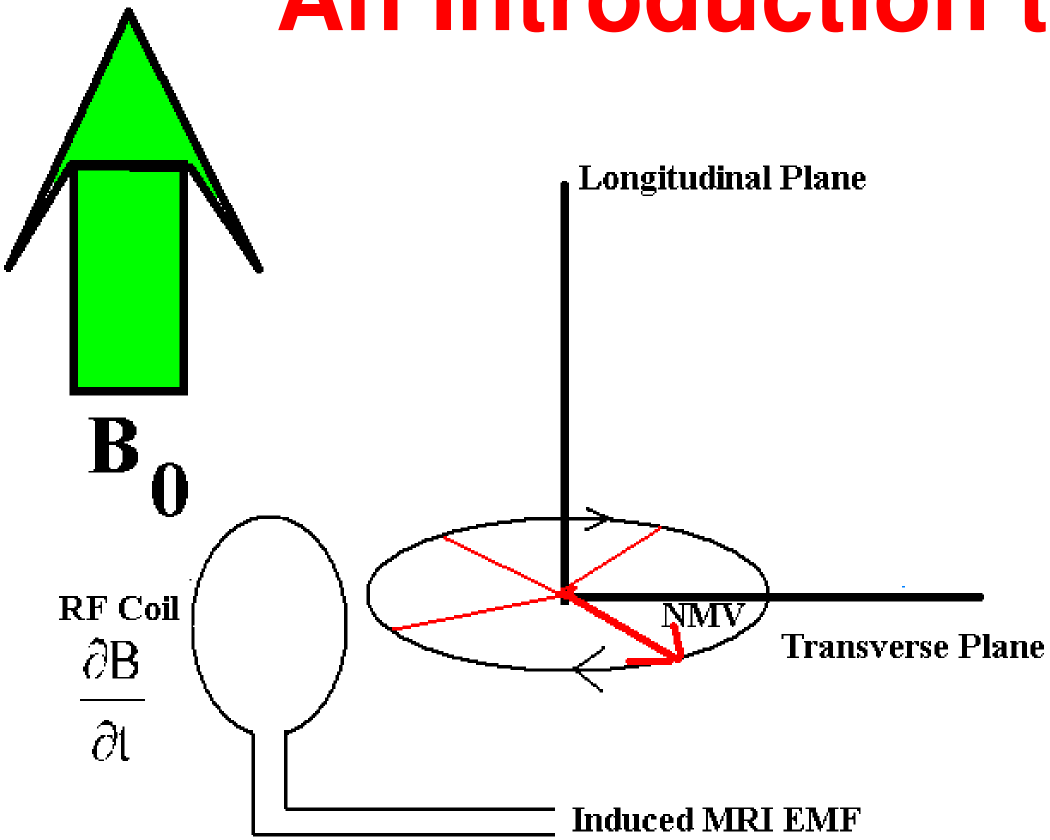



If the RF pulse is of sufficient duration and power, the NMV will have a 90$^o$ flip angle (or greater)

90$^o$ – all transverse

Remember – NMV is still precessing!

# An Introduction to MRI



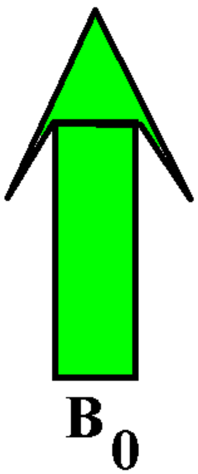

NMV precessing at Larmor frequency

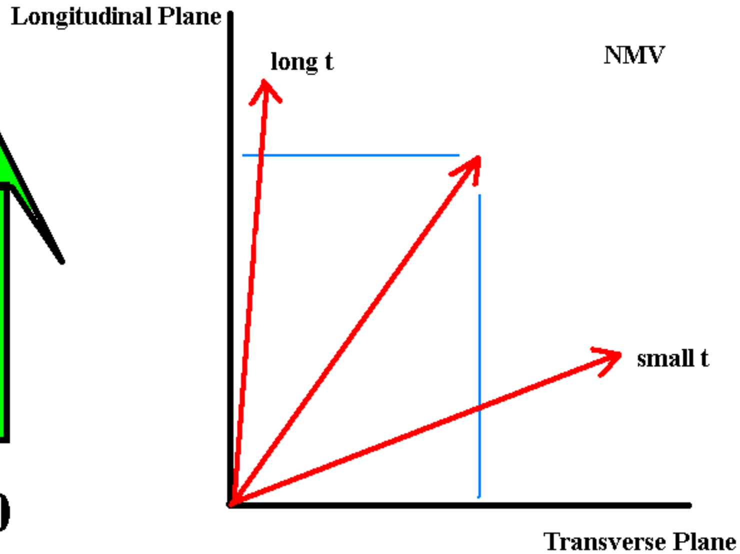
Faraday's Law of Induction

EMF $\propto \omega \int_{vol} \overrightarrow{B1} \cdot \overrightarrow{NMV_{xy}} dV$

**The receive problem: a very weak MR EMF can be received when RF turned off – relaxation of NMV – detection schemes required down to near the thermal noise floor (-170 dBm/Hz)**

# An Introduction to MRI



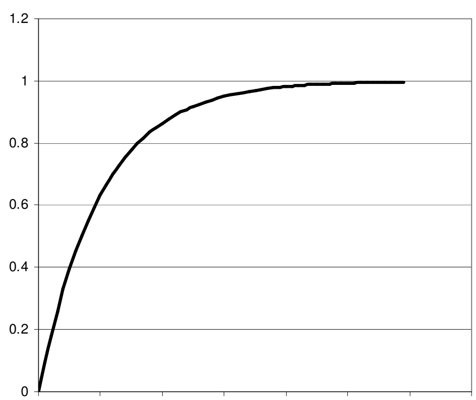

When the RF turns off, the NMV begins to relax back to equilibrium, with the transverse component (received part) **decaying** and the longitudinal part (equilibrium) **recovering**.

T1 – spin-lattice relaxation (Z-plane)

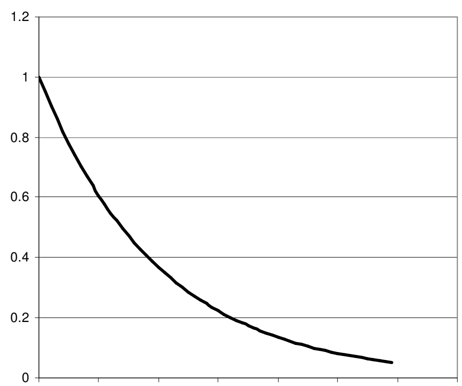
T2 – spin-spin relaxation (XY-plane)

$T2^{*}$ - 1/ [1/T2 + 1/$B_{inhomogen}$]

FID – free induction decay (loss of transverse NMV and resulting loss of MRI signal)




**T1(z) Recovery**

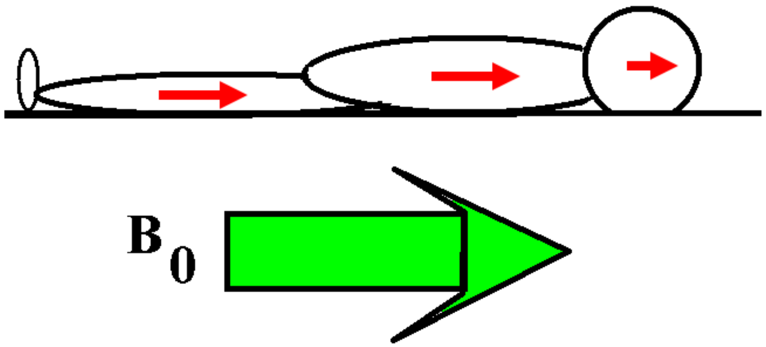



**T2(xy) decay (dephase)**

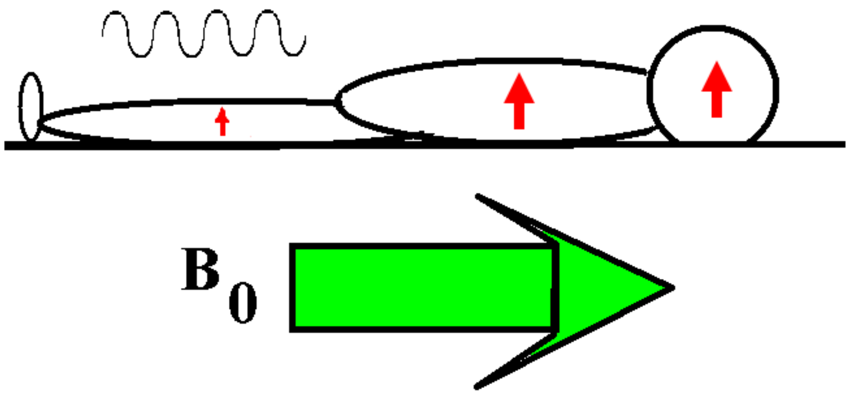
***different for each tissue***

*T1 and T2 originate from two different processes.*

# An Introduction to MRI




In the patient, all the NMV point in the same direction and have the same precessional frequency, $F_0$, with applied B-field.

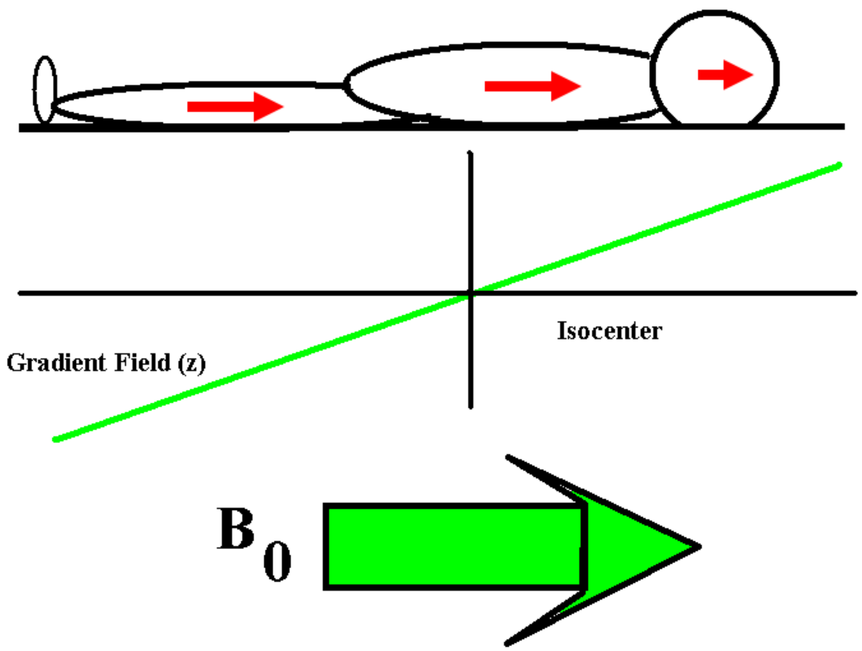



Excite with a 90º RF pulse at $F_0$ and you 'flip' the NMV.

**BUT** – you can't differentiate any part of the body since the entire patient's NMV are in the same direction.

# An Introduction to MRI

- Since the precessional frequency is related to $B_0$, B-field ***gradients*** are used to encode location (Lauterbur, Mansfield, et al.)



