Introduction to the Physics of MRI

Jo Hajnal

jhajnal@ic.ac.uk

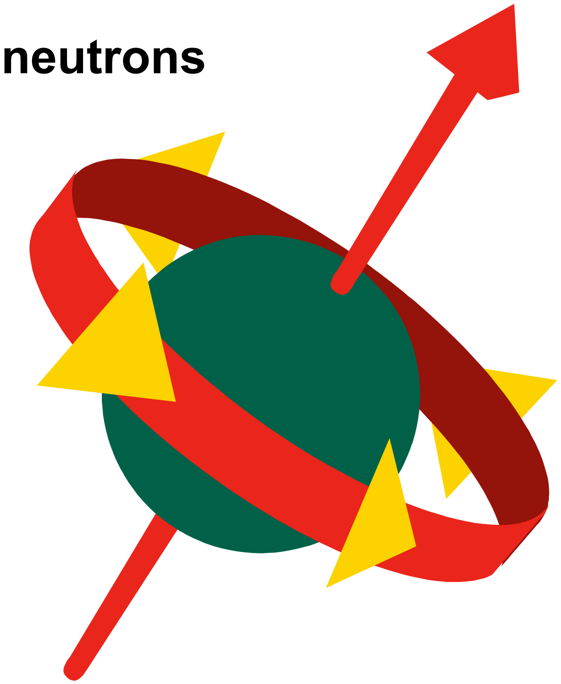
MRI

- Put subject in scanner
  - Large magnetic field (B_0) creates magnetization (M).
- Excite MR process
  - Apply radio frequency (RF) magnetic fields to rotate M away from B_0, typically 90° flip angle.
- Perform spatial encoding to make image
  - Apply phase encoding and frequency encoding gradients.
- Analyze data and display the image.

MRI signals come from Hydrogen

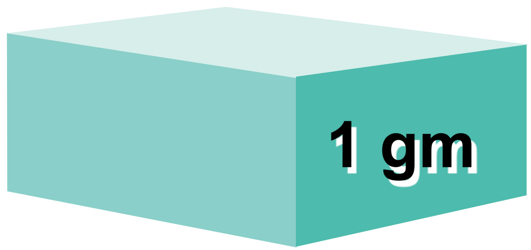
1 proton

0 neutrons

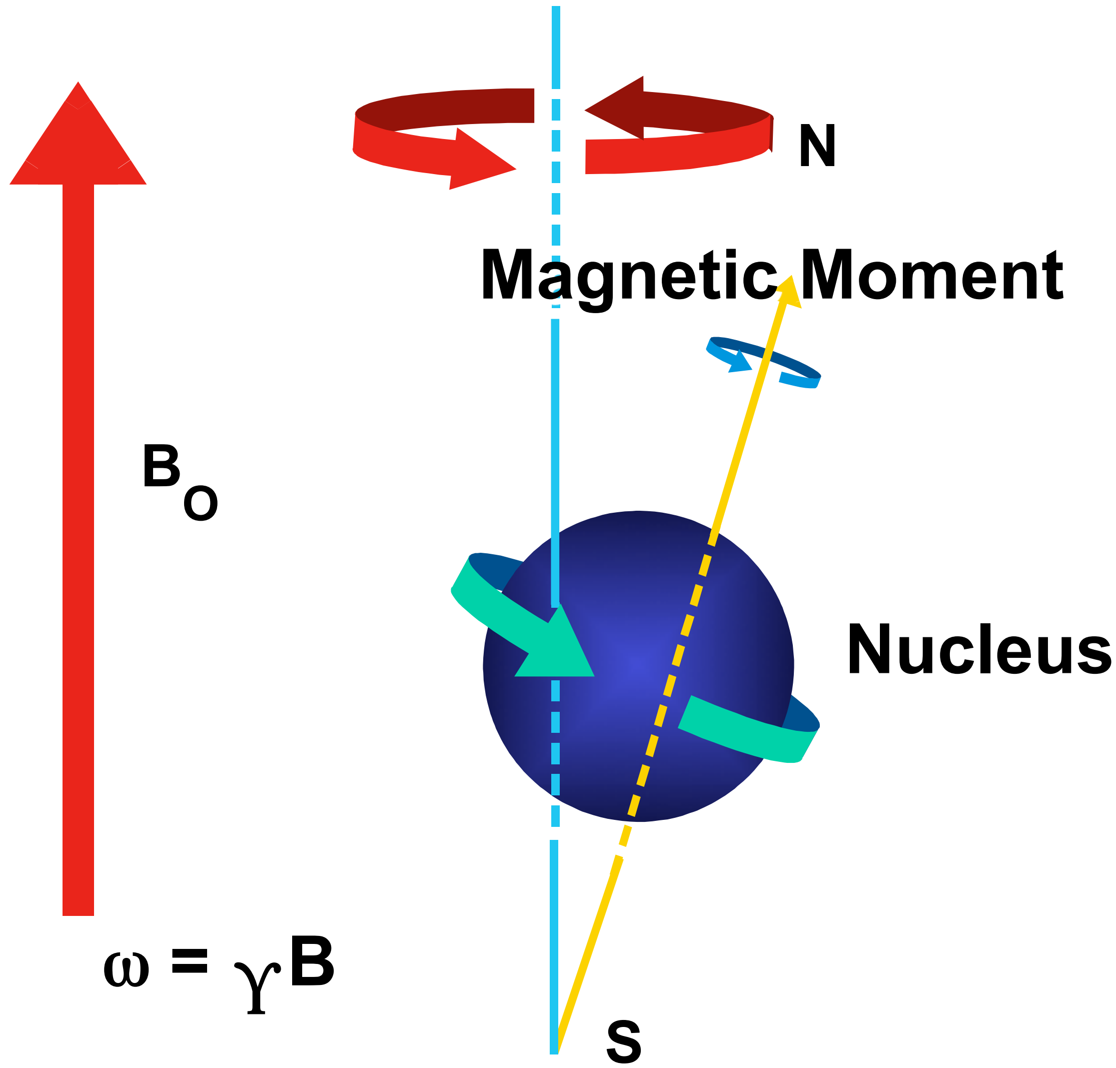


- Has magnetic moment
- Present in living matter
- Sufficient quantity to provide strong MR signal

1 gram of water contains 10^{22} hydrogen nuclei



Precessional Motion



Larmor Equation

$$\omega = \gamma B$$

ω = Larmor frequency (megahertz)
(omega)

γ = Gyromagnetic ratio of nuclei ($\frac{MHz}{T}$)
(gamma)

B = Field strength (Tesla)

i.e. The Precessional Frequency of Hydrogen

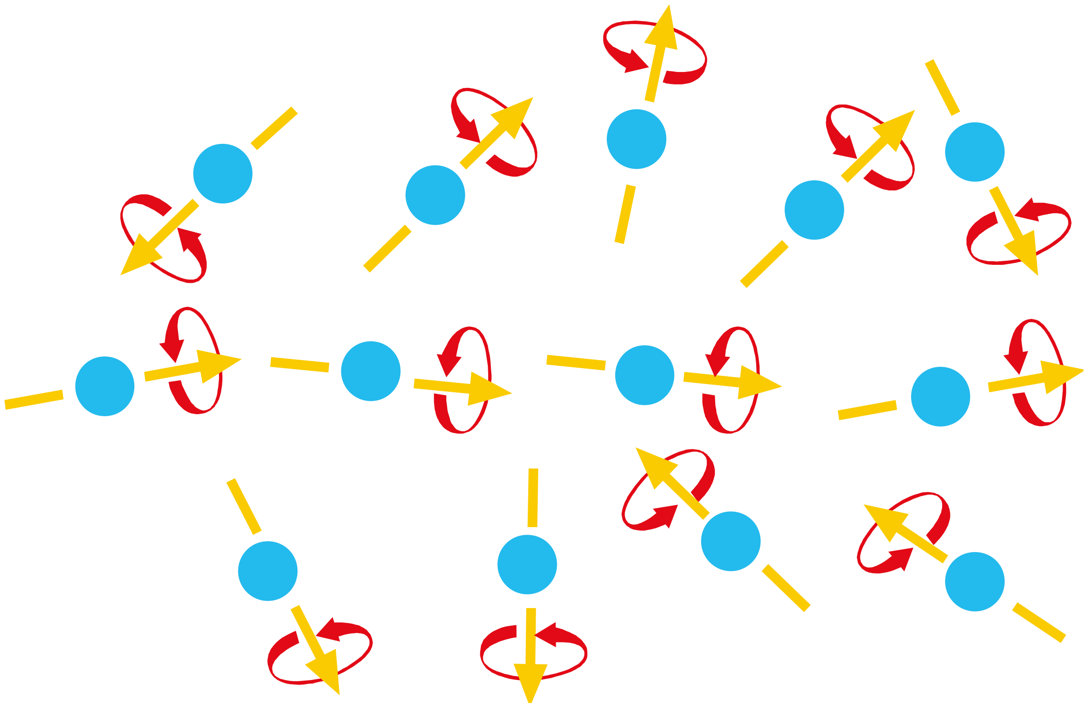
$$63.86MHz = 42.58\ (\frac{MHz}{T}) \times 1.5T$$

$$42.58MHz = 42.58\ (\frac{MHz}{T}) \times 1.0T$$

$$21.29MHz = 42.58\ (\frac{MHz}{T}) \times 0.5T$$

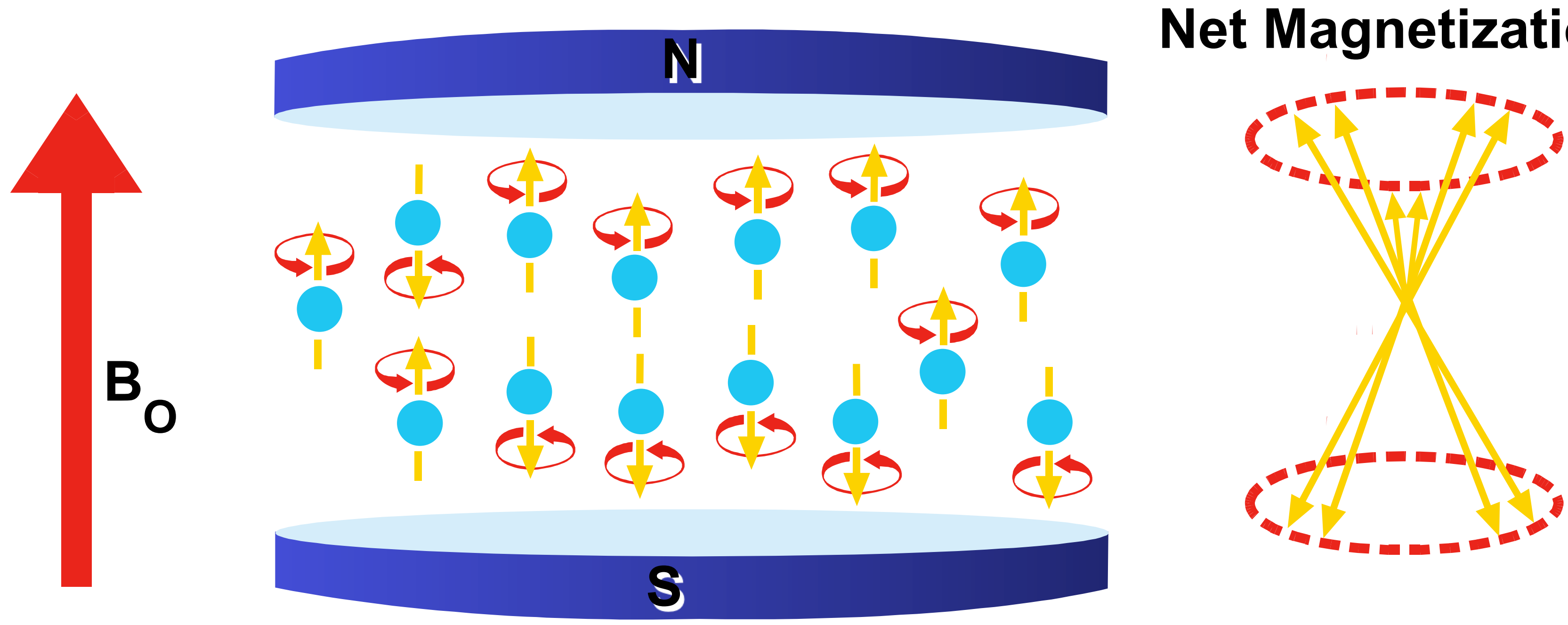
$$9.79MHz = 42.58\ (\frac{MHz}{T}) \times 0.23T$$

Absence of Magnetic Field



In the absence of a magnetic field the nuclear spins are randomly oriented.