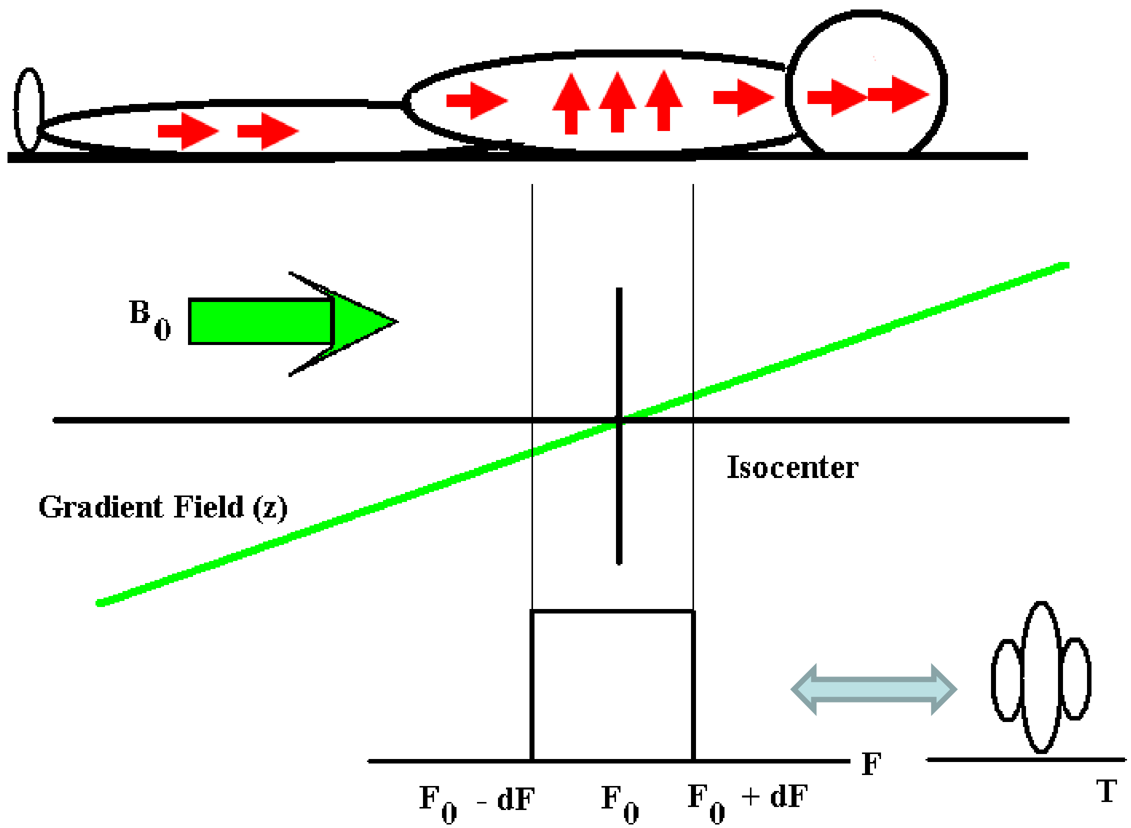

Field gradient G(z)

$B = B_0 + G(z)$

$$\omega(z) = \gamma\left[B_0 + G(z)\right]$$

NMV precession frequency now a function of position (same with x, y)

# An Introduction to MRI




Multiple pulses in time, frequency can be used to select different slices in different locations – complex pulse!

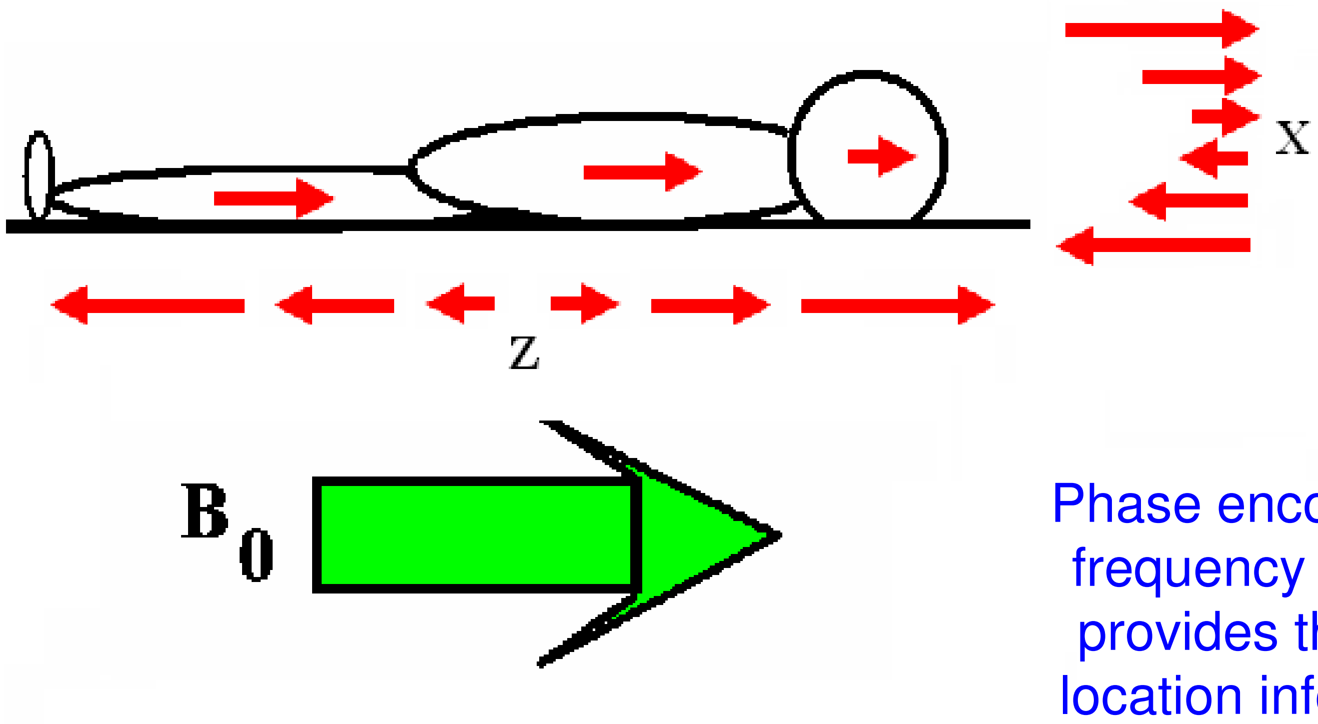
Applying a narrow band RF pulse of BW 2*dF corresponding to the gradient allows excitation of protons (and a 90º flip of the NMV) only in the ***slice*** as indicated.

***The time domain pulse is complex.***

# An Introduction to MRI

B-field gradients are again used for obtaining a 2D image

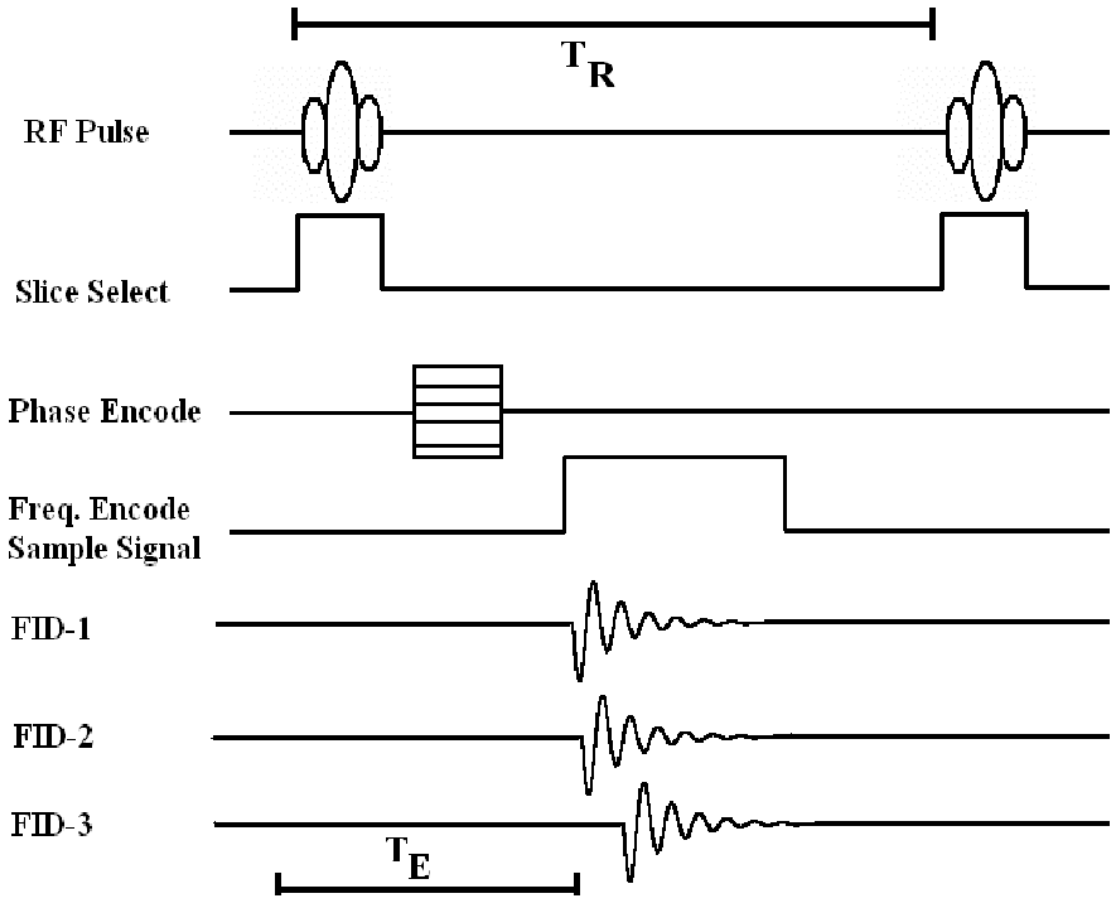
X and Y field gradients still are in z-direction!



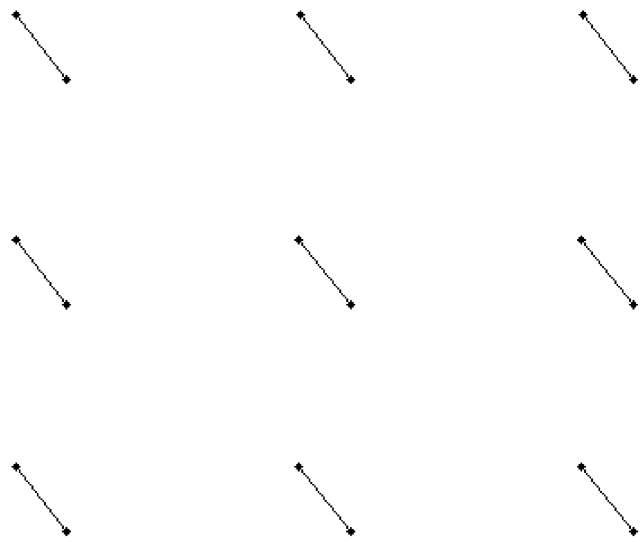

Phase encoding and frequency encoding provides the spatial location information.

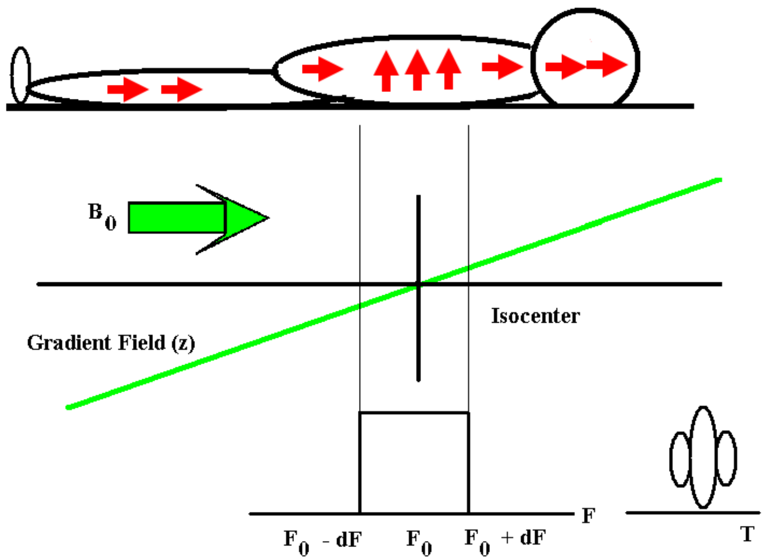
# An Introduction to MRI

Frequency and Phase encoding are required for locating specific regions in the slice of interest



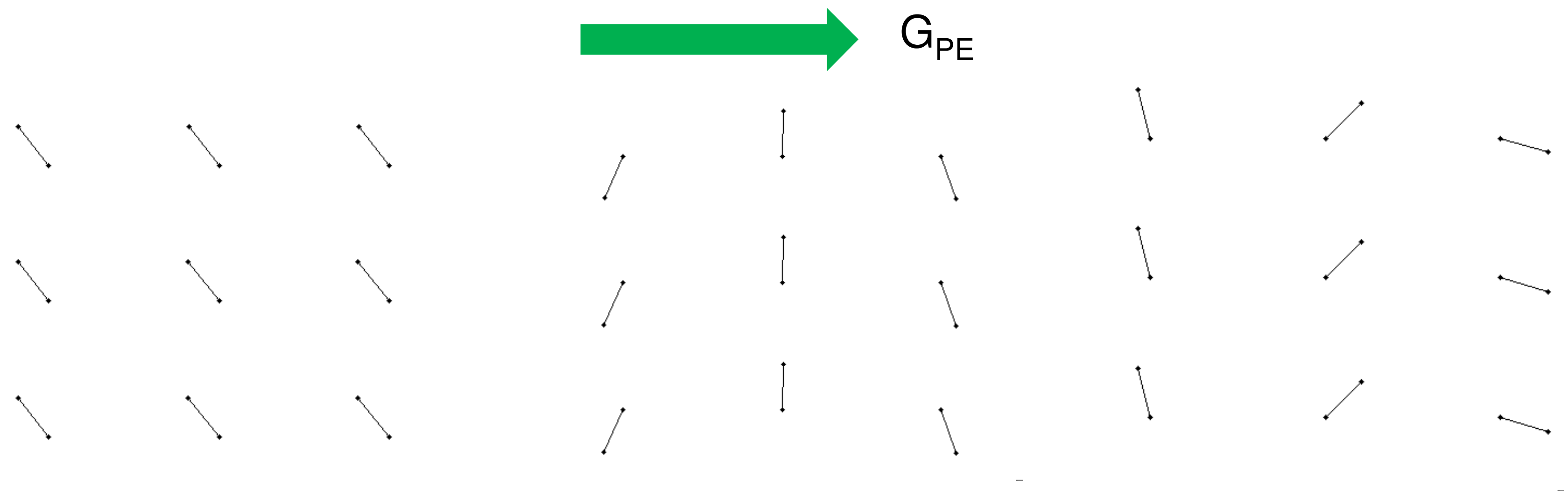
# An Introduction to MRI






**Slice select** – all NMV rotating in phase and at same frequency

# An Introduction to MRI

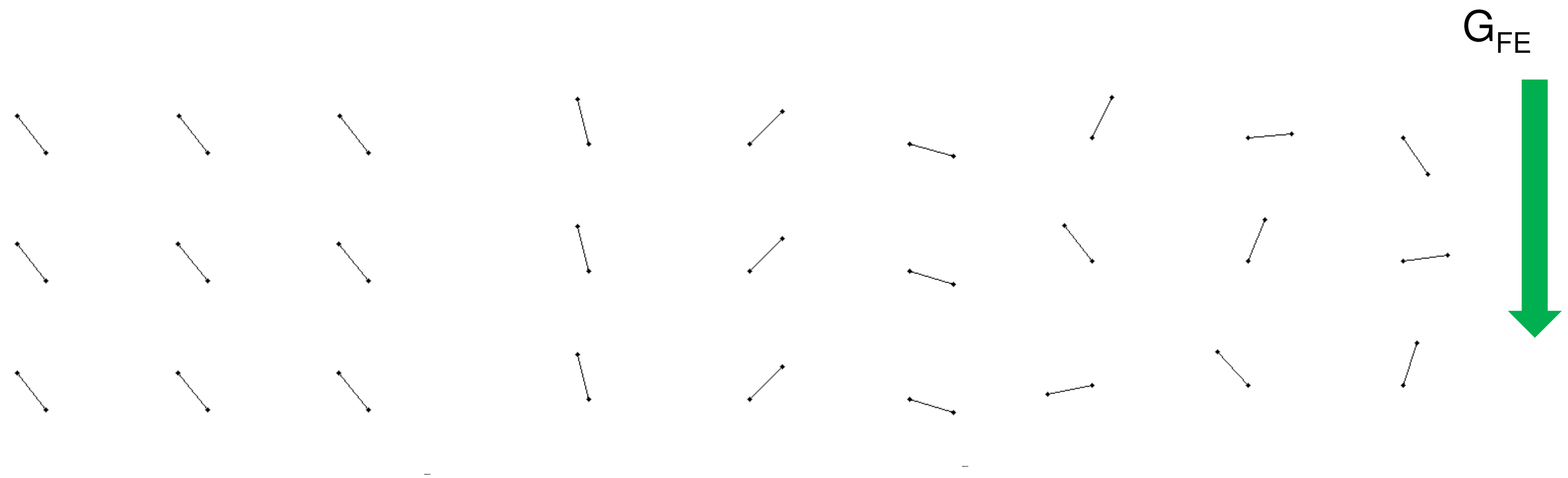



**Slice select** – all NMV rotating in phase and at same Larmour frequency

**Phase encoding ON**– B gradients set up so that each ‘column’ of the region’s NMV has slightly different Larmour frequency

**Phase encoding OFF**– B gradients off so that each ‘column’ of the region’s NMV has slightly different phase but same Larmour frequency

# An Introduction to MRI



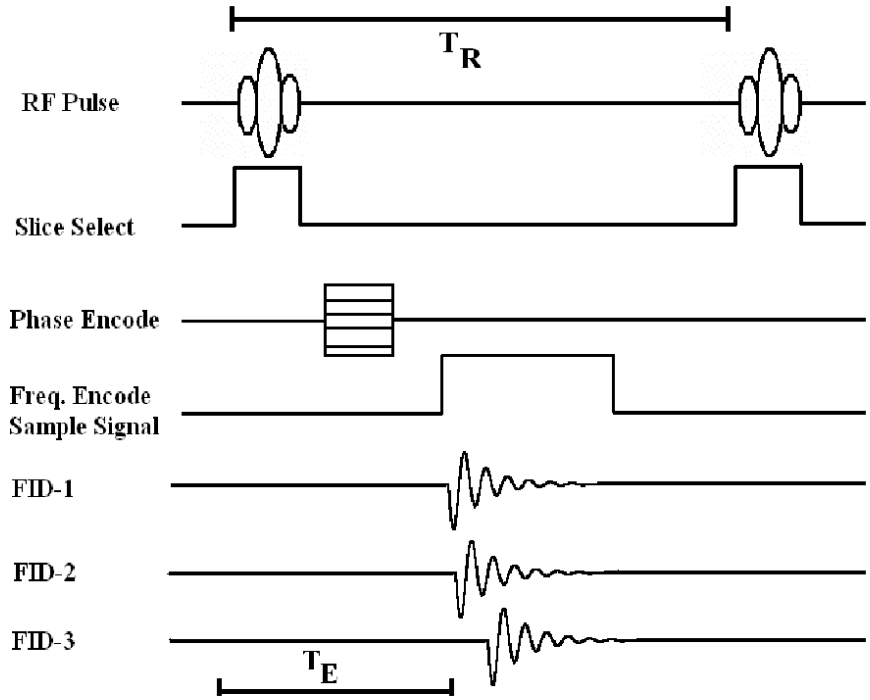

**Slice select** – all NMV rotating in phase and at same Larmour frequency

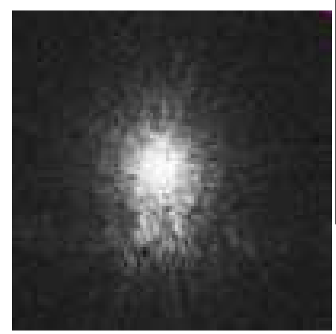
**Phase encoding** – 3d gradients set up so that 'column' of each region's NMV has slightly different phase with same Larmour frequency

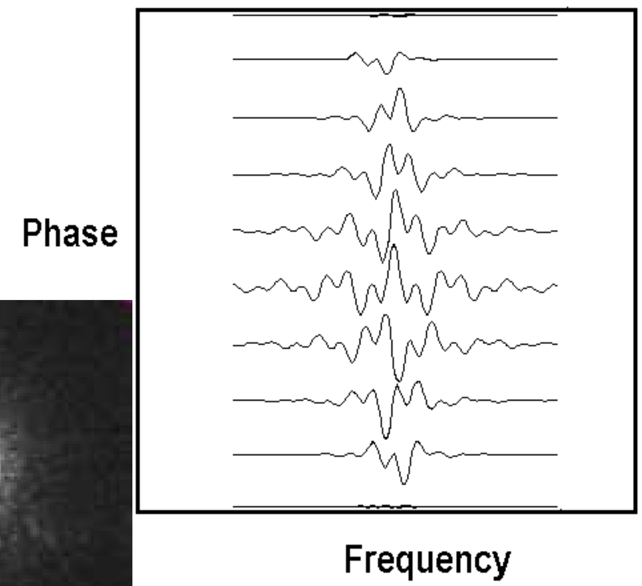
- **Frequency encode** Frequency encode gradient set up so that NMV have unique phase and frequency characteristics at each location

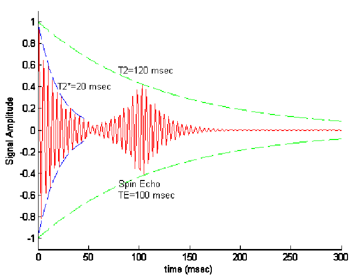
# An Introduction to MRI

The image is must be constructed, unlike a photograph. Frequency and Phase encoding are used to generate a k-space representation of the image…FFT is then used to get the image