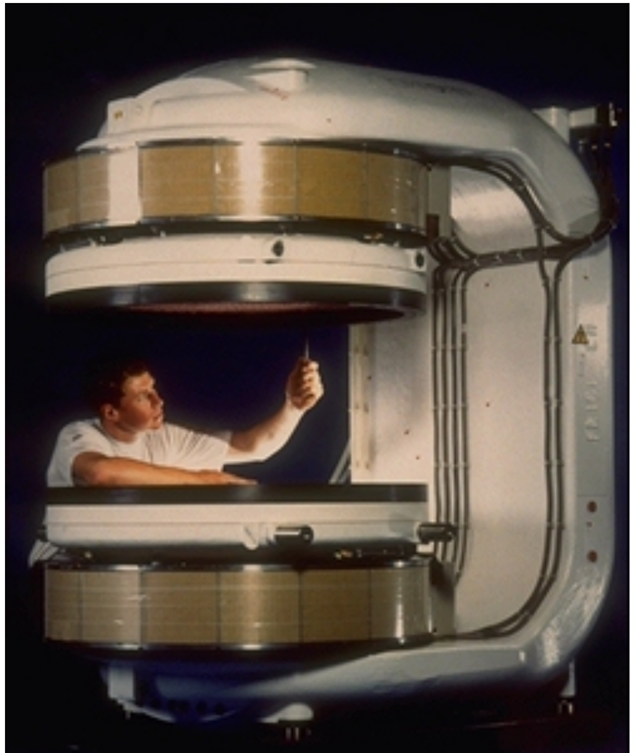
Net Magnetization

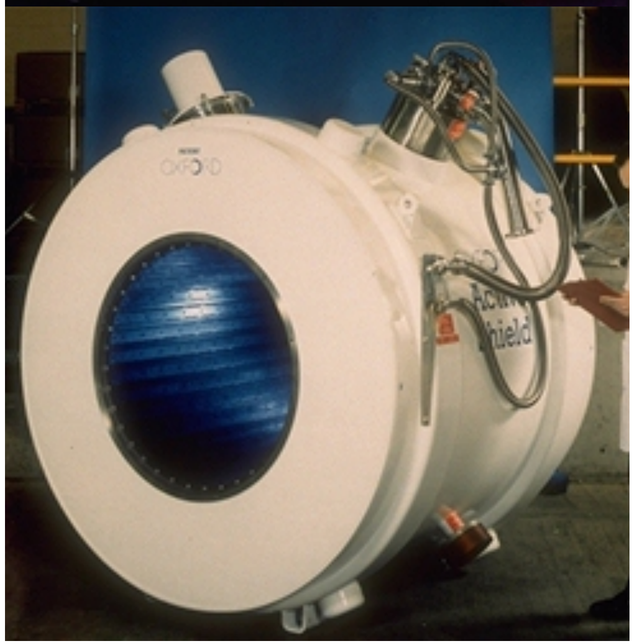


B_O

$\omega = \gamma B$

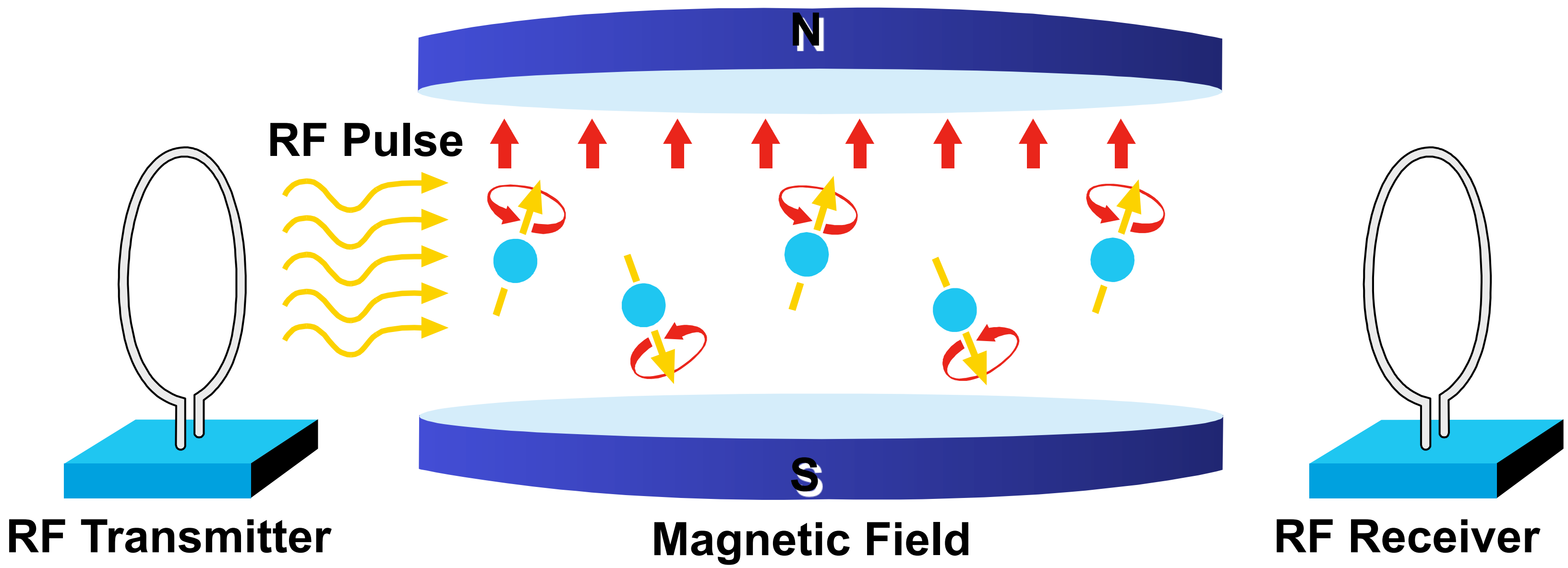
MRI magnets



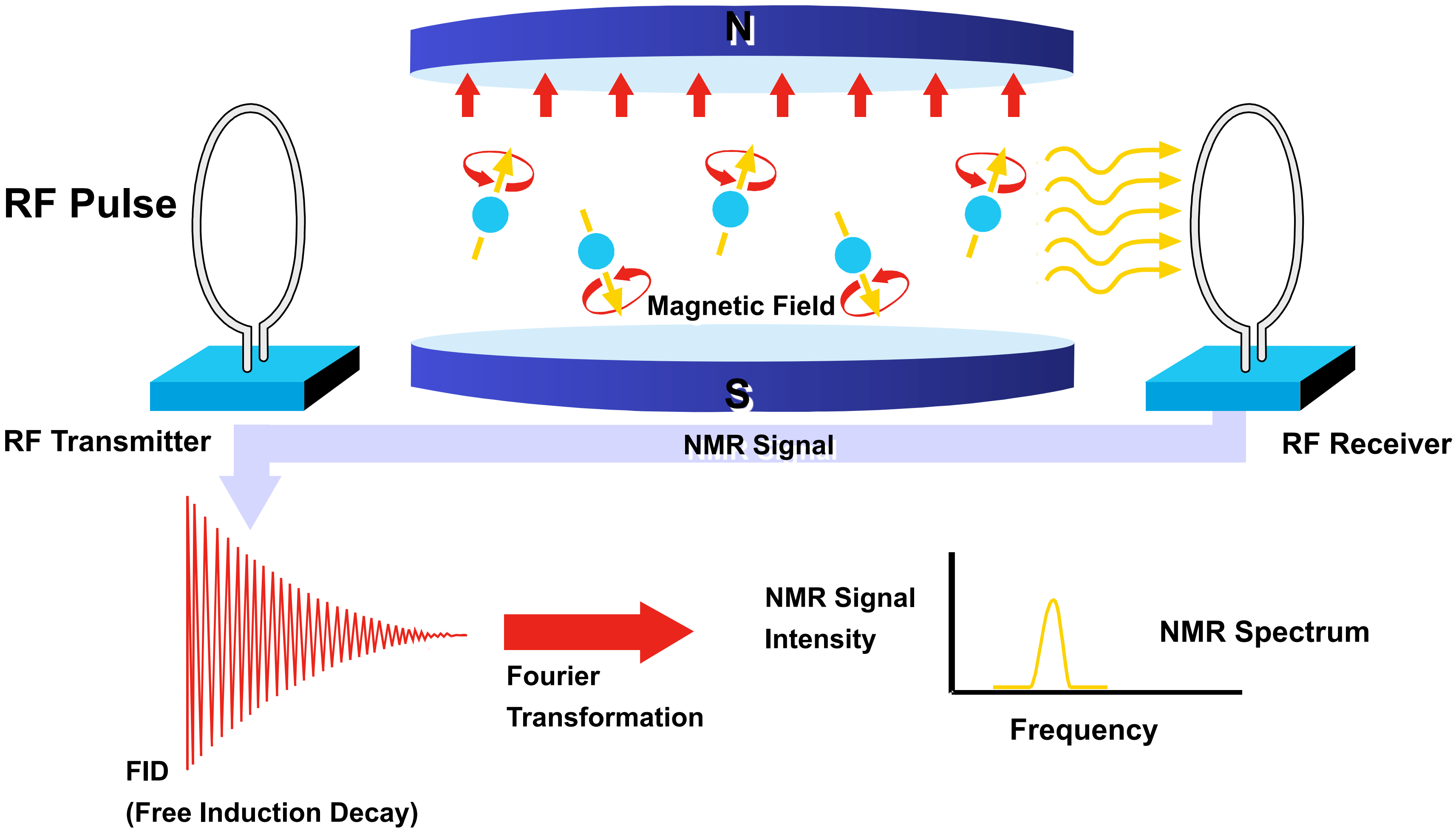


- Electromagnets
- Made with superconducting wire
    - Need to be kept cold
    - Coils in bath of liquid helium
- Always on