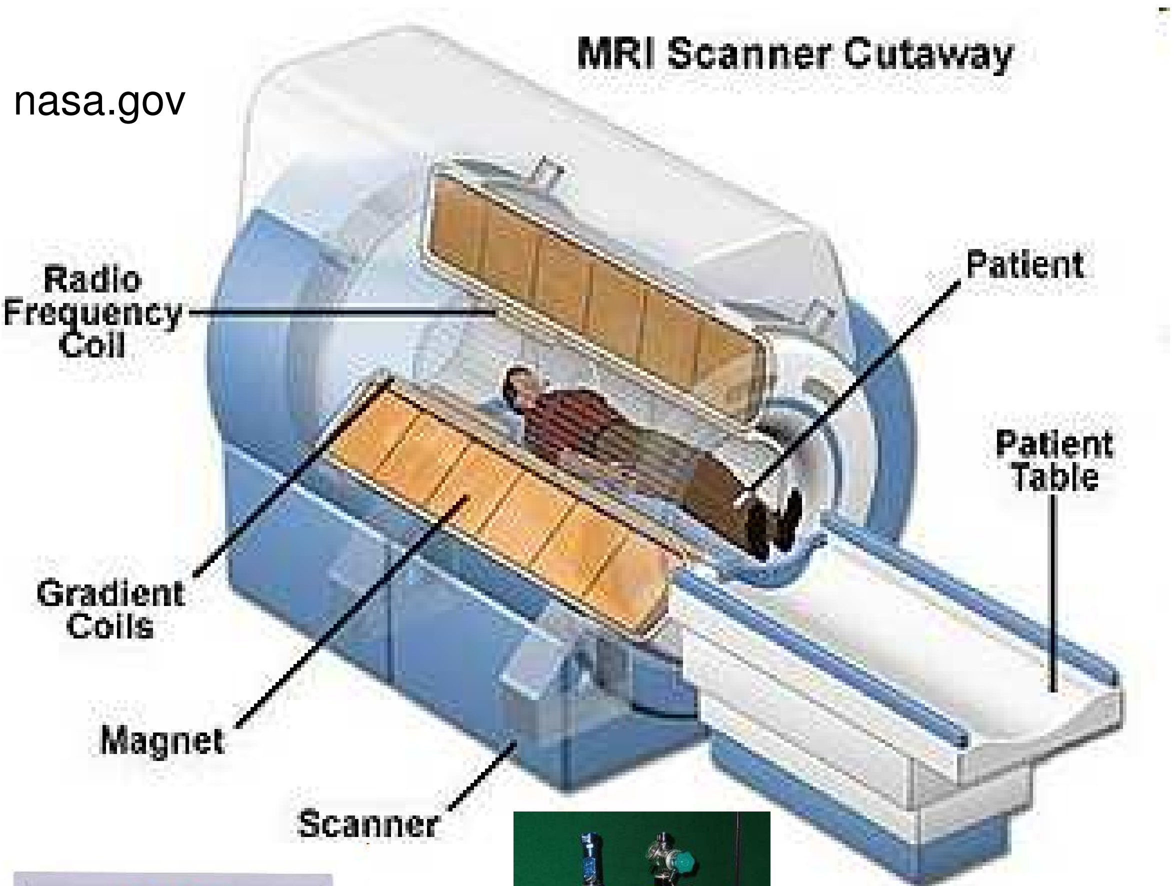



***Phase, frequency and amplitude stability key for sharp images.***

# The Main Coil-Based MRI System

nasa.gov




400km superconducting wire

L=3.5H I=200A  B0=7T

7000 liters LHe

50+MJ stored energy

Other Coils:  shim, gradient, RF T/R

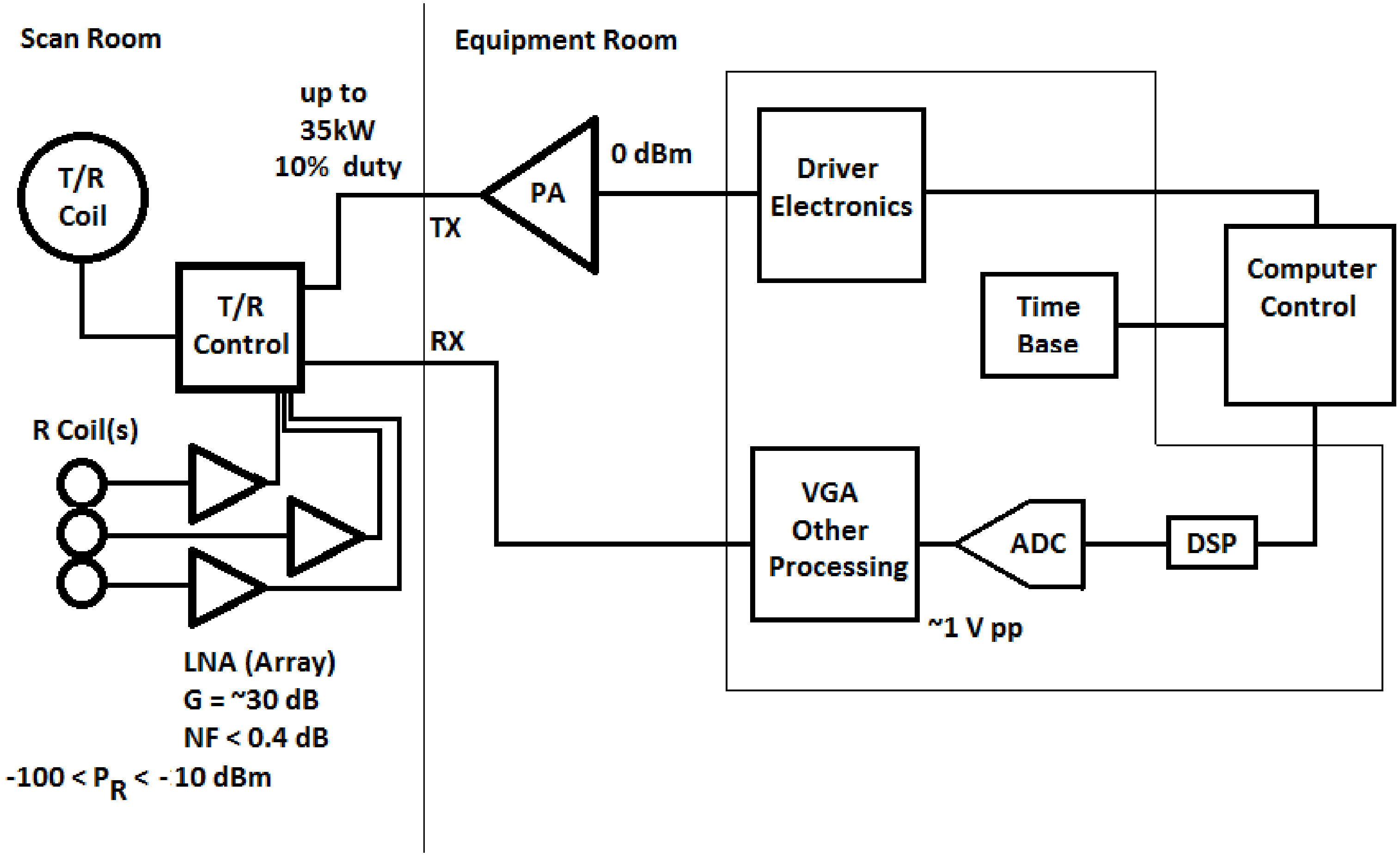


NCI

# MR System – Coils Used Everywhere

- Main B0 coil
- B0 Shim coils
- B0/G XYZ Gradient coils
- Transmit coils (Birdcage < ~3T, TEM > 3T) to provide homogeneous B1 field/shimming
- Receive coils/coil arrays to capture radiated NMV signal

# System Equipment Layout




Extensive cabling required

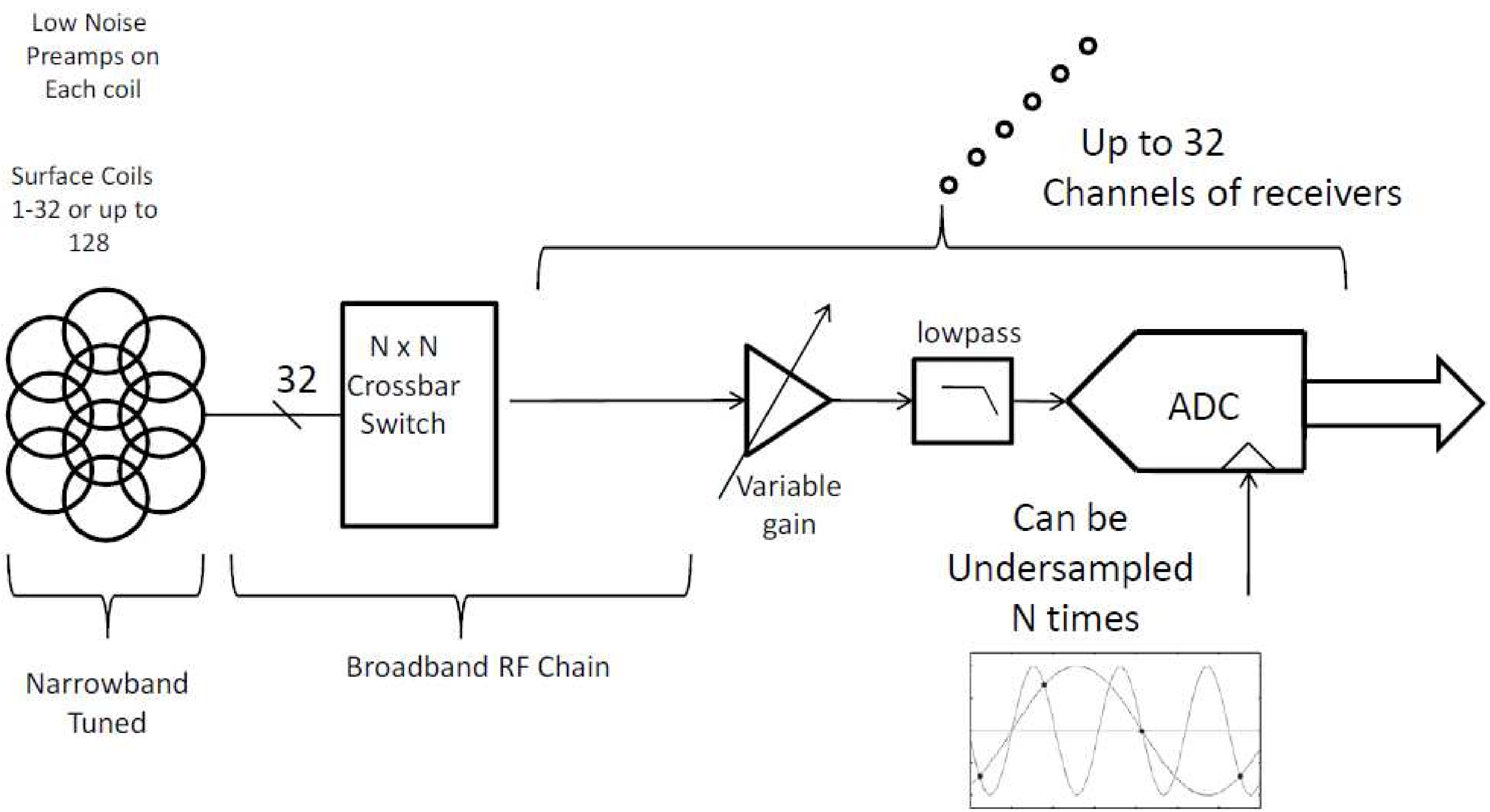
losses, unwanted coupling, pickup

# Receiver Design Considerations

- MRI/NMR Receivers are narrowband, high-dynamic range processors that must operate in a challenging EMC environment.
- The physical environment is typically relatively benign.
- Dynamic range and stability of the receiver electronics are critical to image quality. SNR is king – signals down to thermal noise sought.
- Scalability of the system design and putting as much RF equipment close to coils are important trends.
- Fully analog-based receivers trending towards all digital receivers (digital signals to control room); fiber optics

$$SNR \propto \frac{\omega \int_{vol} \overrightarrow{B1} \cdot \overrightarrow{NMV_{xy}} dV}{\sqrt{4kTBR}}$$

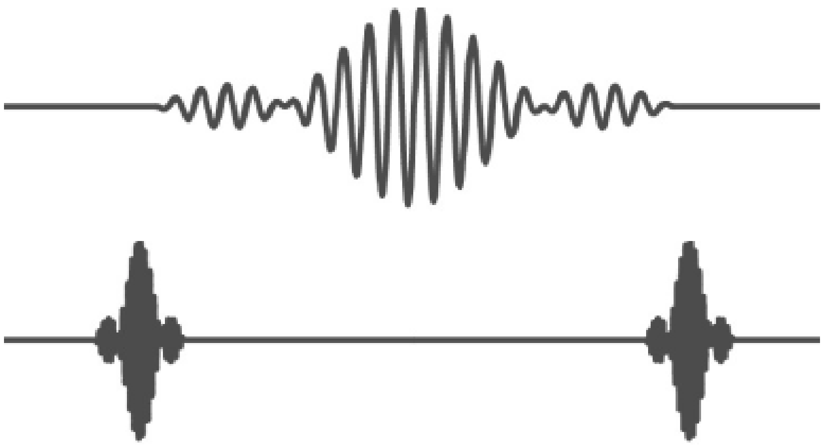
# Example: Direct RF Sampling RCVR




R. Watkins

# Transmitter Design Considerations

**WAVEFORMS**

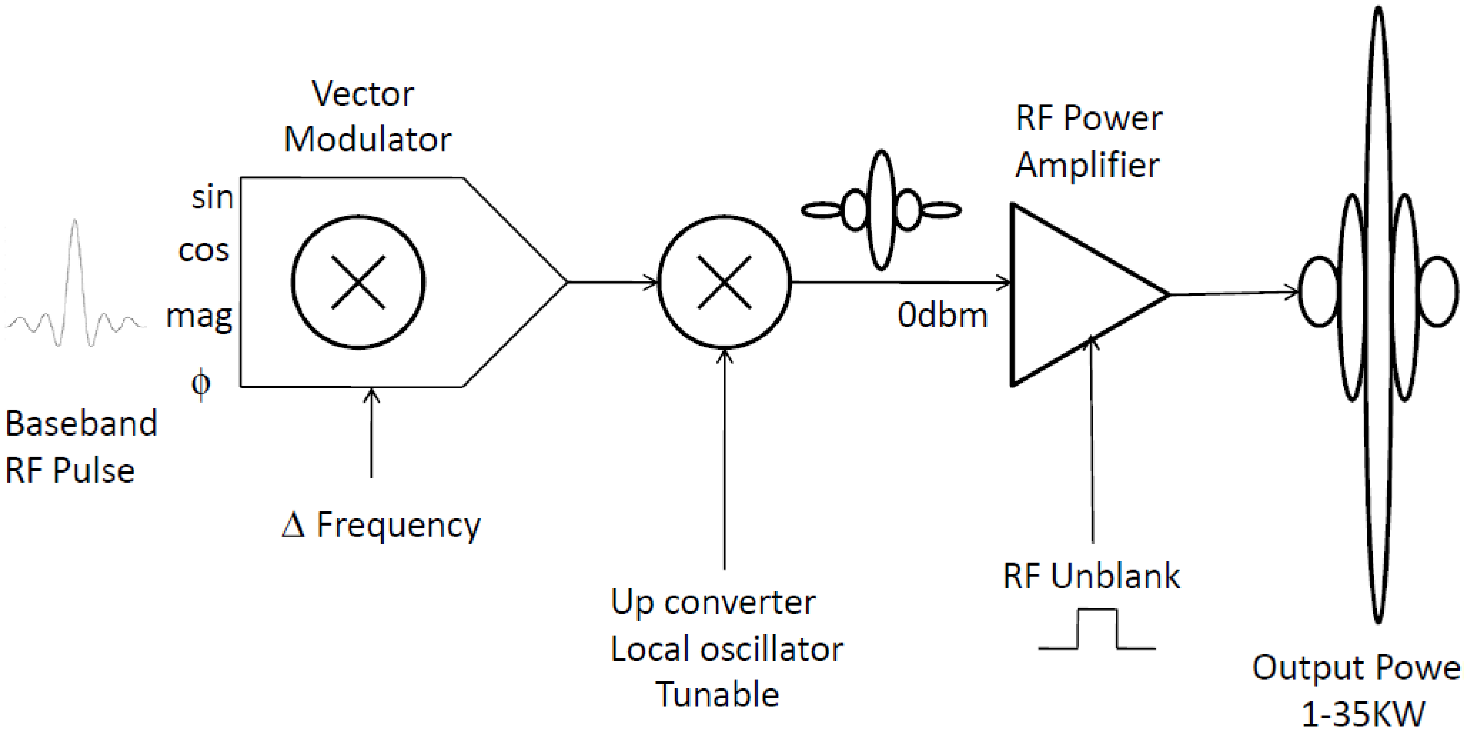


- Linear amplification
- Peak/average = 6.25 dB

**PARAMETERS (9.4T)**

Frequency: 30 - 405 MHz
Bandwidth: 1MHz
Power: Pulse – 8 kW
CW – 100W
Pulse width: 20-100ms (300ms max)
Duty cycle: 10% max
Amplitude Rise/Fall: 500ns, type
Output Amplitude: within 5% to 20ms
Gain (0dBm input): 69 dB
Gain flatness: +/- 3 dB
Phase change: < 12$^{o}$
Harmonics: -20/-12 dBc (2$^{nd}$ /3$^{rd}$)

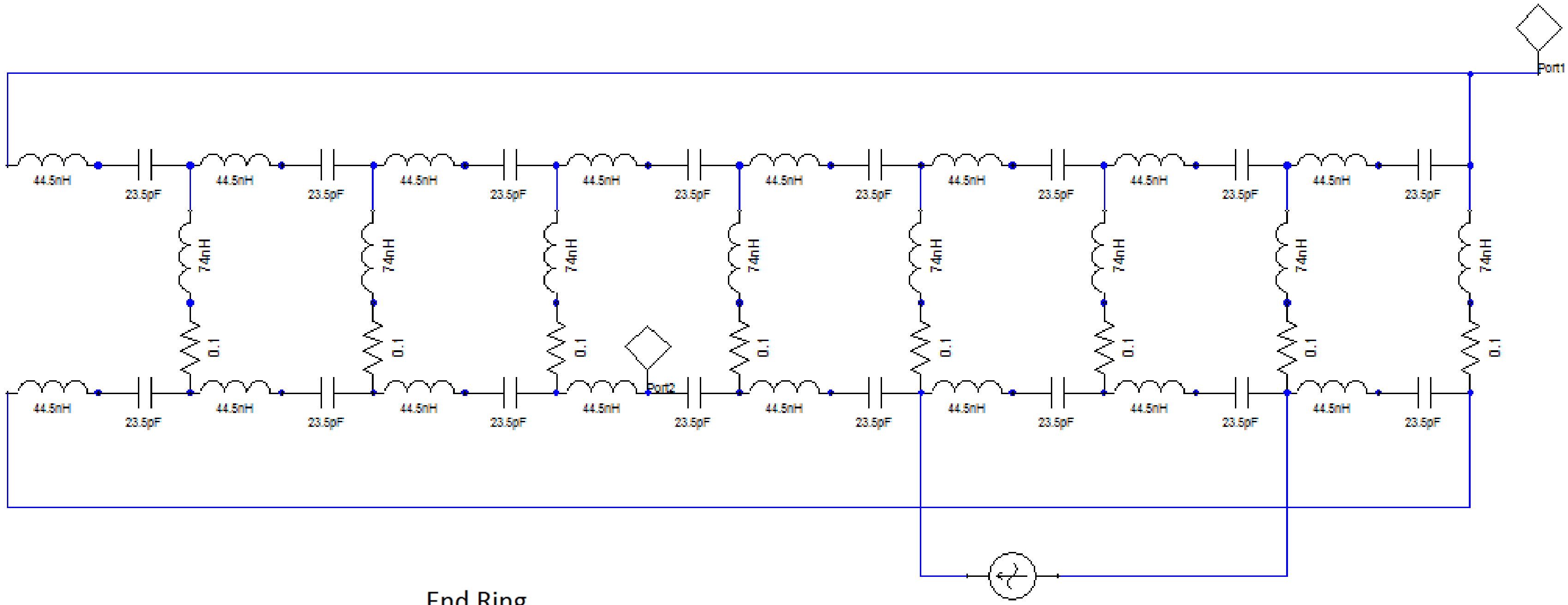
# Example: Transmitter

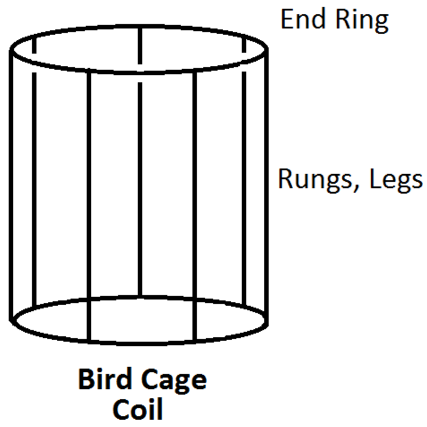


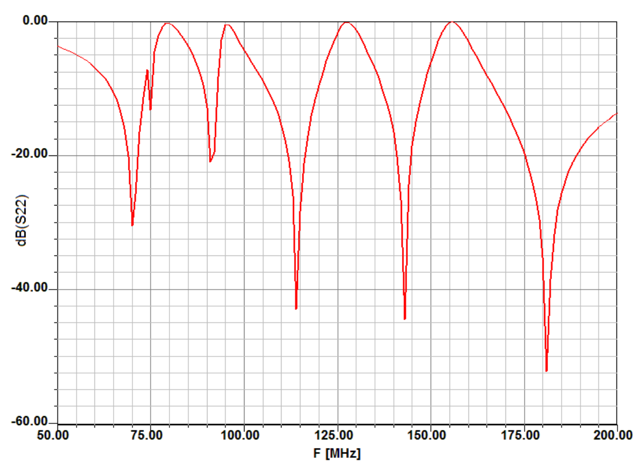

16 channel (2KW per channel) PA for MRI applications. Courtesy of CPC.

Coil mounted, magnetic field tolerant, RF power amplifiers,16 channels at 7 T. Courtesy of CPC.