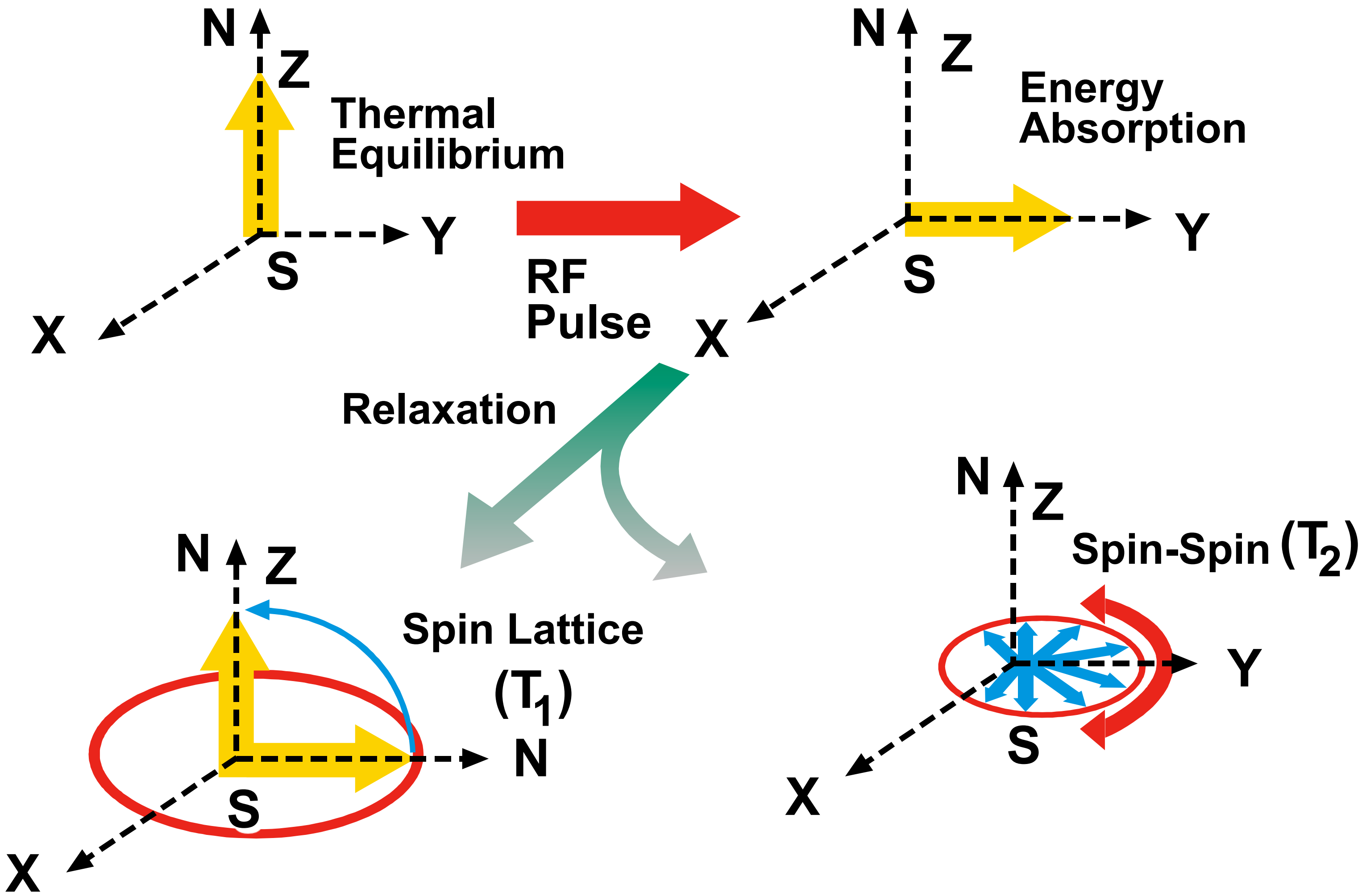
RF Excitation



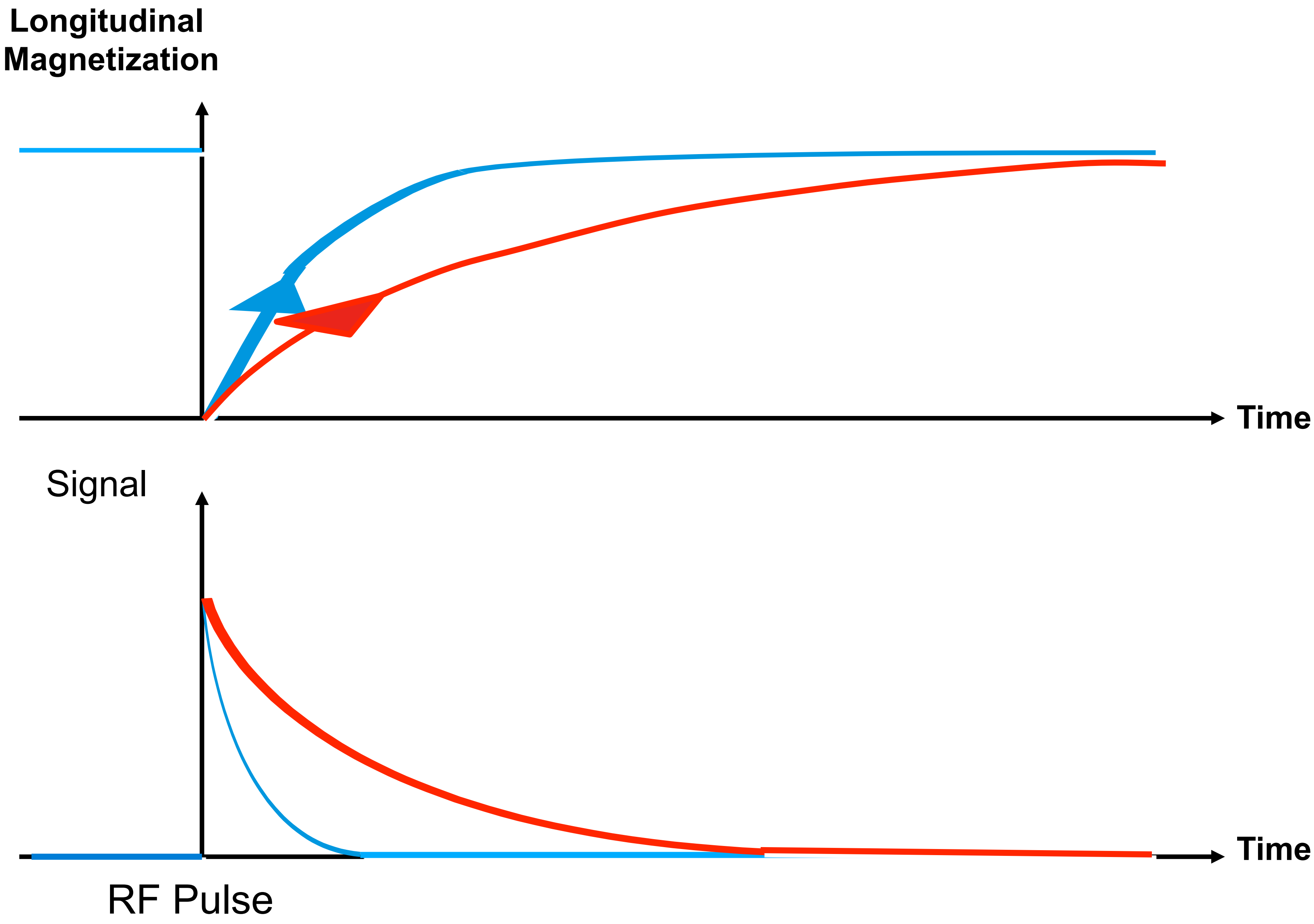
Received Signal



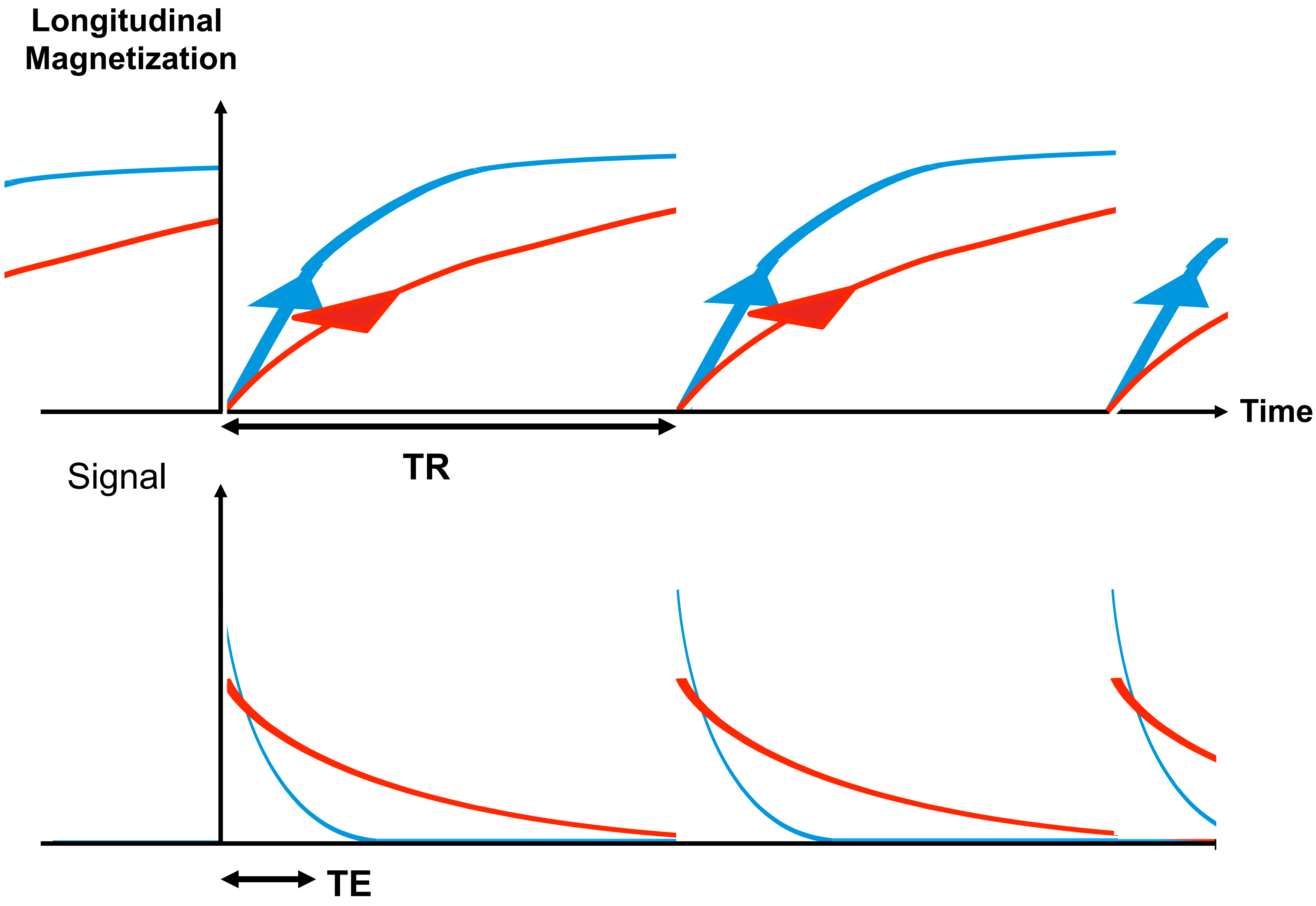
Relaxation Process



Time course behaviour



Making useful signals



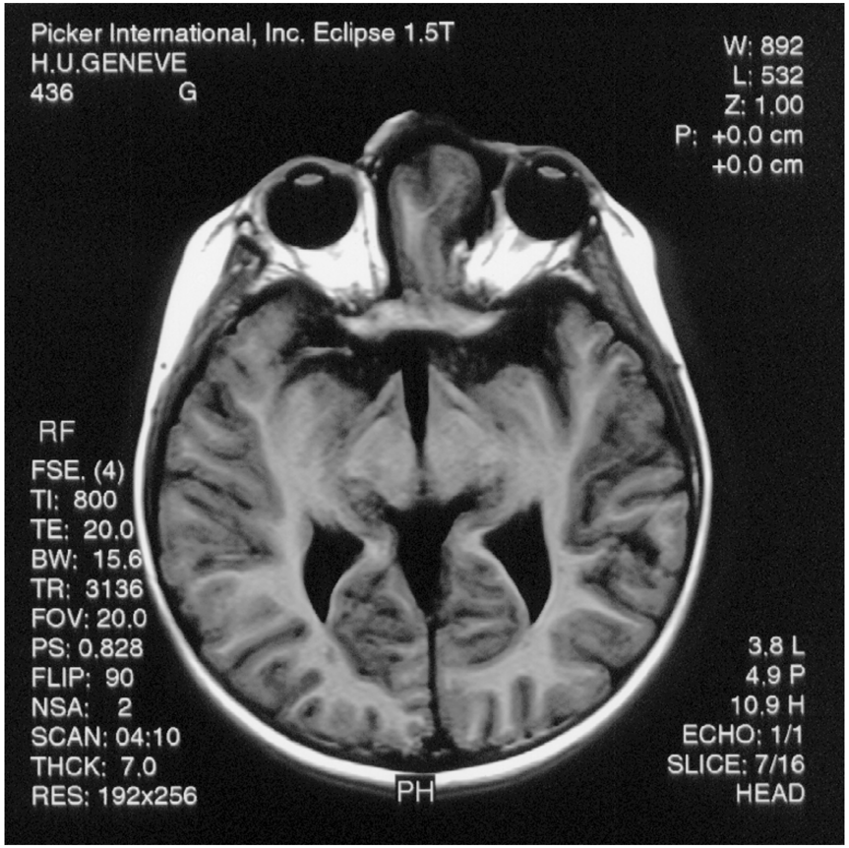
Contrast between tissues

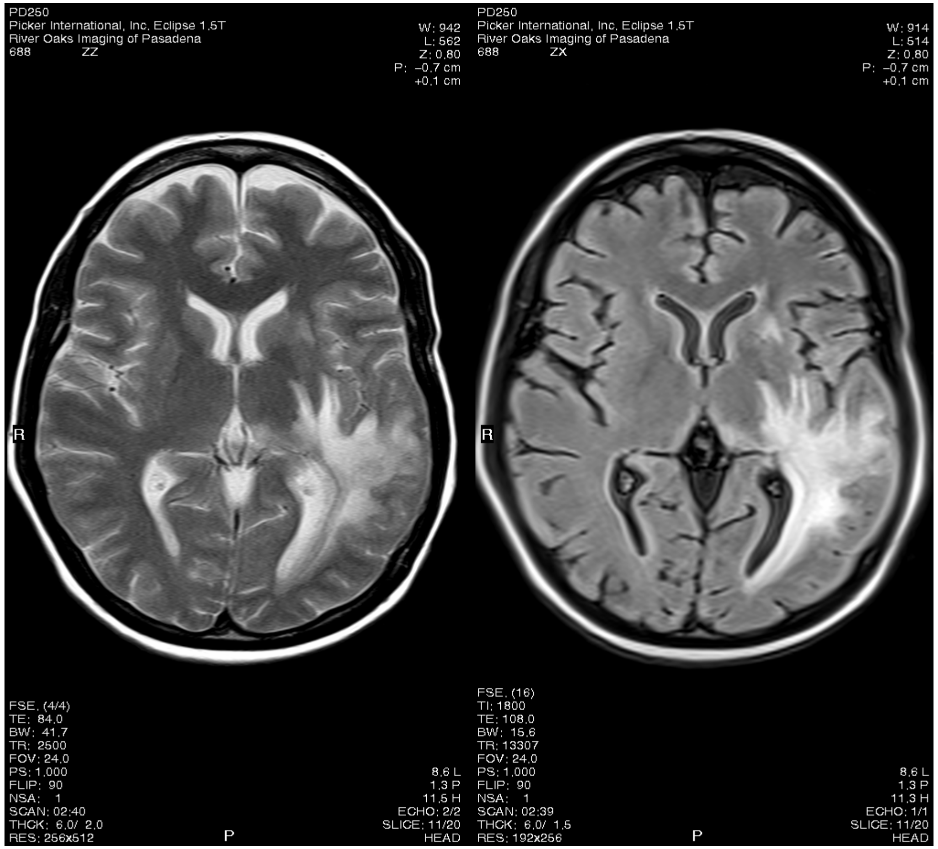
- Timing of RF pulses controls contrast between tissues
- Depends on
  - T1, manipulated by TR
  - T2, manipulated by TE
- Also
  - proton density (total available signal)
  - Flow, manipulated by RF pulse
  - Other factors……...

Tissue Relaxation Times at 1.5 Tesla

Tissue Type	T1 (ms)	Signal	T2 (ms)	Signal
Adipose tissues	245	High	70	Low
Liver	490	↑	40	↓
Kidneys	650		70	
White matter	780		90	
Muscles	880		50	
Gray matter	920		100	
Whole blood - oxy	1350		200	
(Whole blood - deoxy)	(1350)		(50)	
Cerebrospinal fluid	4000		4000	
Pure water	2500		2500	

Change scan parameters to change contrast





T_1weighted

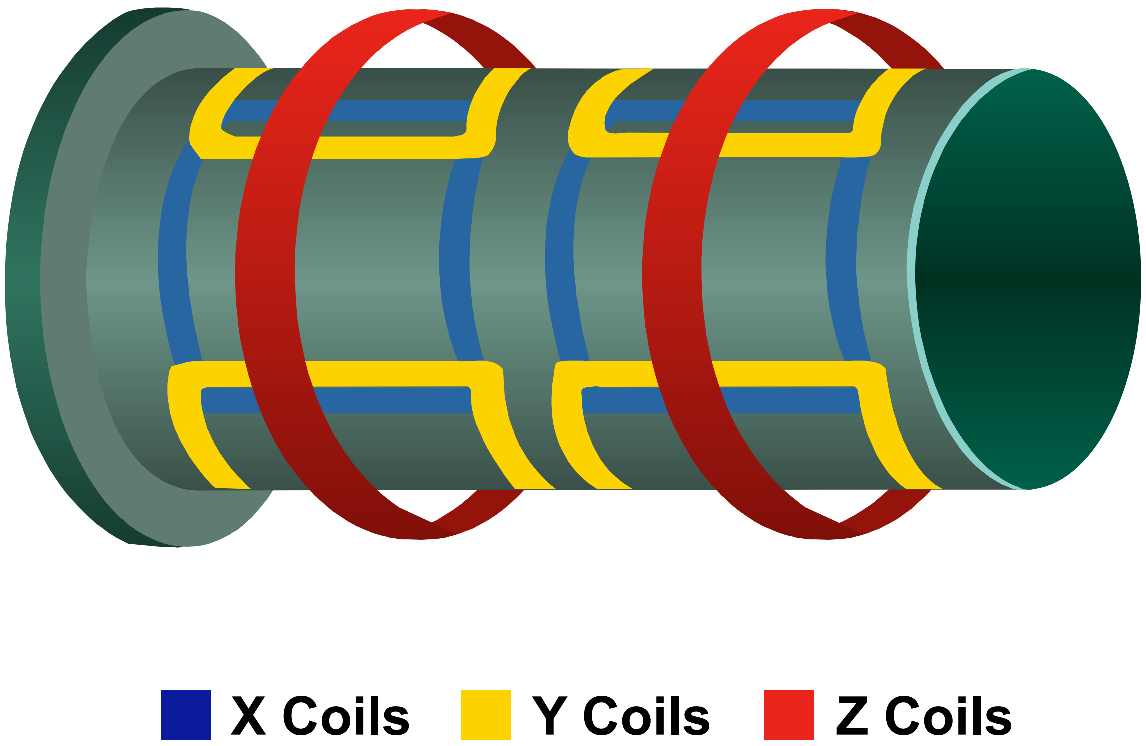
T_2 weighted

FLAIR- T2

Image Formation

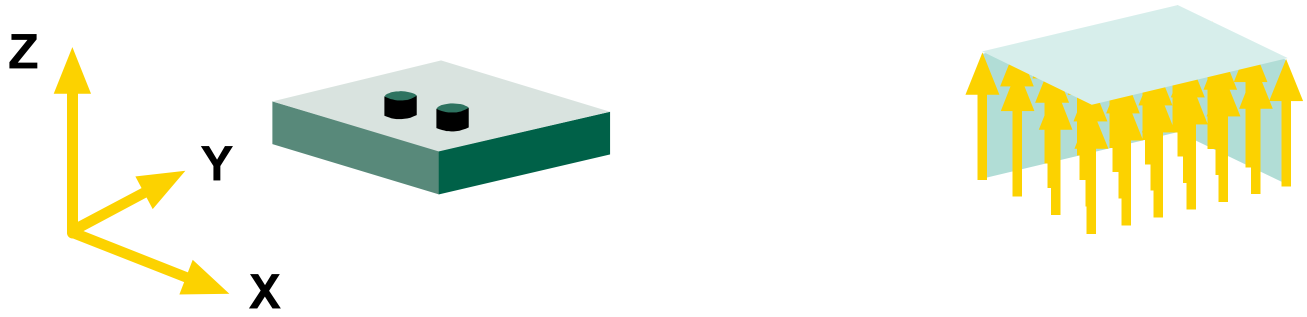
- Use Larmor Frequency
- Resonant Frequency is proportional to B_0
- Manipulate frequency by changing magnetic field

Gradient Coils

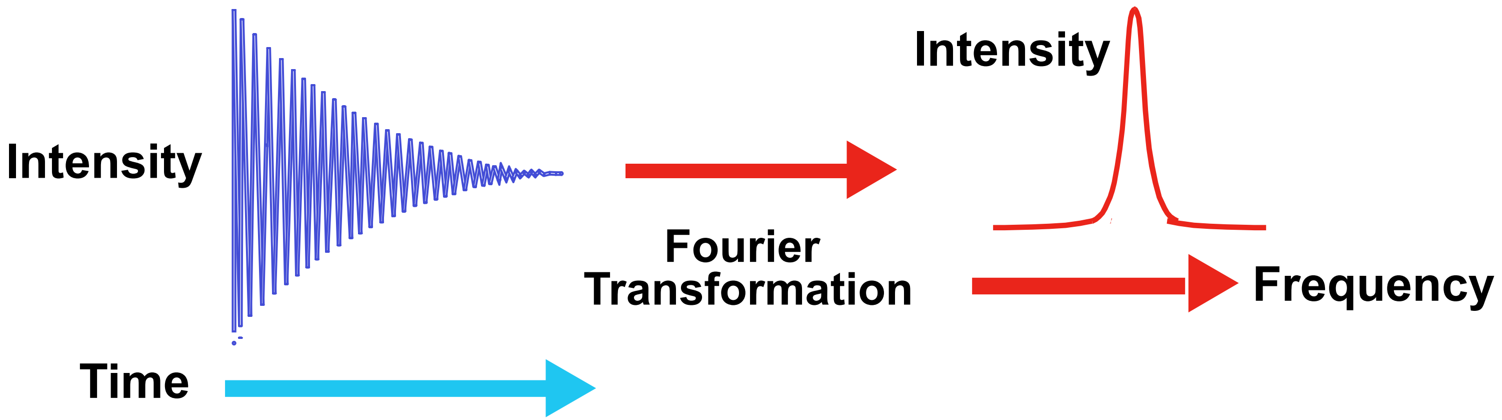


(Gradient Turned Off)

Why Gradients are used?



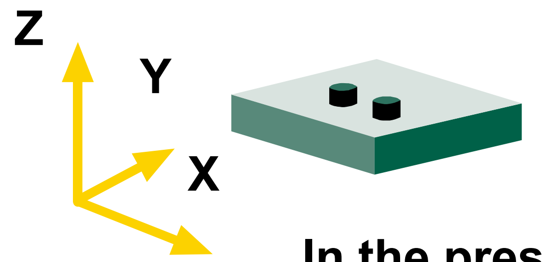
In the absence of the gradient both samples sense the same field...

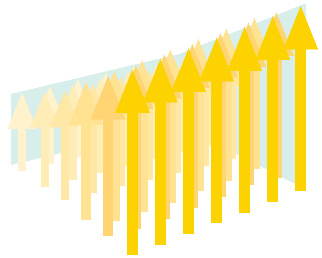


...resulting in a signal consisting of one frequency.

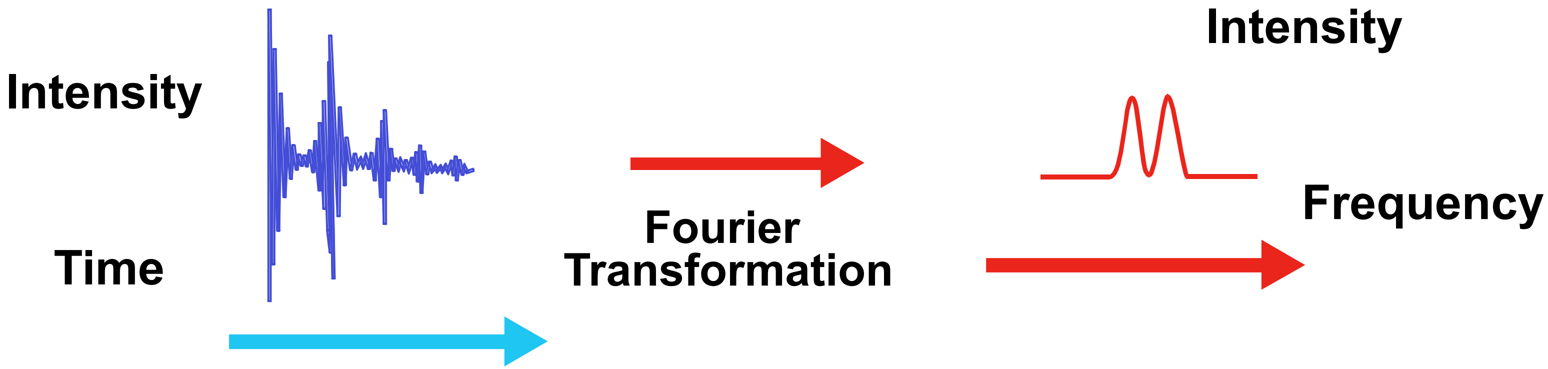
(Gradient Turned On)

Why Gradients are used?





In the presence of the gradient both samples sense different fields...



...resulting in a signal consisting of two frequencies.

Role of Gradients

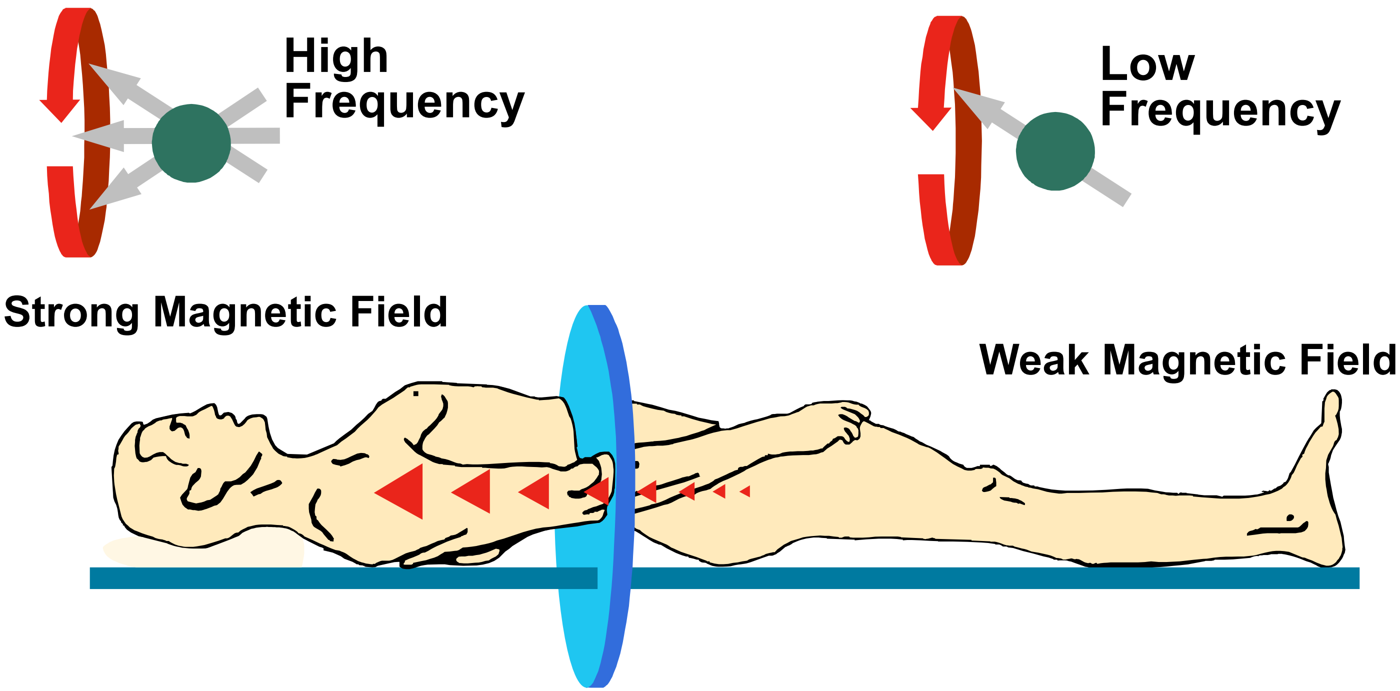
Gradients allow spatial localization of the NMR signal

3 Sets of Gradient Coils:

- Slice Select gradient provides excitation of a single slice in space
- Frequency and Phase Encode gradients encode spatial location of each point in the image plane