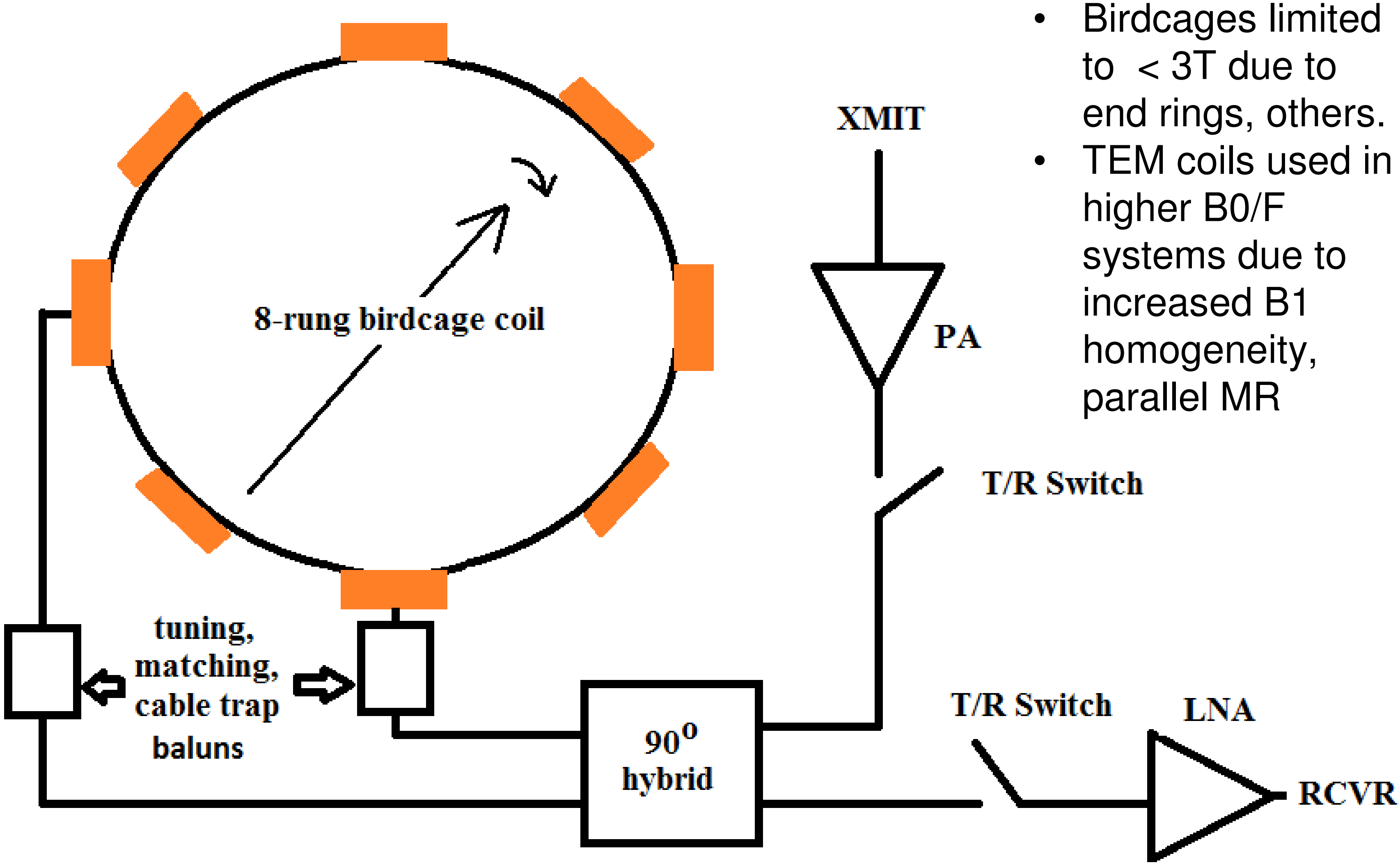
# Example of a Transmit Coil (birdcage)



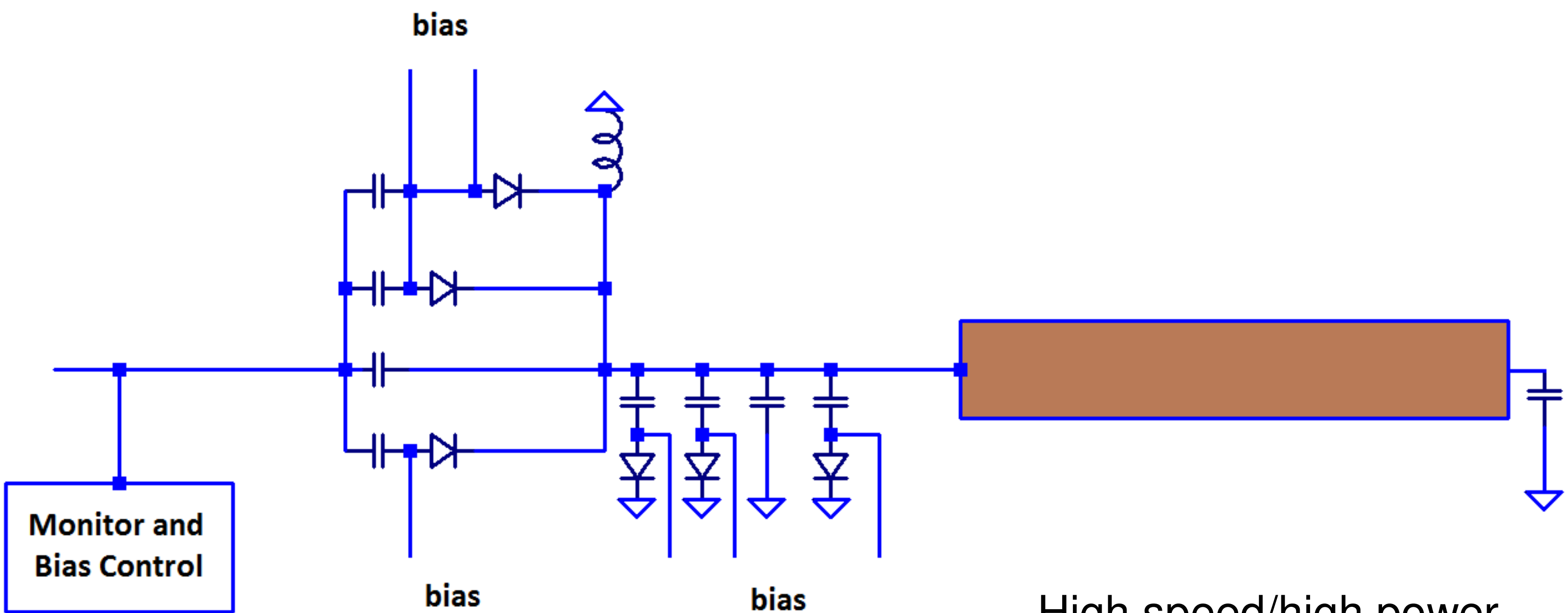
# Example Coil Feed




- Birdcages limited to < 3T due to end rings, others.
- TEM coils used in higher B0/F systems due to increased B1 homogeneity, parallel MR

# Automated Coil Tuning

- The transmit coil will be de-tuned when a patient is moved into the bore, causing a shift in resonance away from Larmor and reduction in Q varies with patient
- Electronic tuning algorithms employed for optimized tuning time/response



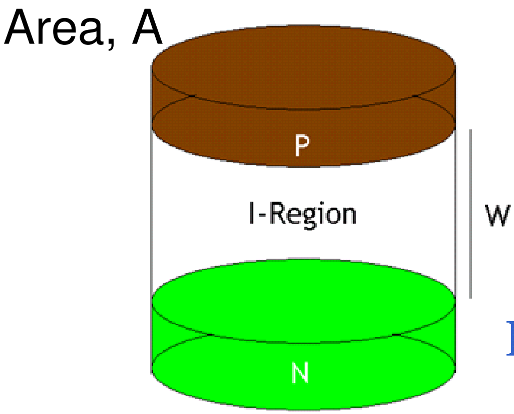

High speed/high power switching requires the use of PIN diodes

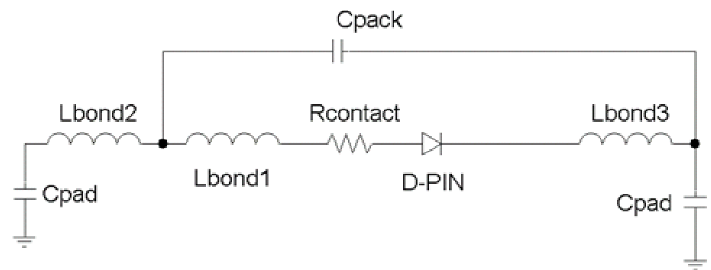
## MR Coil Switch Functions – Active or Passive

- **Block** – open circuit a coil by turning on a diode terminating a $\lambda/4$ line
- **Detune** – changing the resonant frequency of receive / transmit coils by turning on a diode in a resonant circuit across a gap capacitor
- **Decouple** – detuning a receive coil during transmit so the coil does not absorb energy / distort the RF transmit field (B1)
- **Disable** – patient safety circuitry to disable the transmitter drive circuit by shunting the transmitter power to a matched load.
- **LNA Protector** – Limiter placed at the LNA input – usually combined with matching circuits + A/D converter in a module.

***PIN Diodes are primarily used for these switching and control functions***

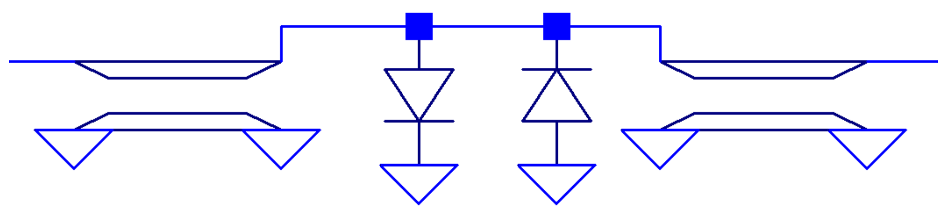
# Physical PIN Diodes



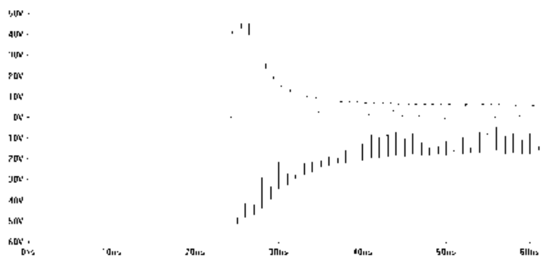

Detailed equivalent circuit for packaged PIN diode

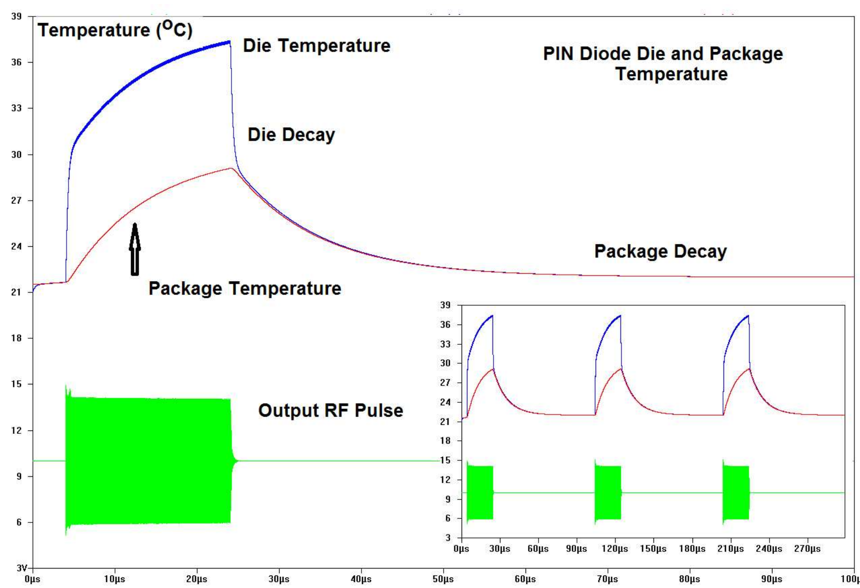
New SPICE model: time-domain operation of PIN diodes. Example of anti-parallel pair shows a period of 'spike leakage' before full turn-on.