Slice Selection

Design RF excitation pulse to excite a range of frequencies and combine with gradient

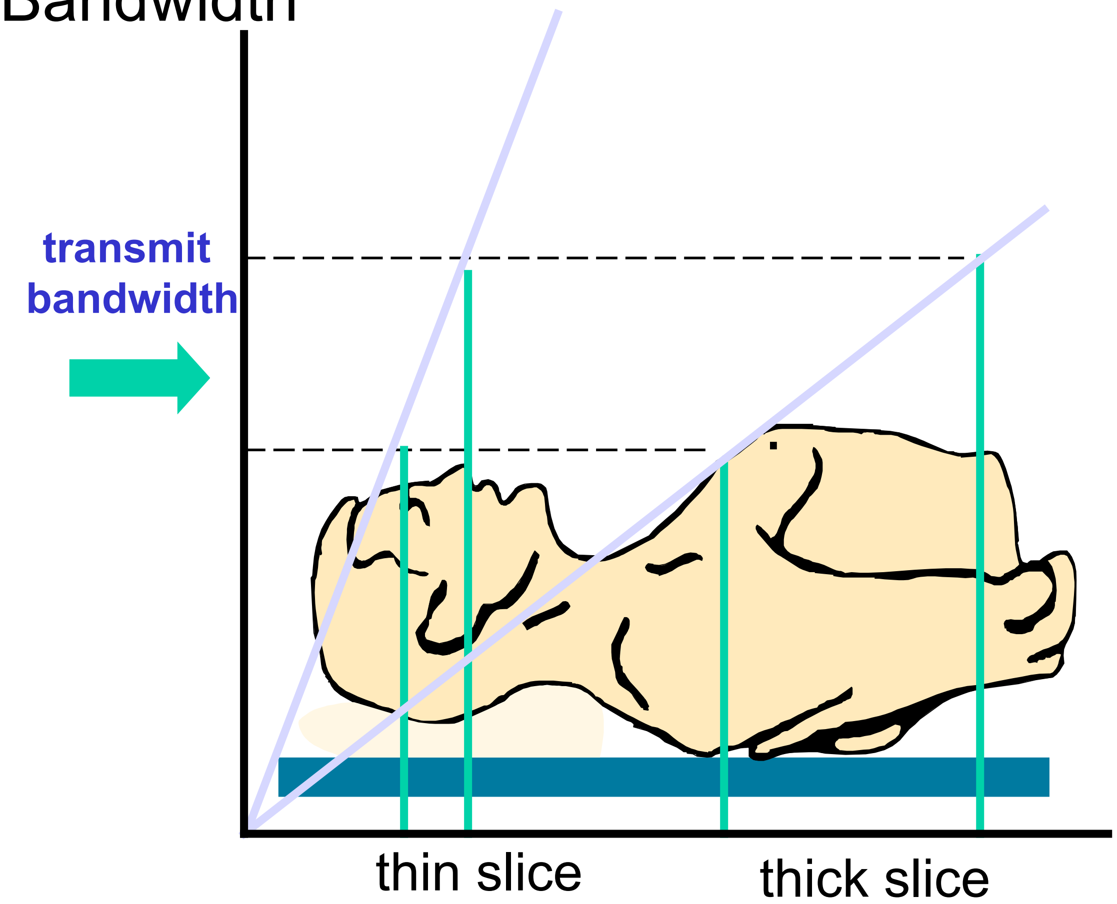


The slice of tissue imaged is defined by changing the strength of the magnetic field along the patient.

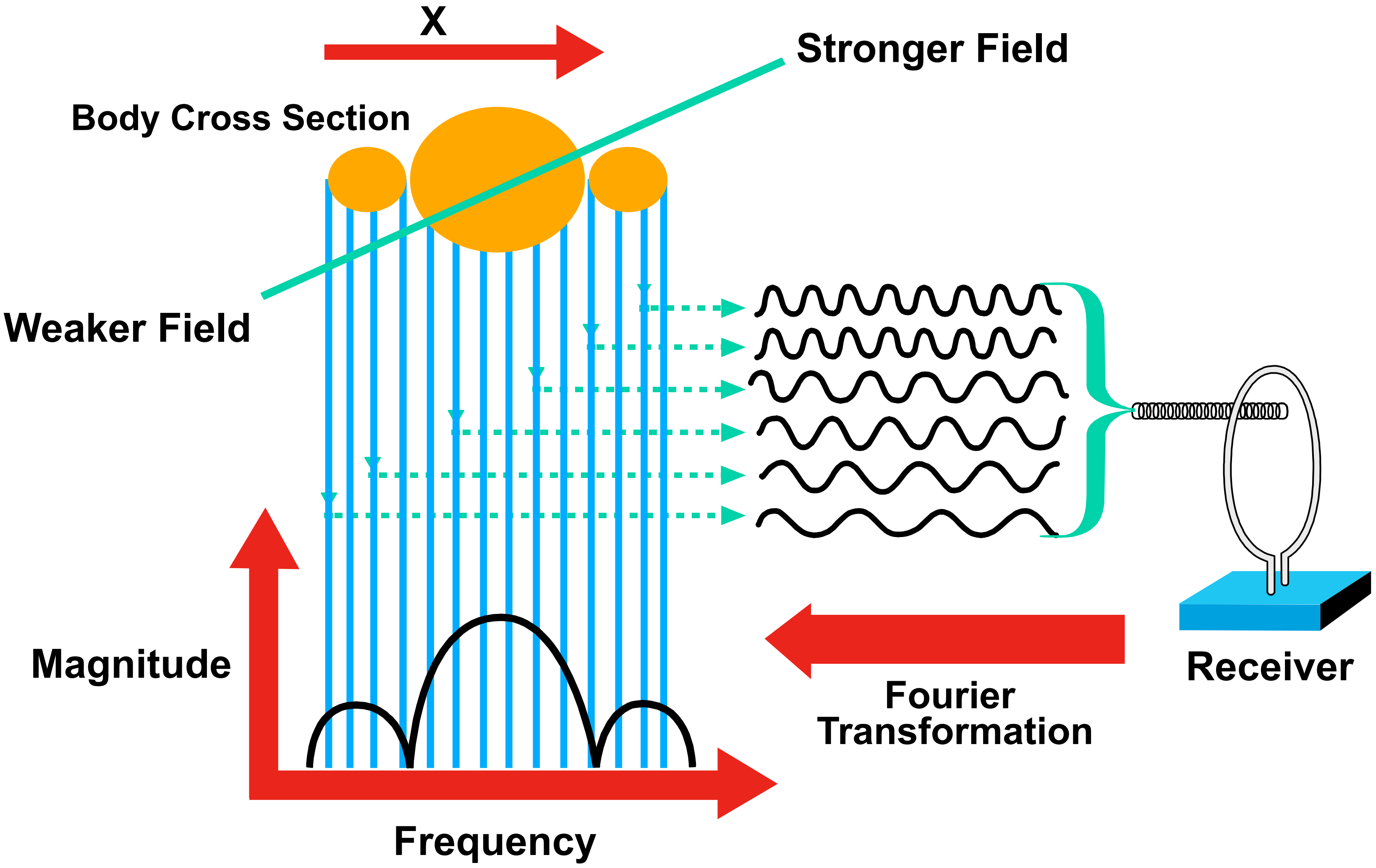
Slice Selection

Slice Thickness

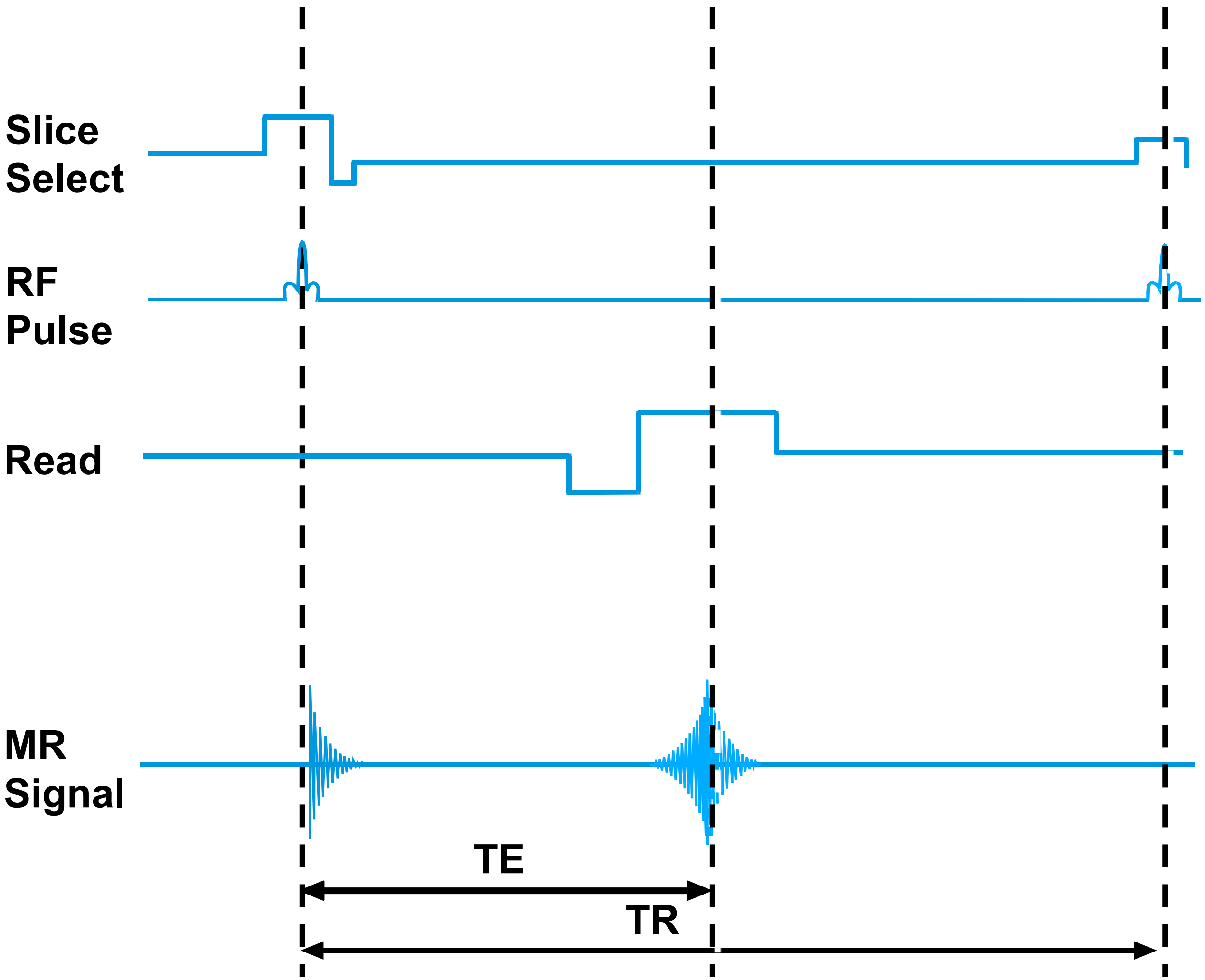
- Gradient Strength
- RF Pulse Bandwidth



Frequency Encoding



Basic Imaging Sequence



Need to encode a third direction

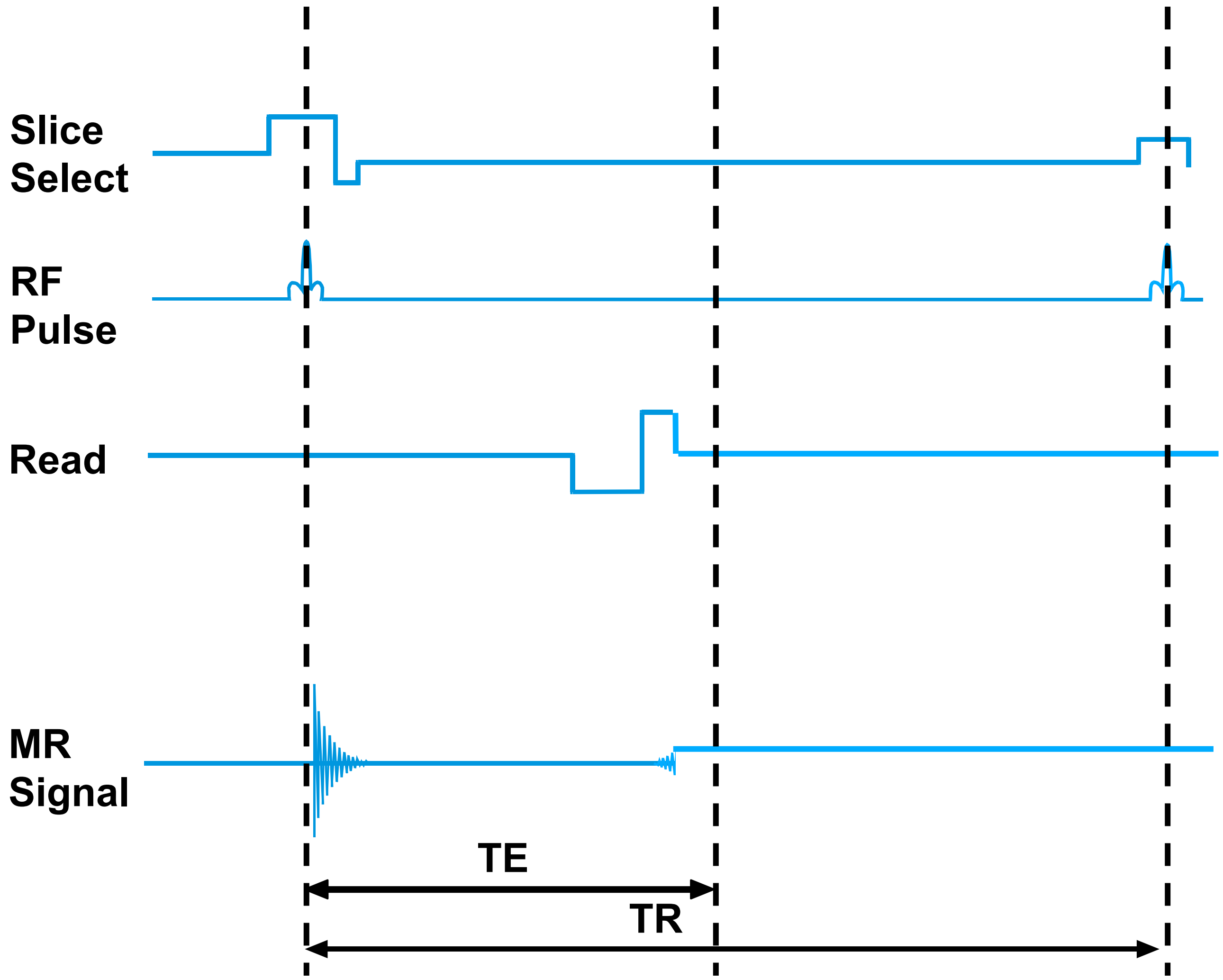
Only one in-plane direction

- Cannot frequency encode in two directions at one time
- Synthesise a second direction using multiple repeated measurements

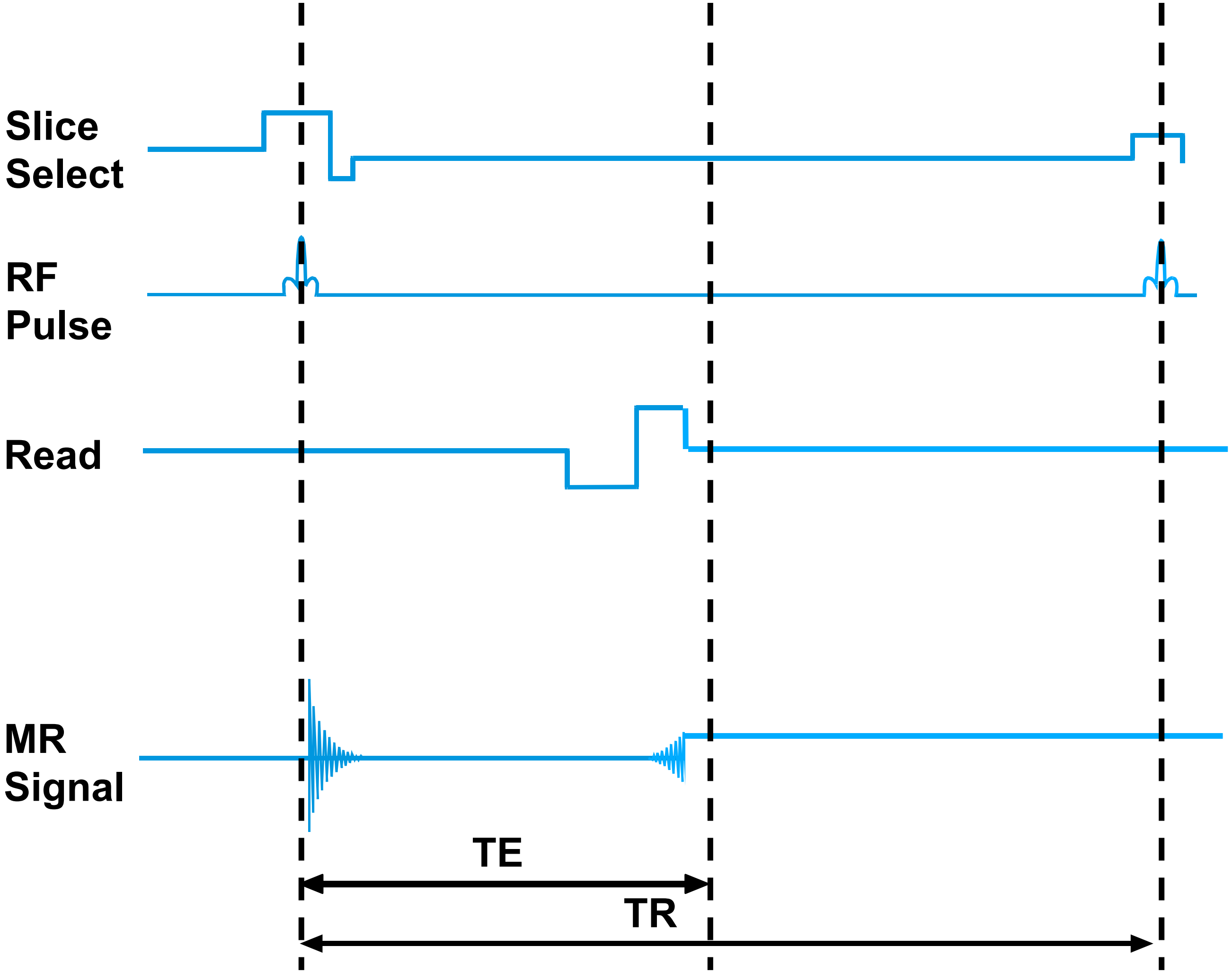
Take a closer look at frequency encoding

- The signal is acquired in time
  - time point by time point sequentially

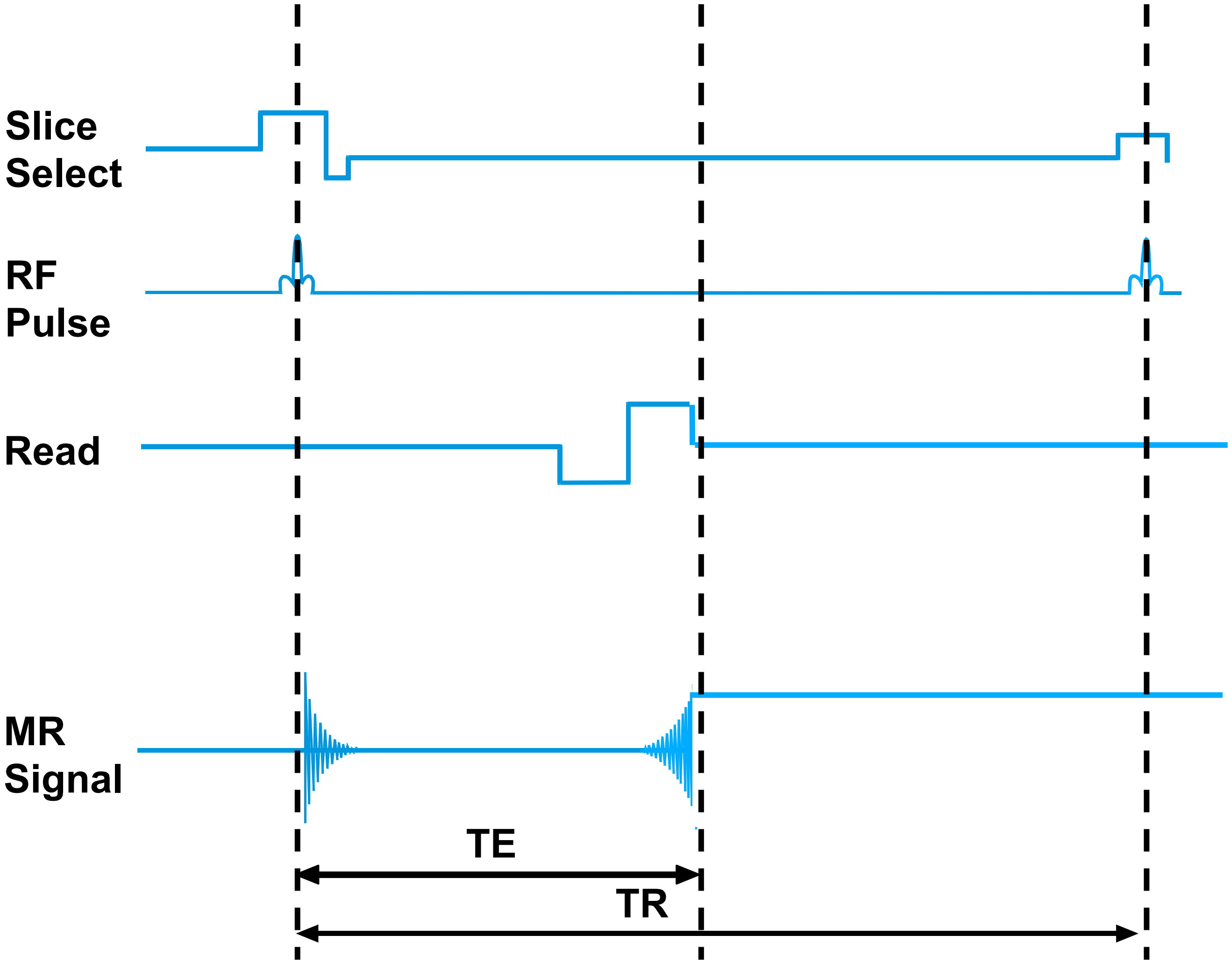
Basic Imaging Sequence



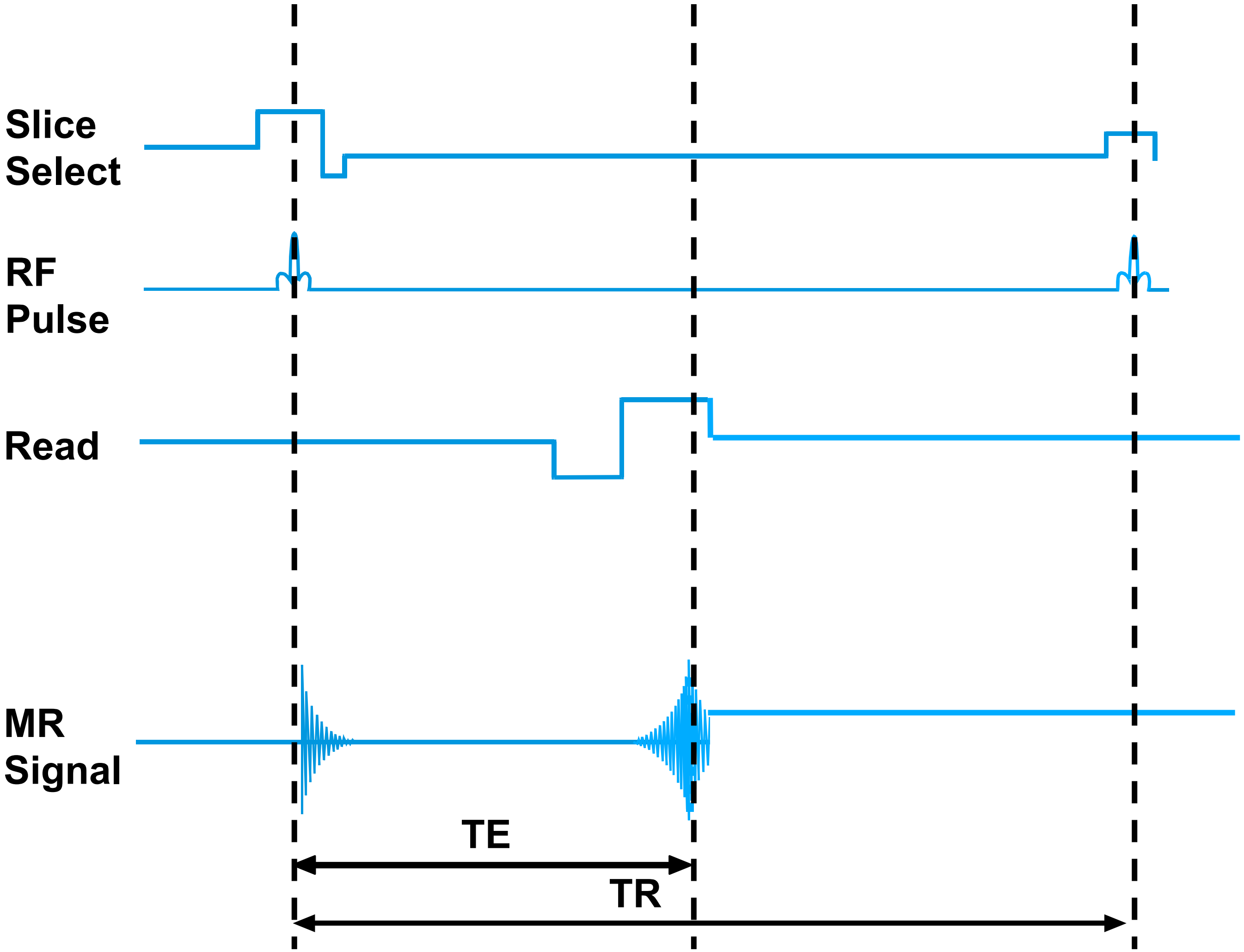
Basic Imaging Sequence



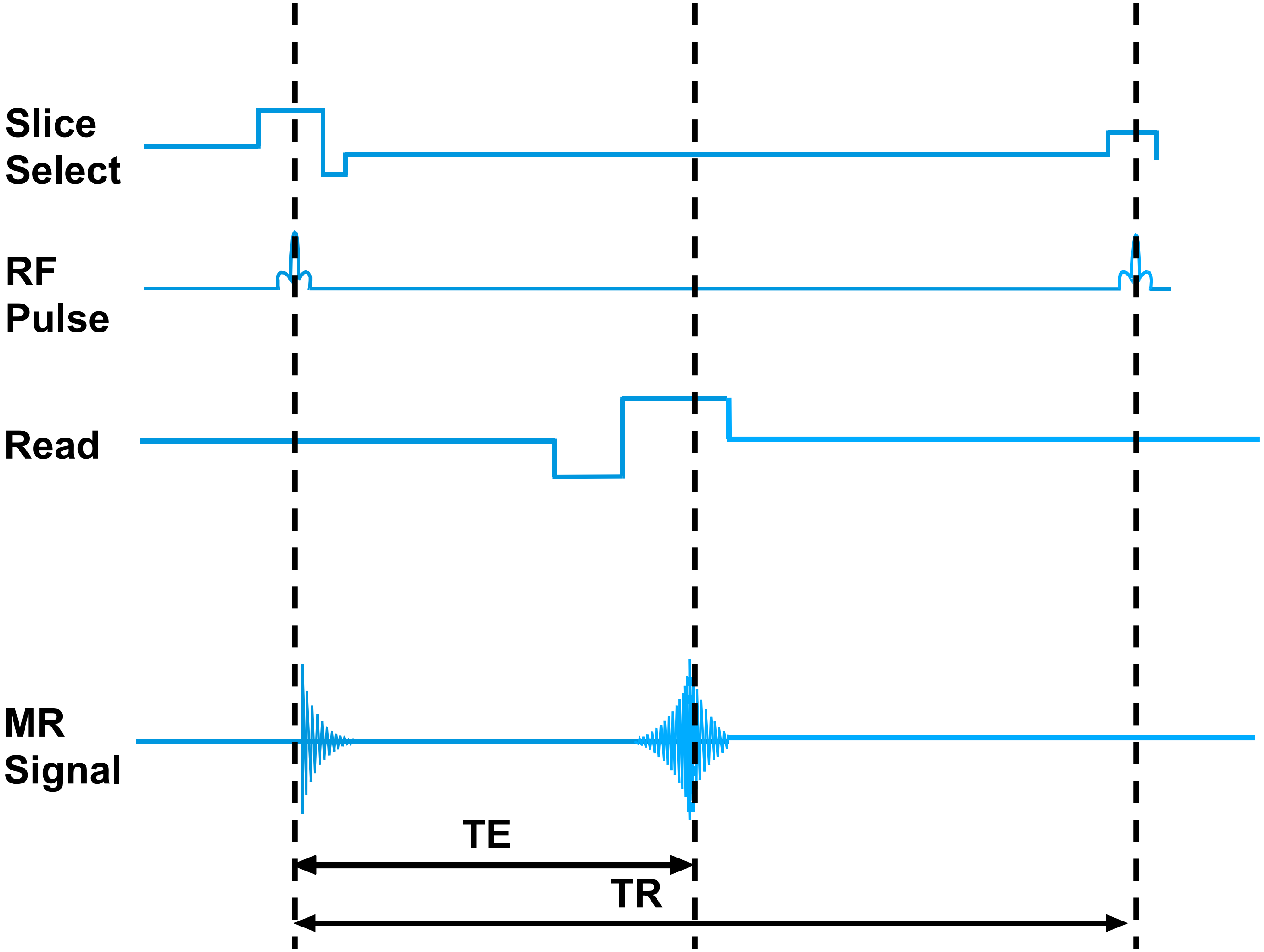
Basic Imaging Sequence



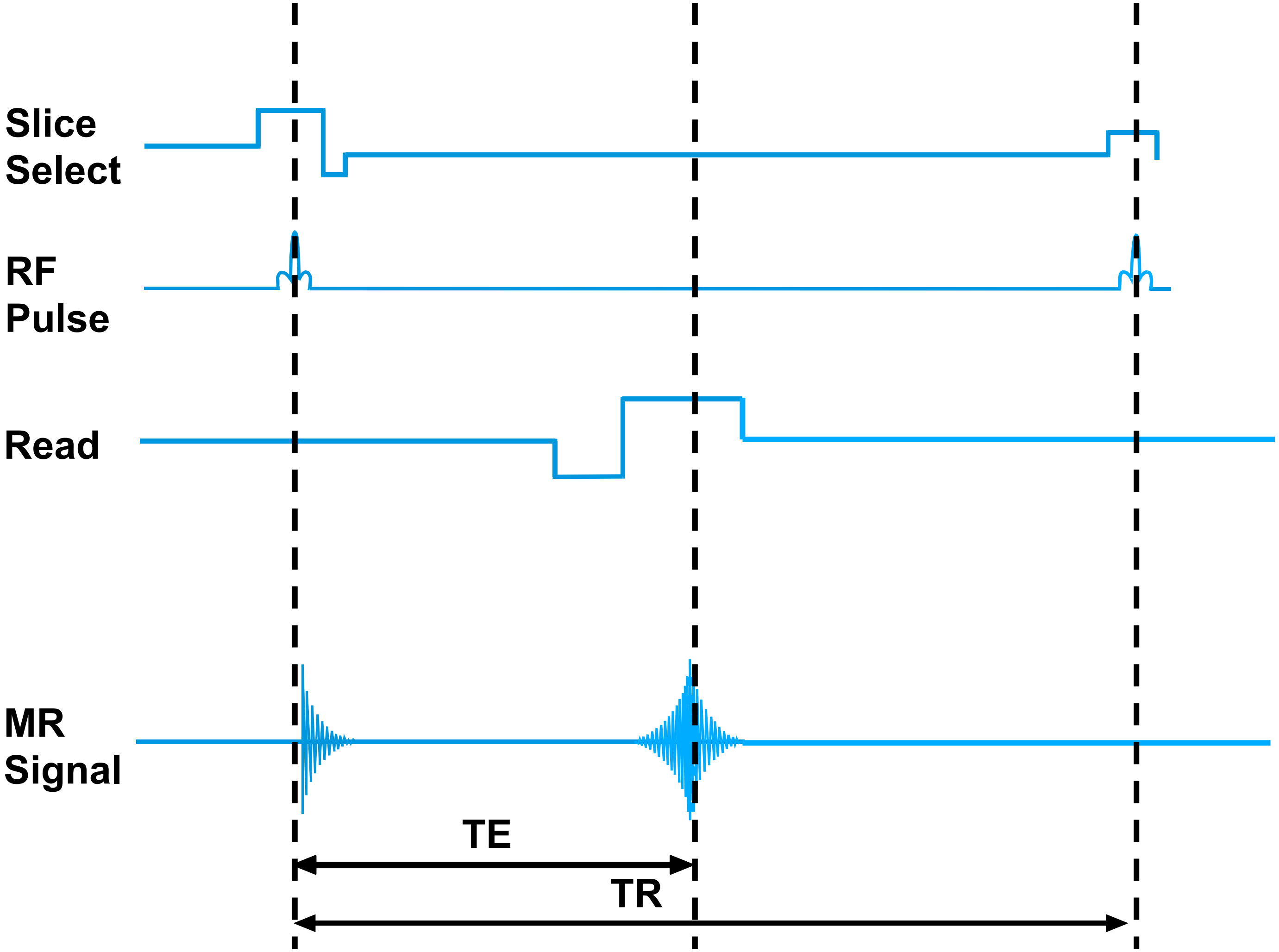
Basic Imaging Sequence



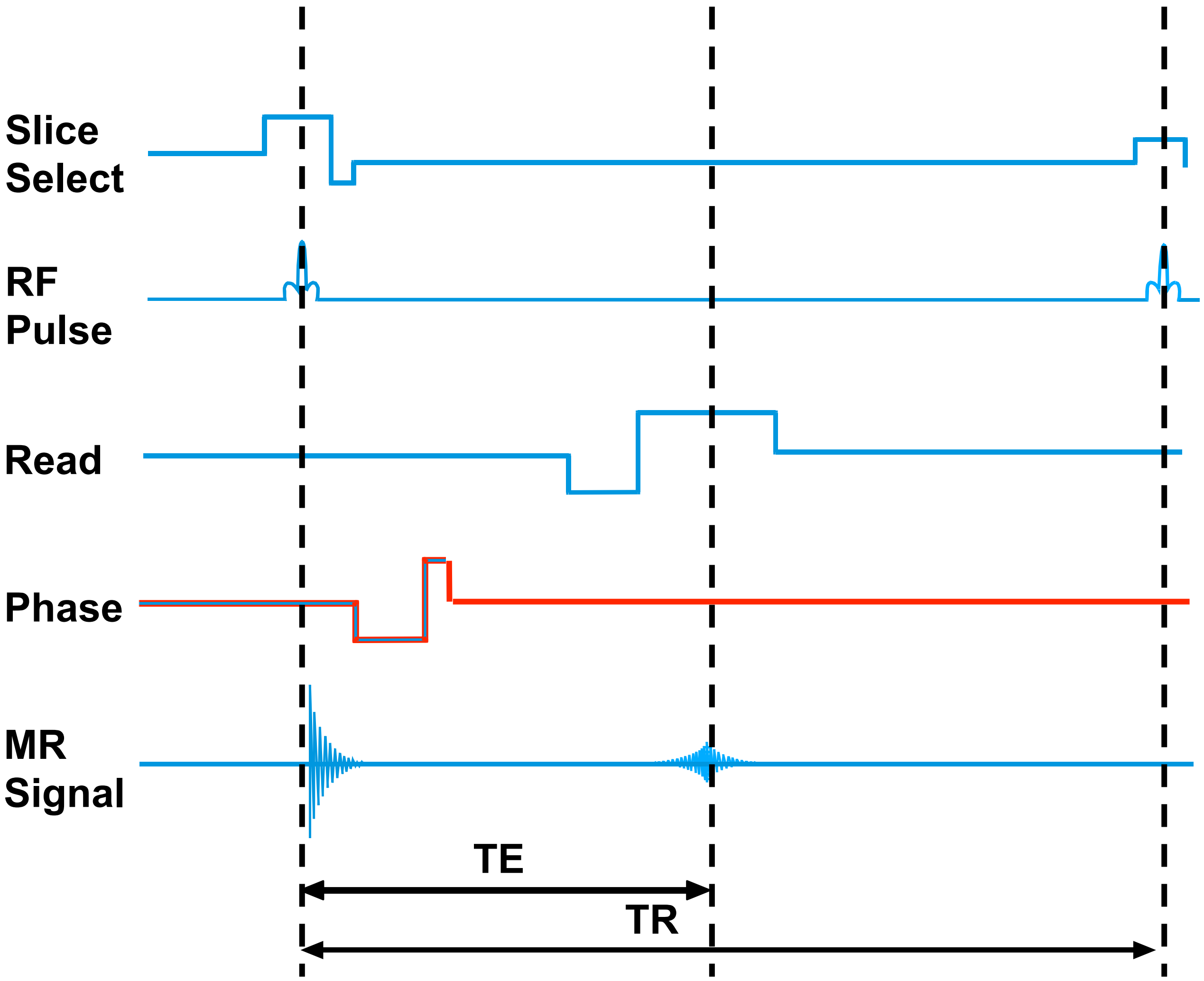