$$R_{FB} = \frac{W^2}{2\mu I_{DC}\tau}$$

$$C_{RB} = \frac{\varepsilon A}{W}$$





# Transmitter: T/R Switch

In Transmit Mode (diodes in on state)

a. RF Transmit is connected to antenna

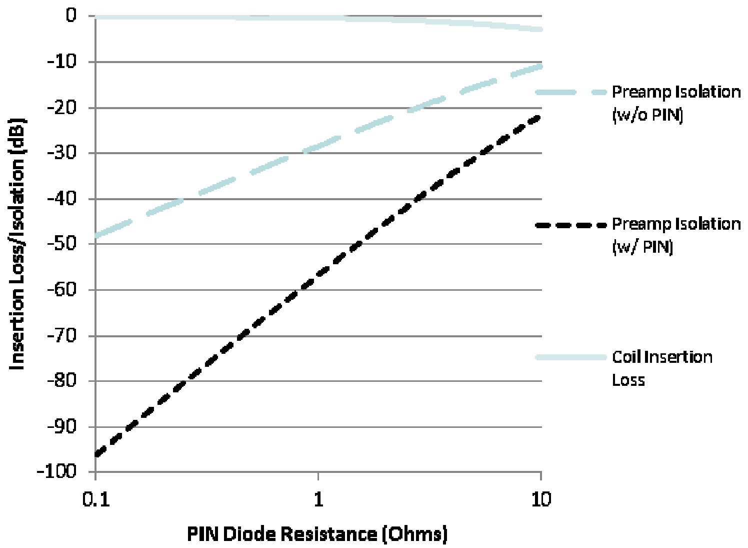
b. b. preamp is protected from high power Xmit

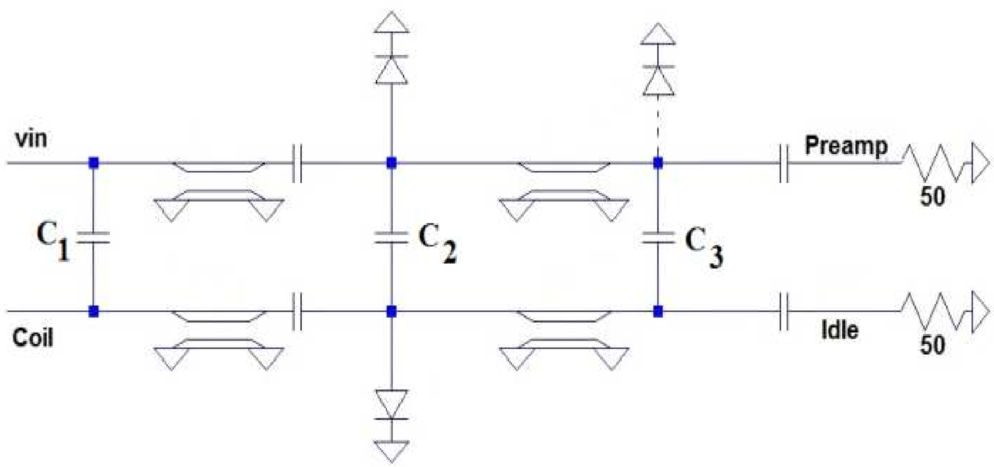
In Receive state (diode back biased or off state)

a. antenna is decoupled from transmitter

b. antenna is connected to preamp

c. preamp is decoupled from the noise from idle-transmit path



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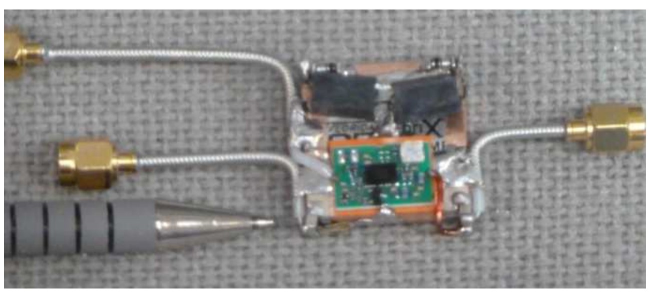

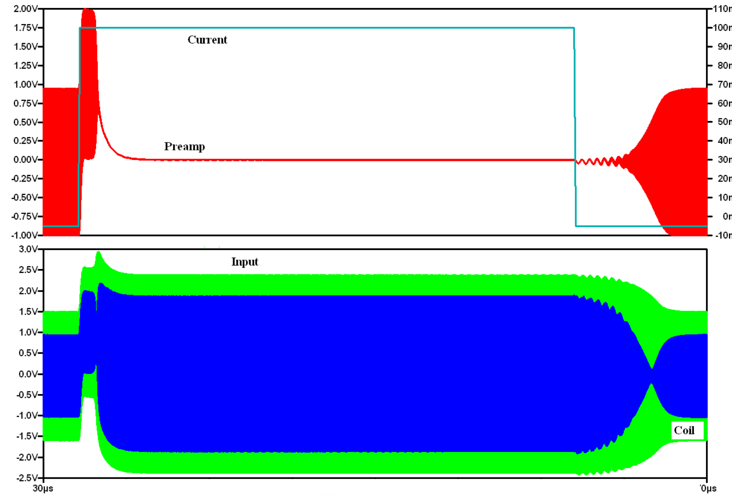


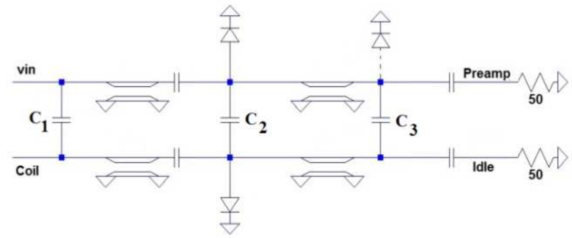


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# In-Bore Electronics

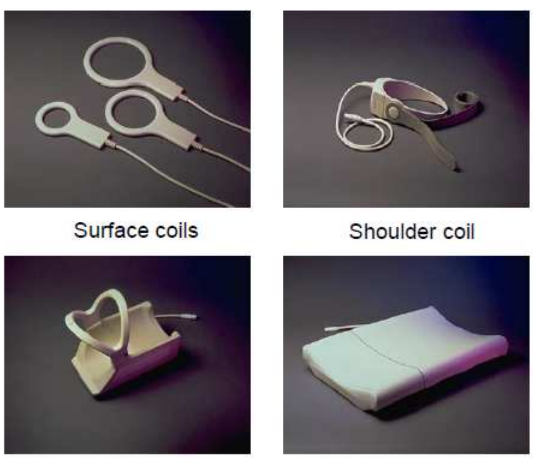
- Short cable runs (low losses) require some electronics to be in high B0
- LNAs are one of the main elements  [F=F1+(F2-1)/G1+…]
- Residual magnetism can cause unwanted image artifacts
- Mechanical stresses also an issue
- Utlra-low Magnet Moment components necessary
- ferromagnetic – retains magnetism      Nickel
- para – magnetic only when B0 applied (positive)      Tungsten
- dia - magnetic only when B0 applied (negative)      Silver
- Use combination to compensate for low device MM

Voskoboynik *et al, 2006*

# Receive Coils

Surface coils are placed close to the area to be imaged. Single or double loops are used. Exhibit high SNR and allow for very high-resolution imaging. Lose signal uniformity very quickly when you move away from the coil. Depth penetration is about half coil diameter.

Surface coils



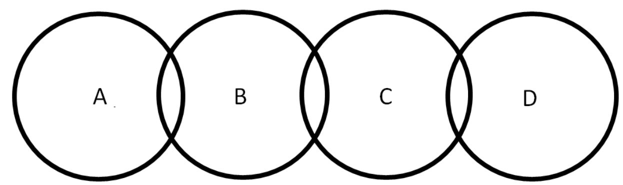
Surface coils — Shoulder coil — Neck coil — Spine coil

E. J. Blink

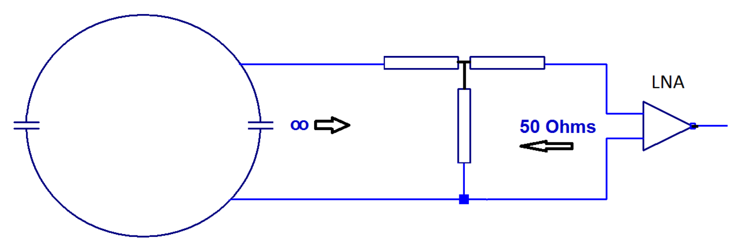
$$SNR \propto \frac{\omega \int_{vol} \overrightarrow{B1} \cdot \overrightarrow{NMV_{xy}} dV}{\sqrt{4kTBR}}$$

Further improve SNR by having many small receive coils – ***'phased array'***. Each coil is close to anatomy, so signal is improved, and minimizes receive noise from areas away from the anatomy of interest. Data acquisition from all channels is simultaneous. Image reconstructed afterwards.

To increase the field of view with small coils requires many coils to be used




Mutual inductance between nearest neighbors must be reduced to minimize unwanted couplings; limiting current also helps



# A few (of the many) examples of receive coil arrays.

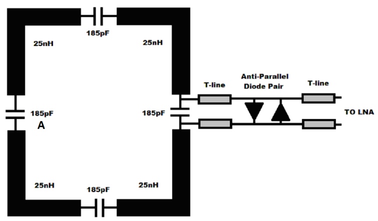
In receive coil arrays, for best SNR, the coils must be very close to the patient.  Coil detuning/disable is important for patient safety, image clarity and less coupling to strong RF field. Many coils improve SNR- decoupling important!

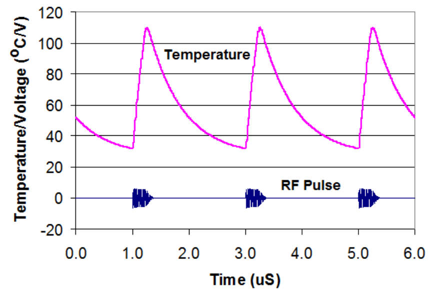
'Jedi' helmet for brain MRI.