Basic Imaging Sequence



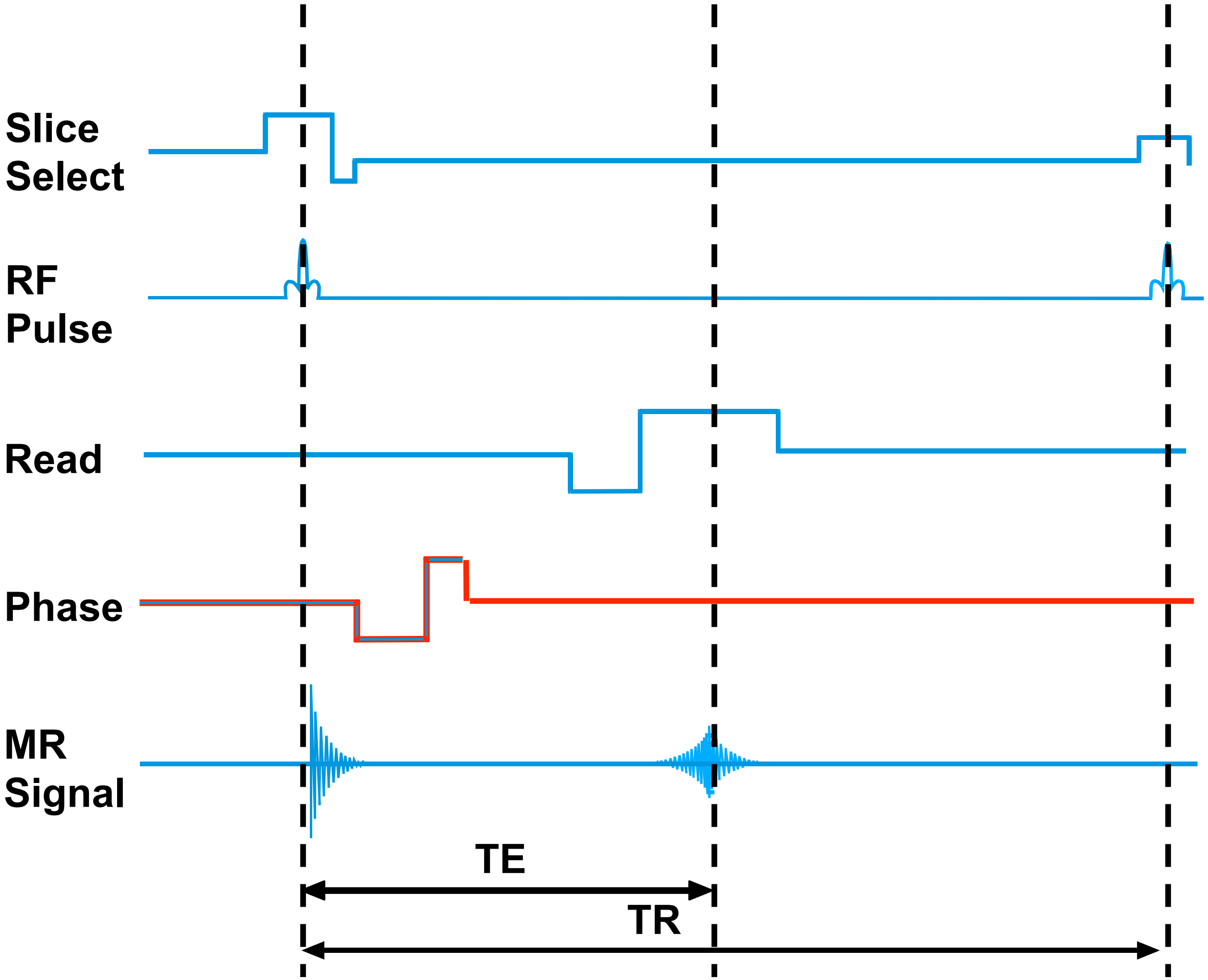
Basic Imaging Sequence



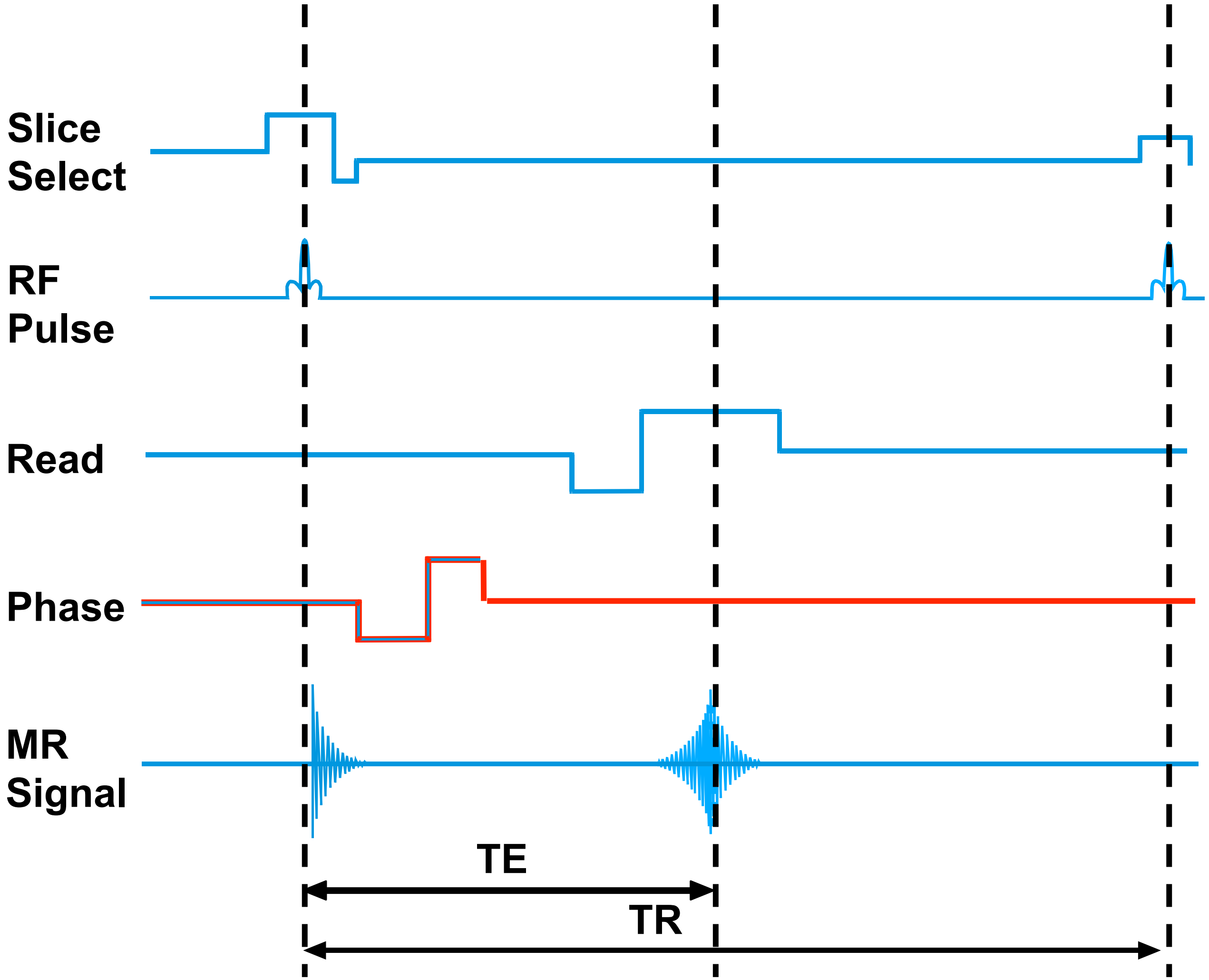
Full spatial encoding



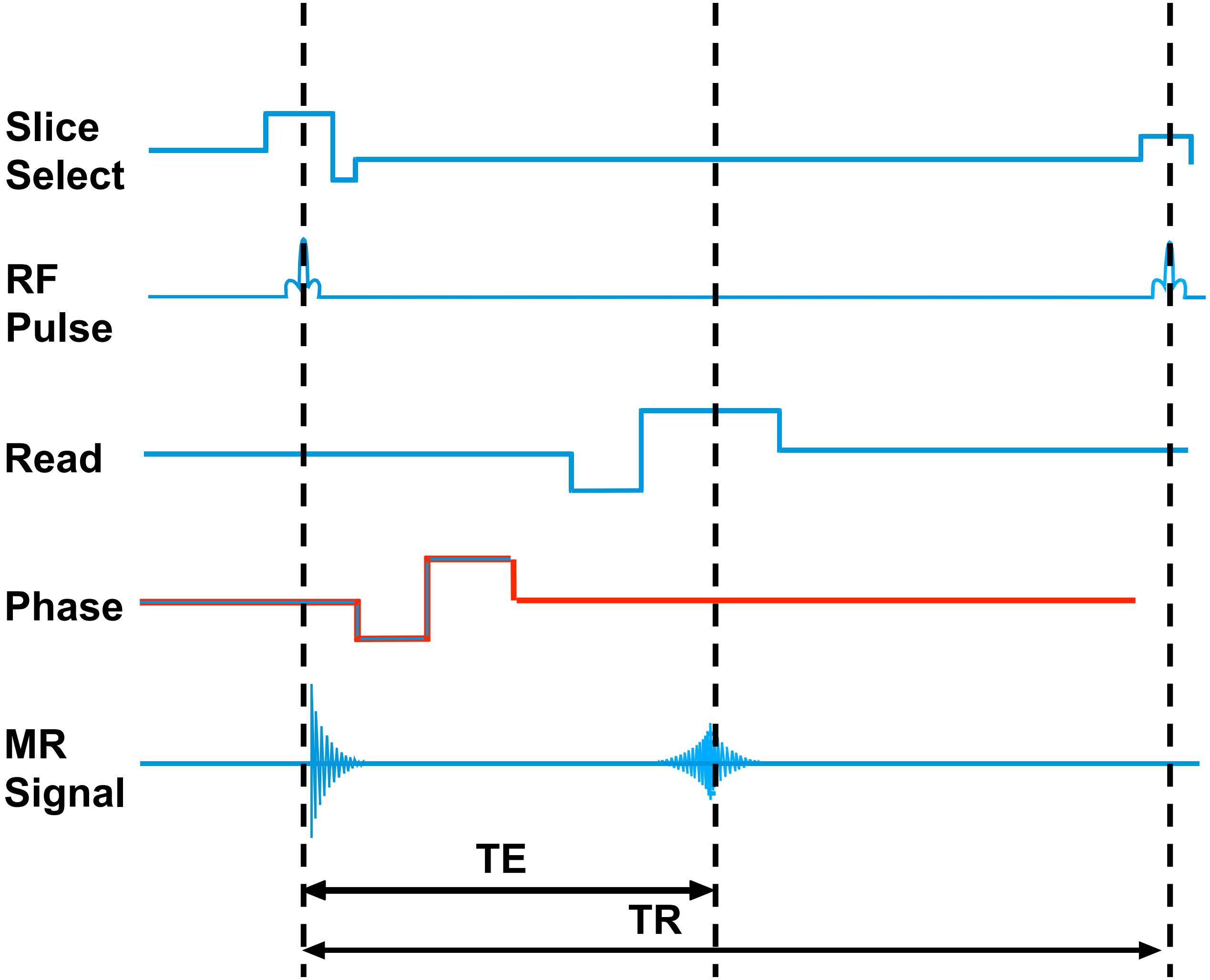
Full spatial encoding



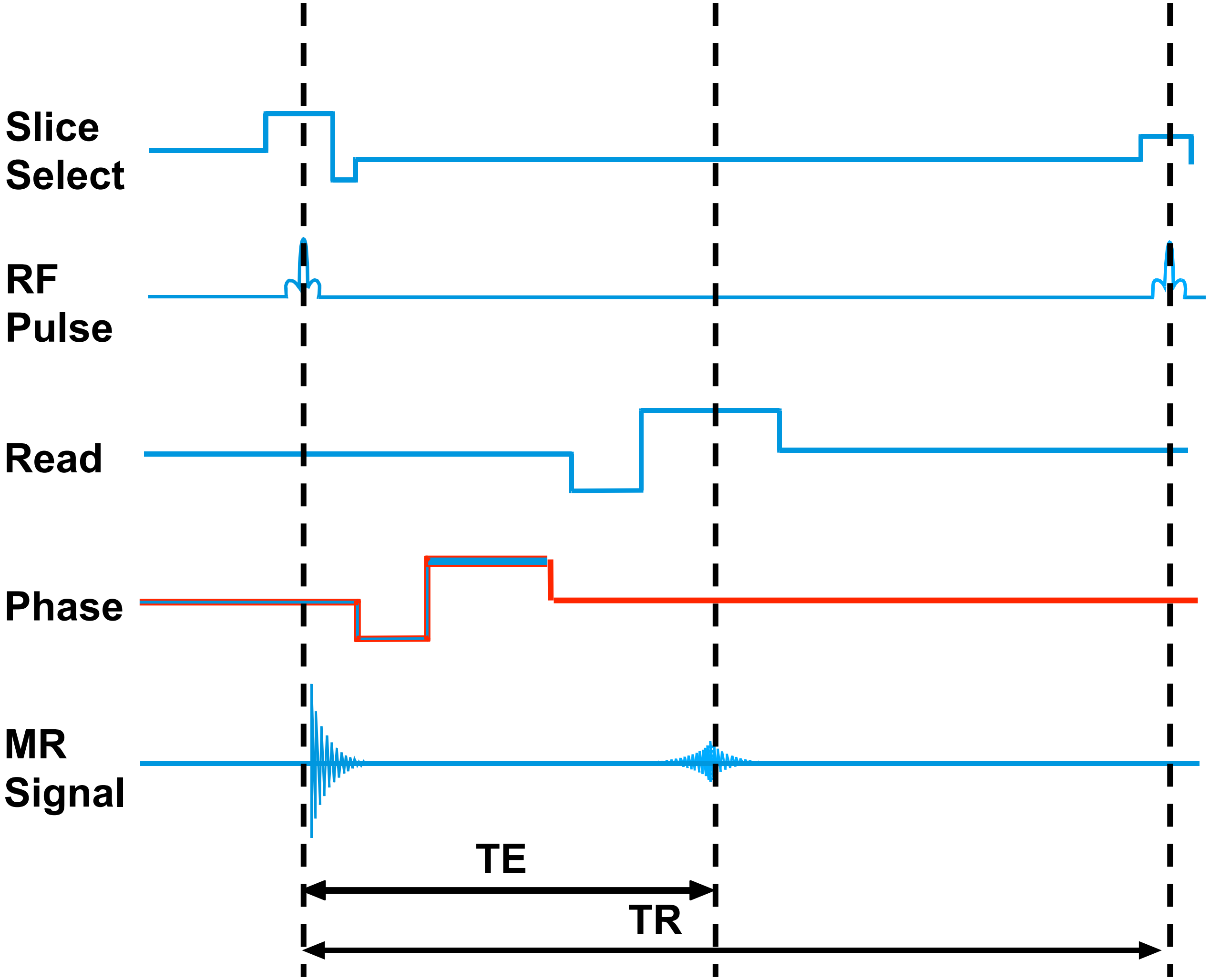
Full spatial encoding



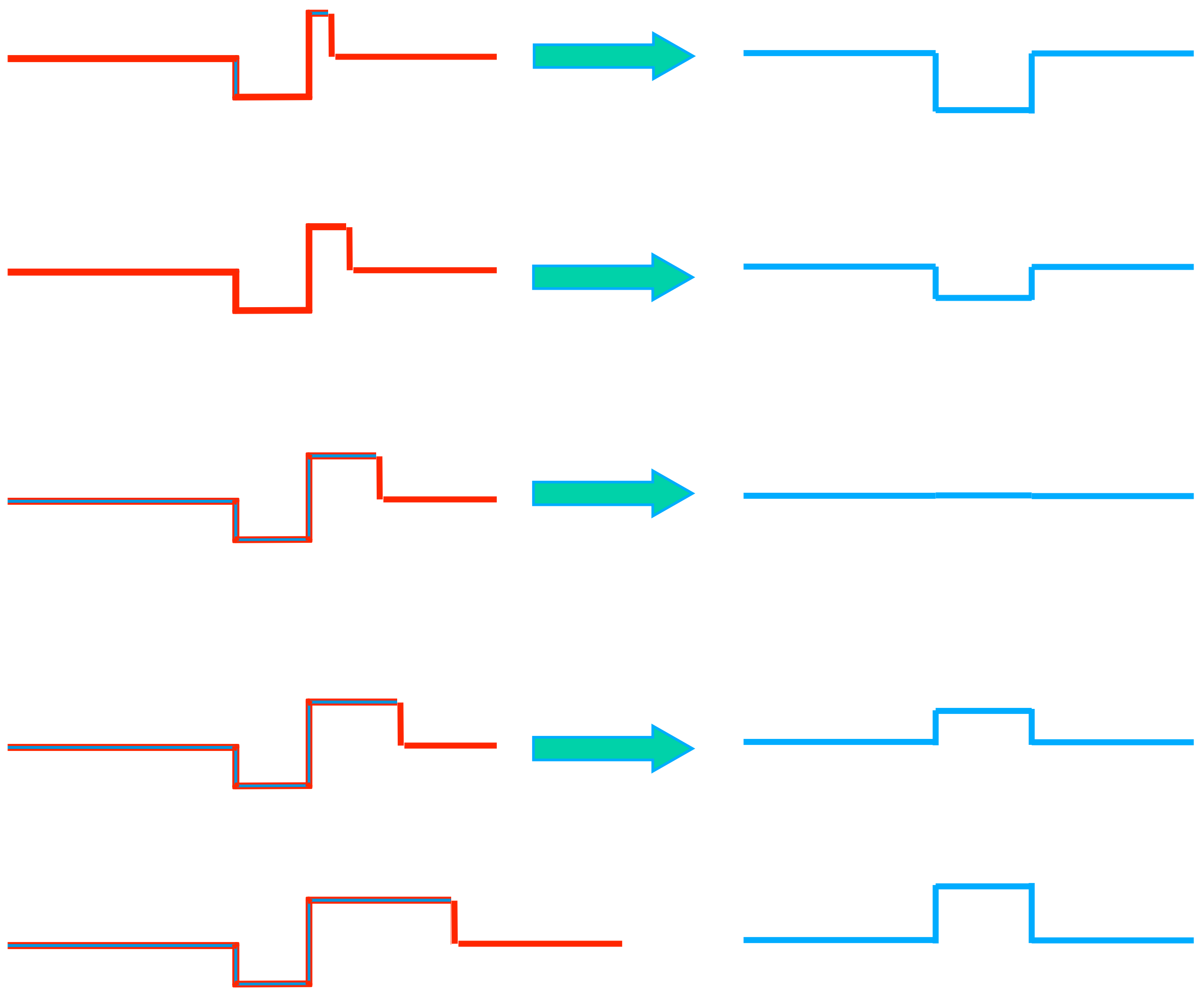
Full spatial encoding



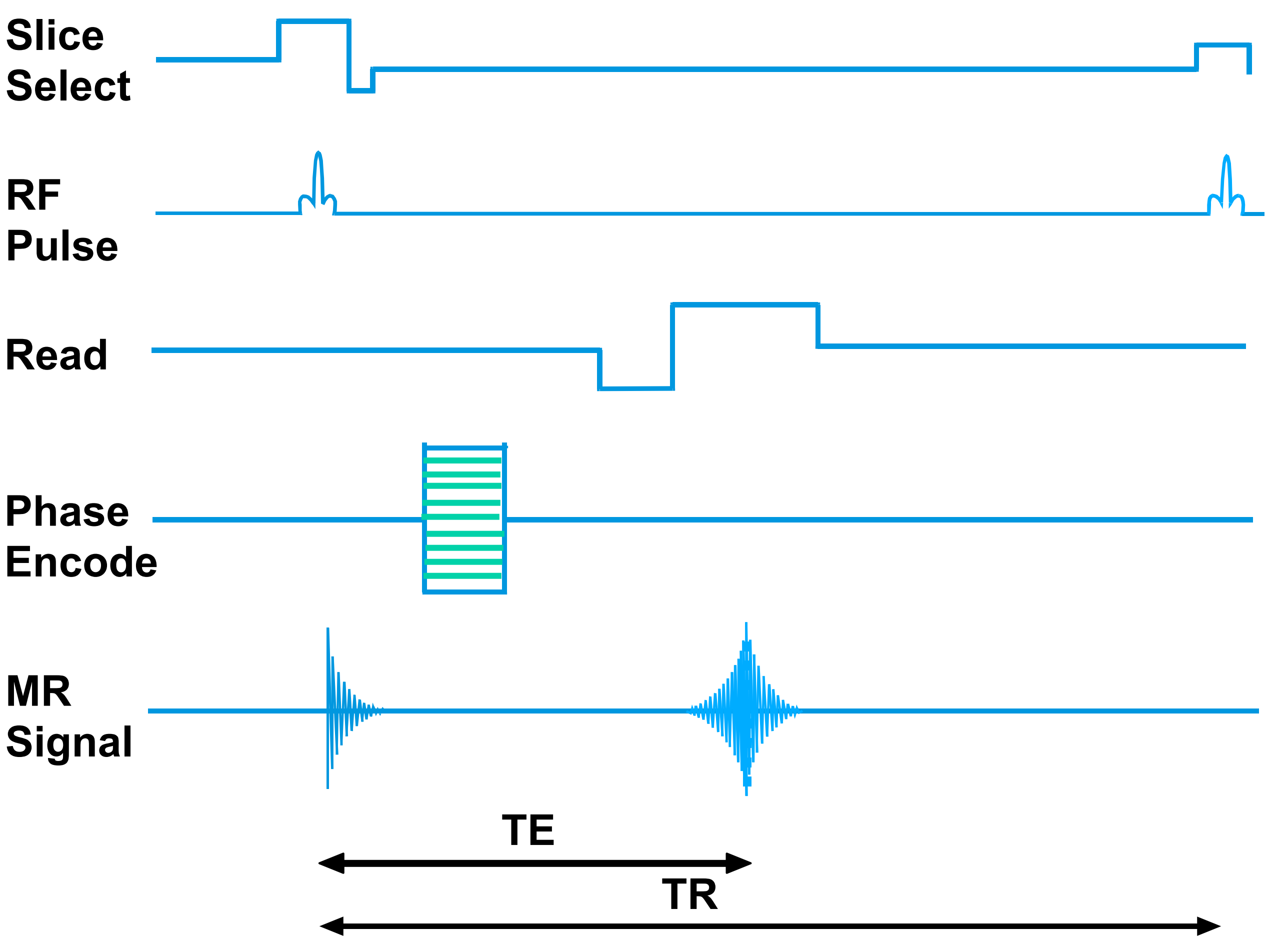
Full spatial encoding



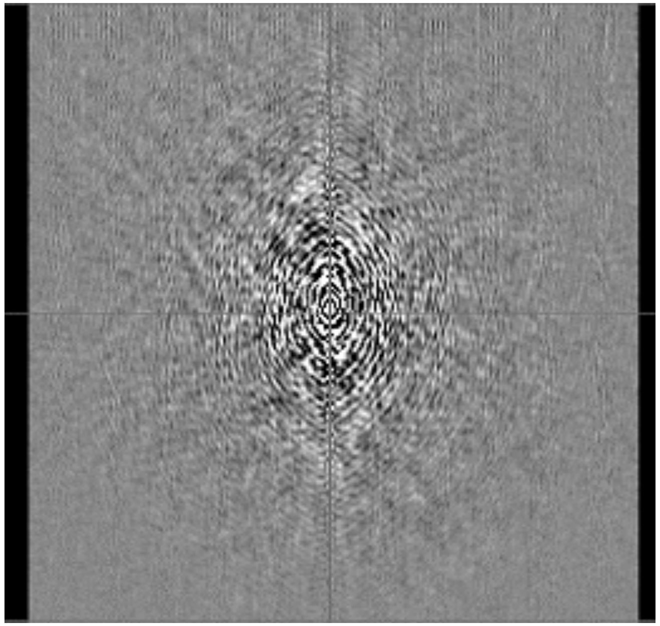
Phase encode gradient



Gradient Echo Sequence



Frequency analysis by Fourier Transform



Raw signal
or
Fourier domain
"K-space"

Fourier
Transform

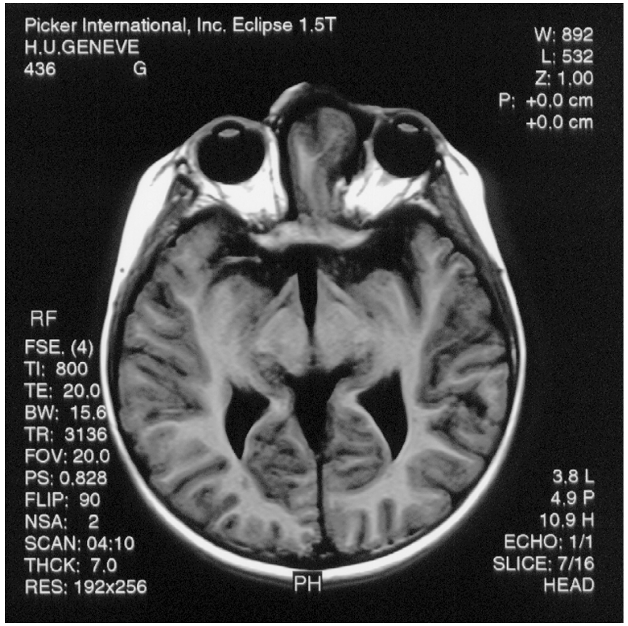
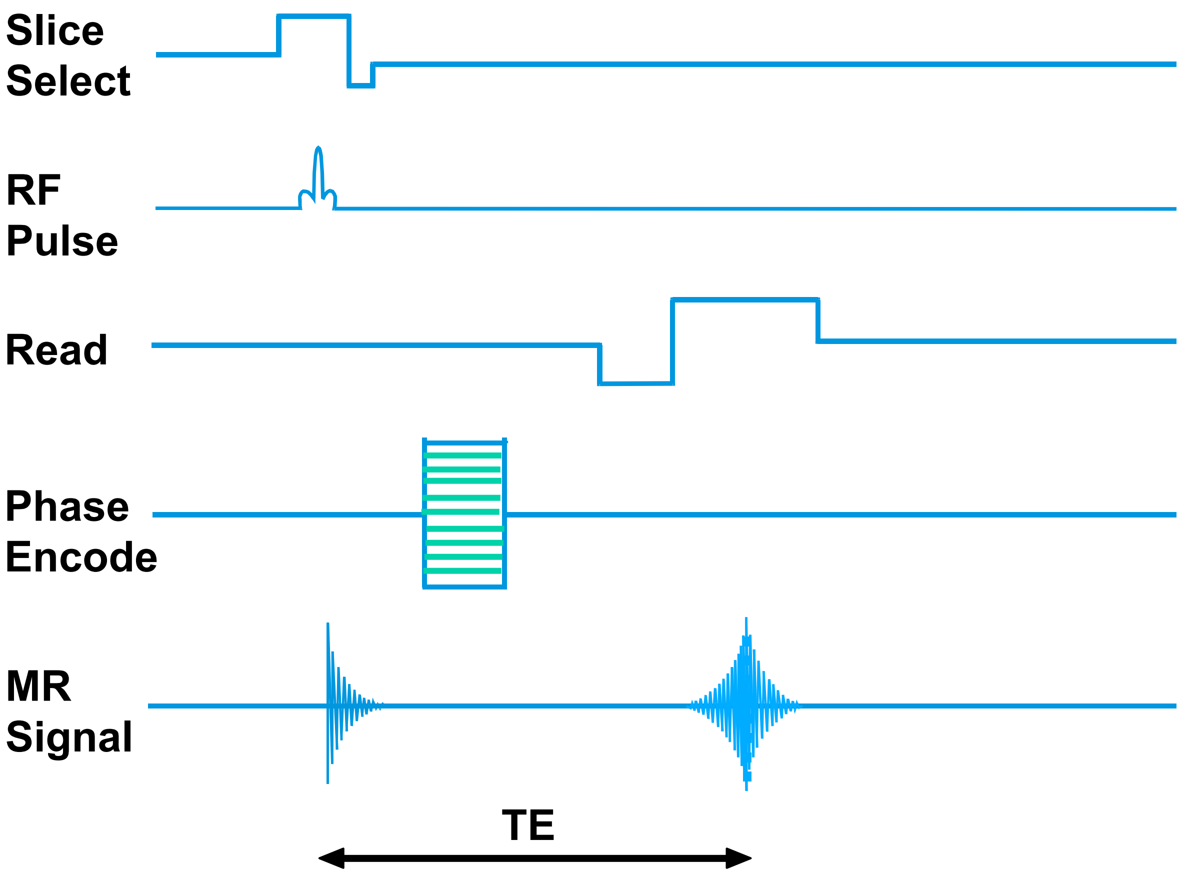
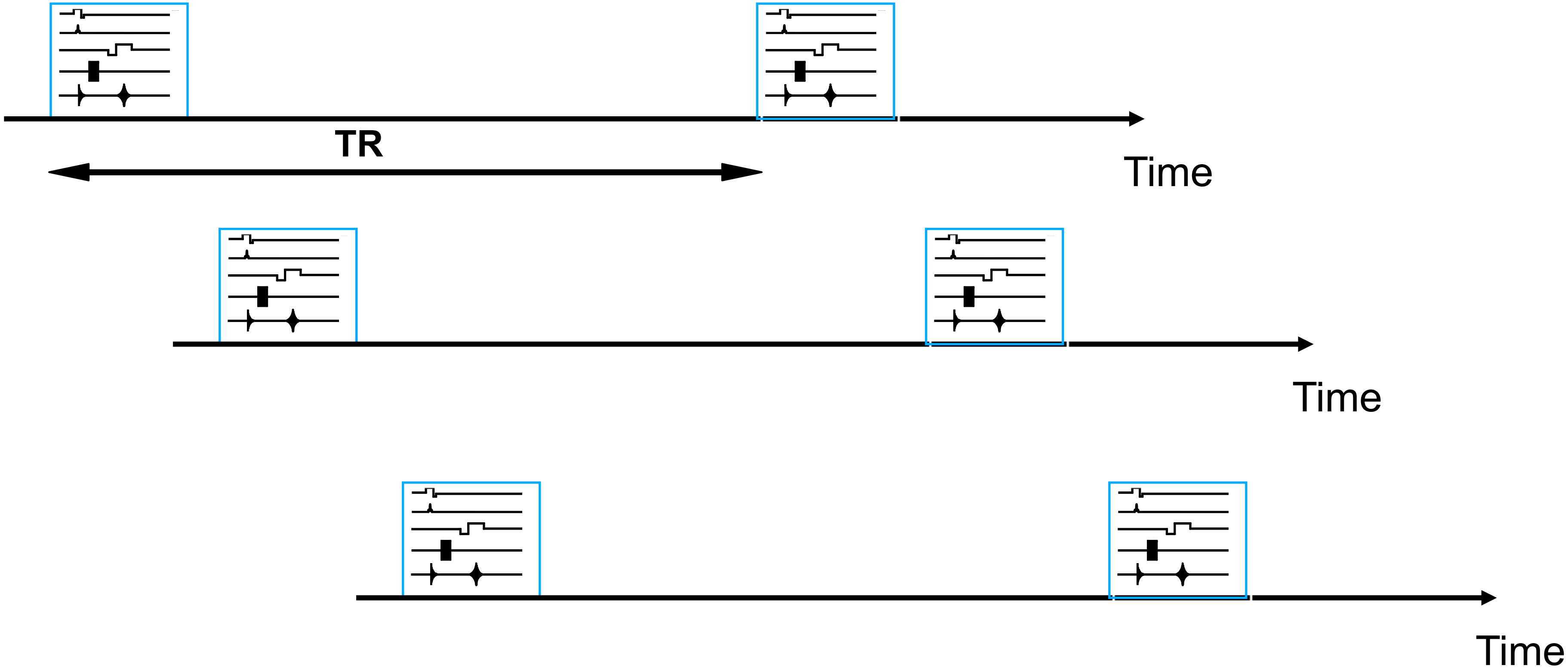