Wellcome Images

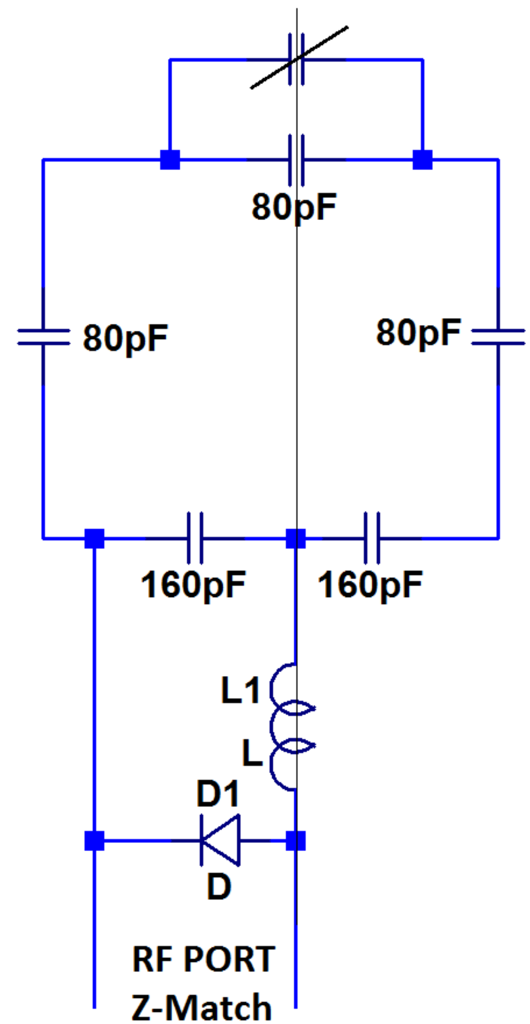


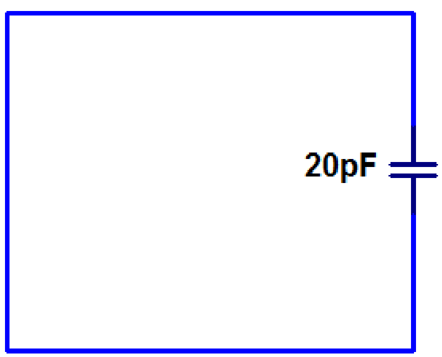
# Receive Coil Design Sequence



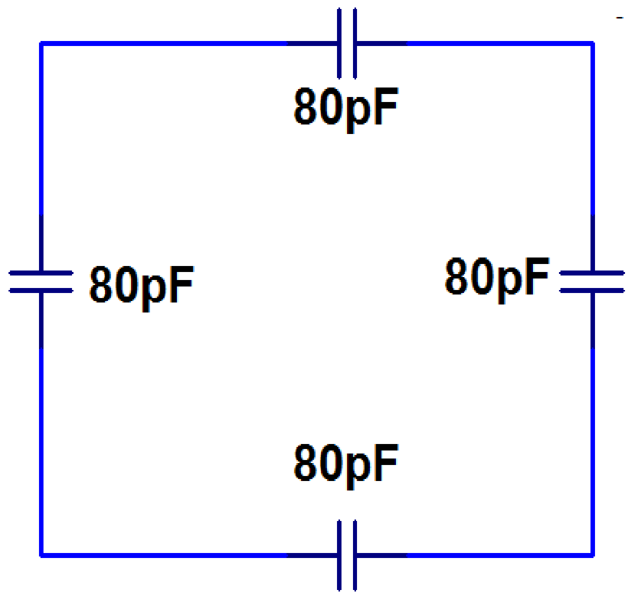




Rule of Symmetry (balance)



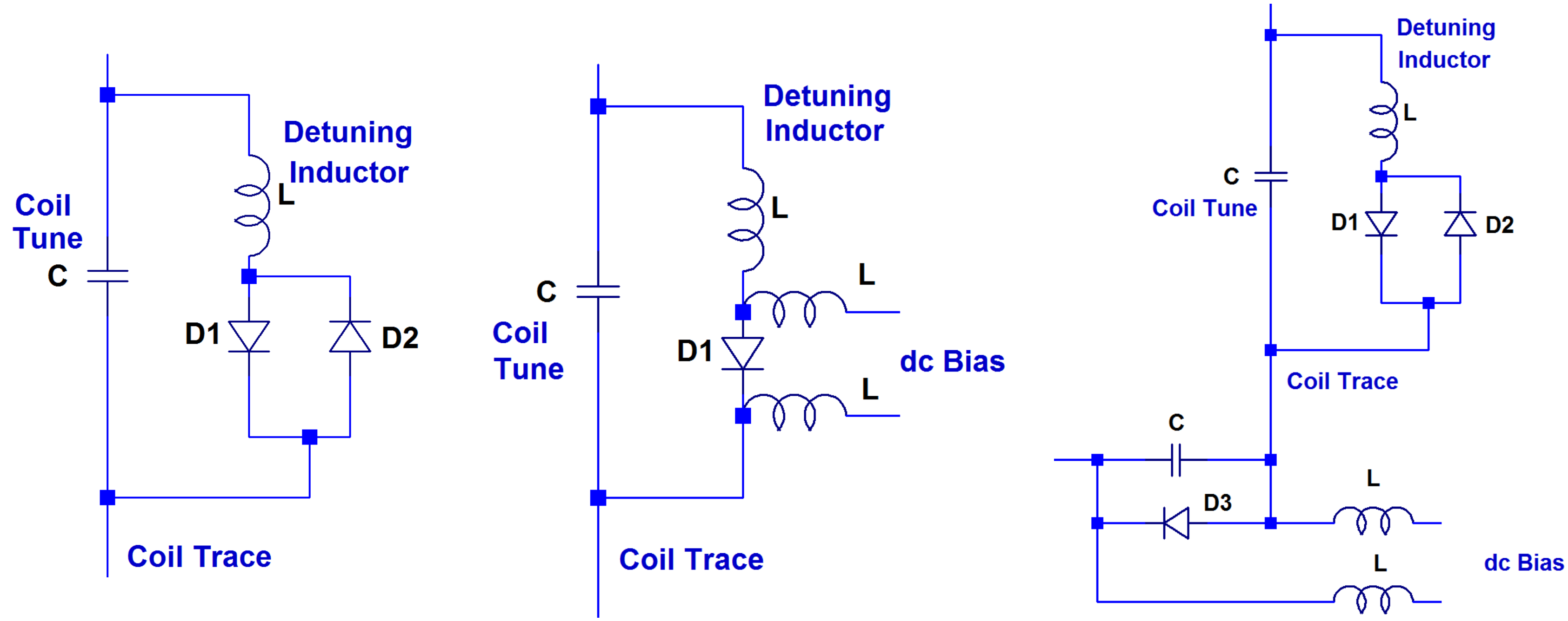

Coil inductor tuned to frequency with capacitor




Q varies 5-10X between empty, patient states – 'phantoms'

# Example Circuits

# Receive Coil Detuning with PIN Diodes



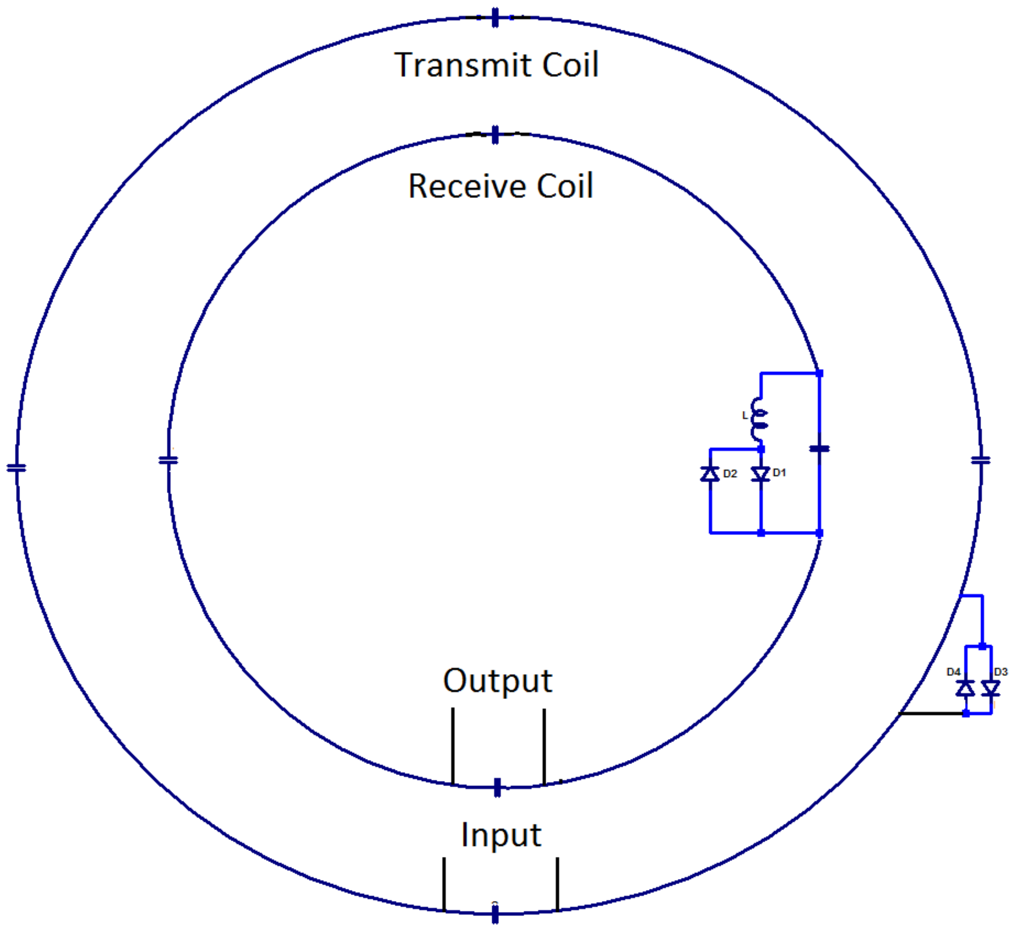

Passive Coil Detune
Block/Detune

Active Coil Detune

Active/Passive

# T/R COIL SWITCHES

## Active switching only (active bias network)

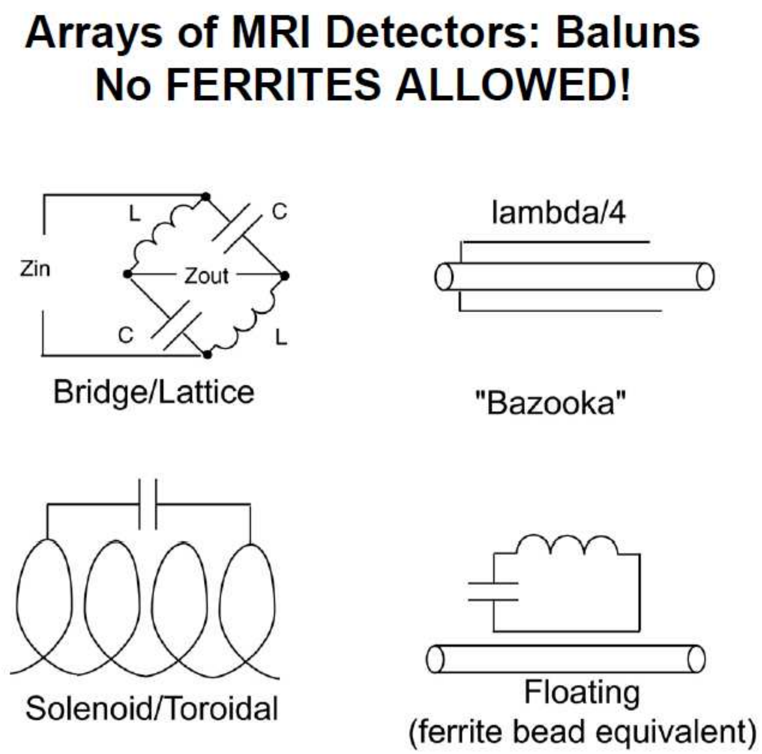



T/R Coil Decoupling using Concentric coils

W. A. Edelstein et al, 2000 “A Transmit-Only/Receive-Only (TORO) RF System for High-Field MRI Applications”,

# Even Cabling Needs to be Studied

- Coil cables required to carry bias and RF signals from the RF coil detectors
- These cables are an appreciable fraction of a wavelength long
- Coax shields from multiple MRI detectors form Yagi-like dipole antennas with multiple resonant modes
- Coax shield dipoles couple to the body transmit coil high SWR unsafe heating, RF burns
- Coax common mode current degrades array performance by coupling coils together through resonant interactions with cable modes
- Careful cable layout, baluns, shielding are all approaches used to reduce cable interactions



# Conclusions

- MRI Scanners have ***many*** coils
- RF Engineering a necessary (and interesting!) part of MRI systems
- High transmit power, low receive signals; SNR is everything
- Receive coils require detuning to minimize coupling to transmit coil, patient protection
- PIN diodes used liberally throughout

# Some Web Links for Further Information on MRI

1. http://www.cis.rit.edu/htbooks/mri/ *
2. http://www.e-mri.org/
3. http://www.mritutor.org/mritutor/
4. http://www.mr-tip.com/serv1.php
5. May 2011, July 2015 IEEE Microwave Magazine