Image domain

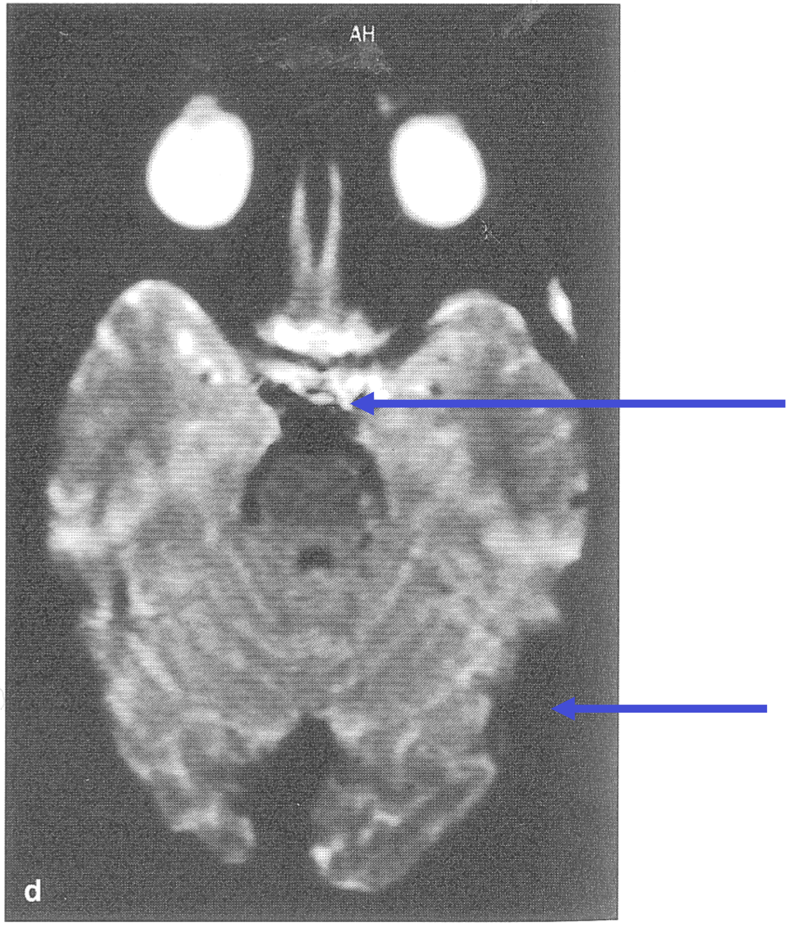
Single-slice imaging



Multi-slice imaging



Gradient echoes and B_0 inhomogeneity

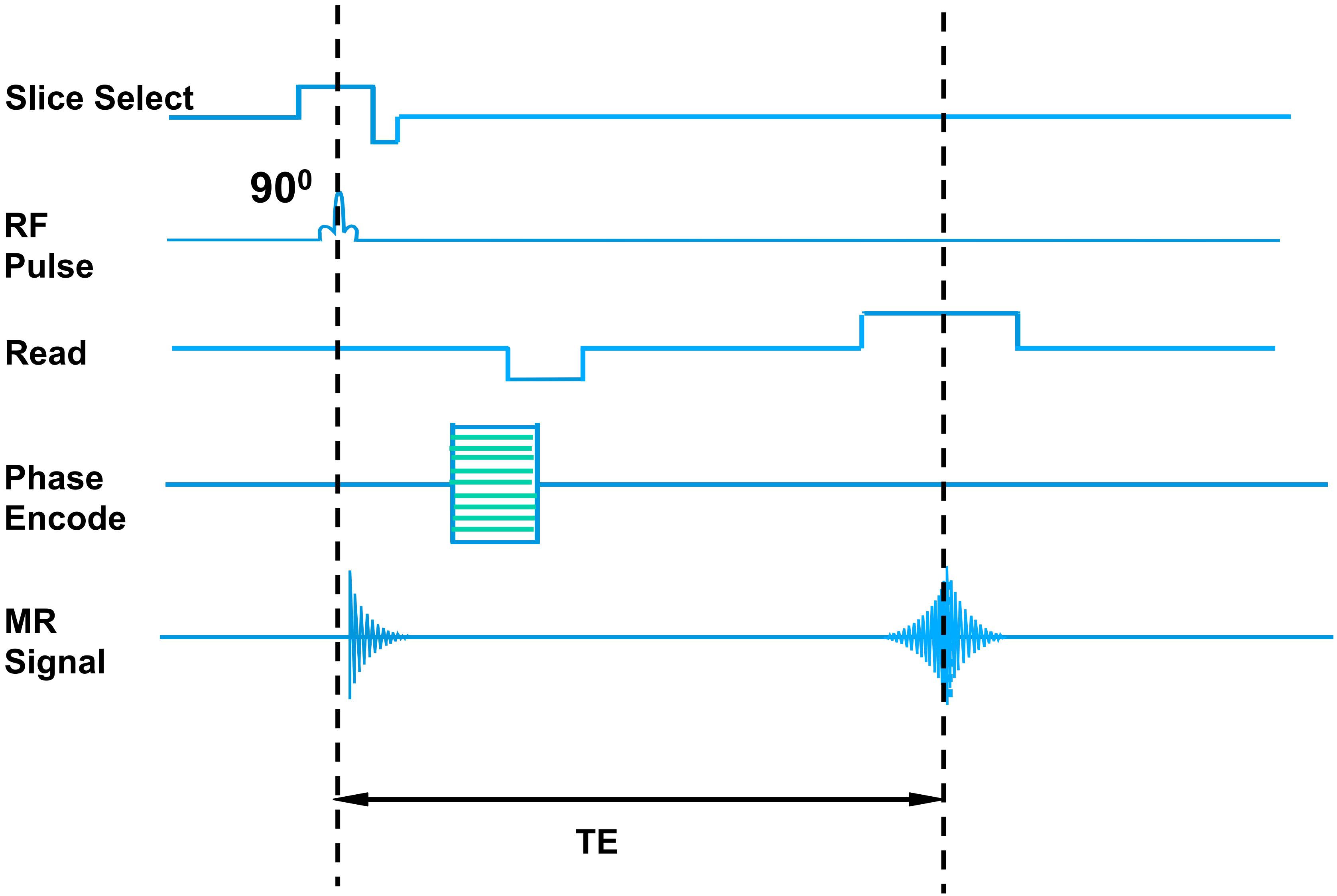


Non-uniformity in the main magnetic field causes image distortion and signal loss

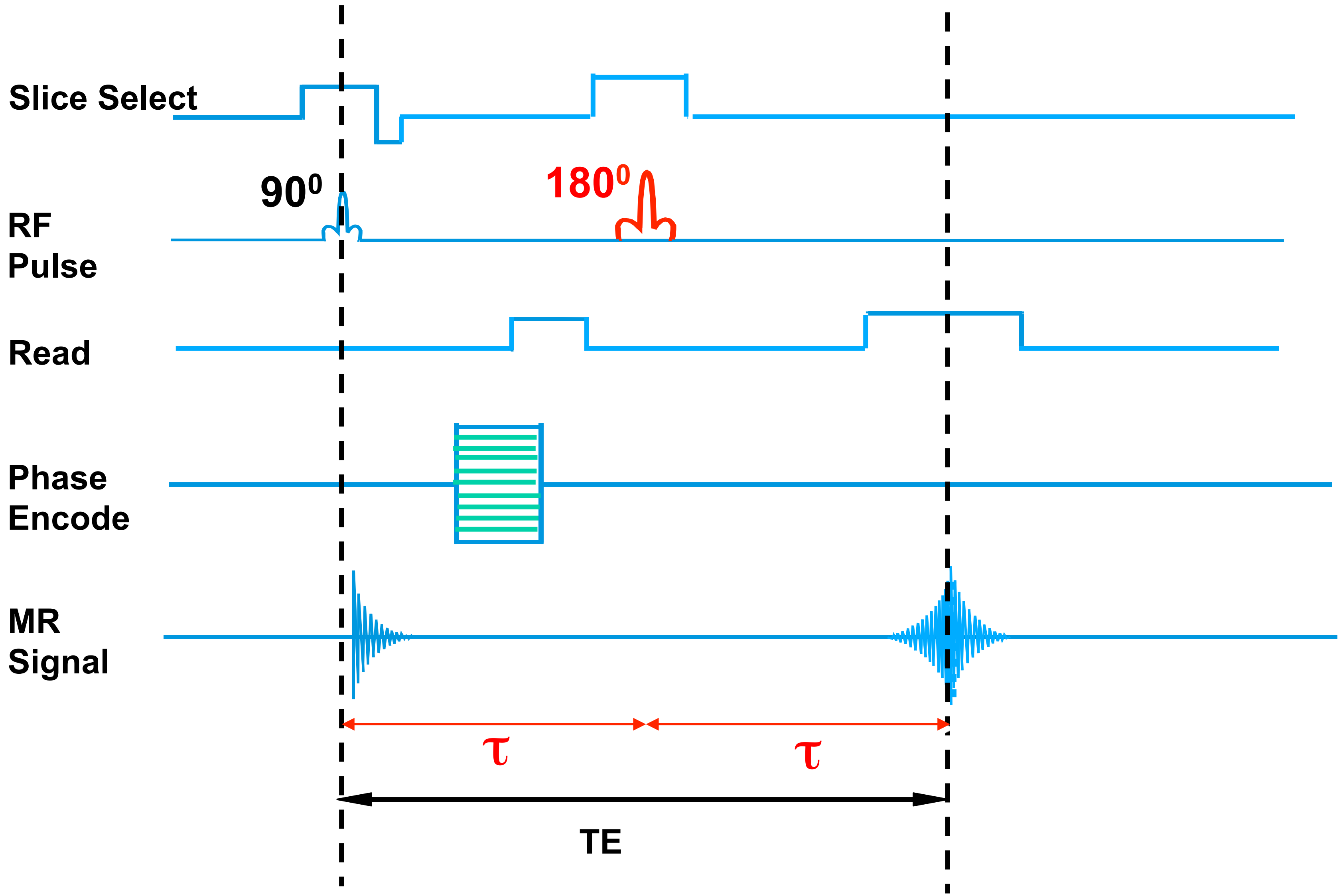
distortion

Signal loss due to tissue/bone susceptibility effects of $1{:}10^{-9}$

Gradient Echo Sequence



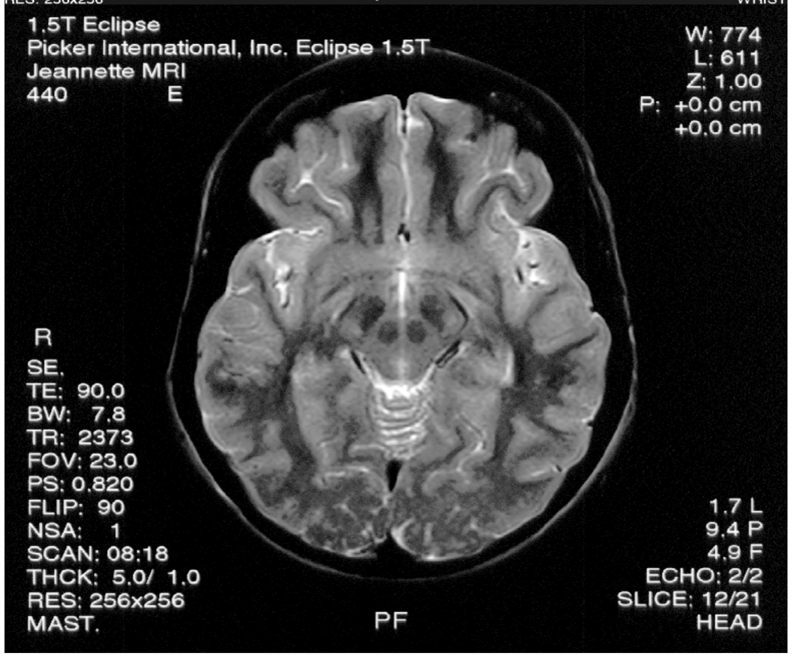
Spin Echo Sequence



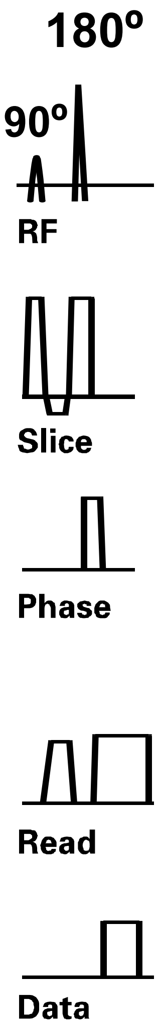
Spin Echo

- **Advantages & Limitations**
  - **Image Quality**
  - **Artifacts**
  - **Flexible sequence**
  - **True T2 contrast**
  - **Scan Times- Long**

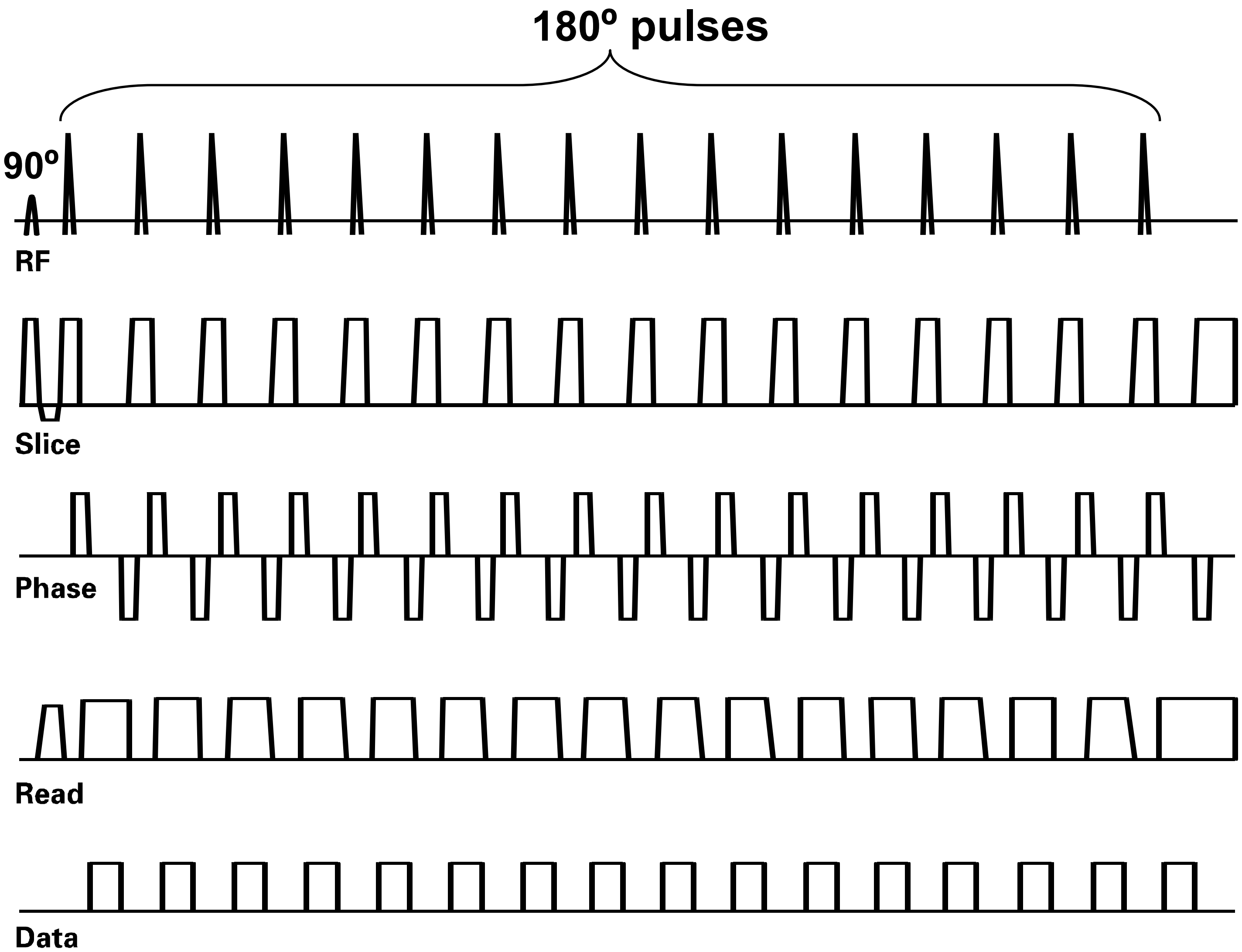
e.g. TR = 2400msec
256 PE lines
Acq time >8min



Spin Echo



Fast Spin Echo

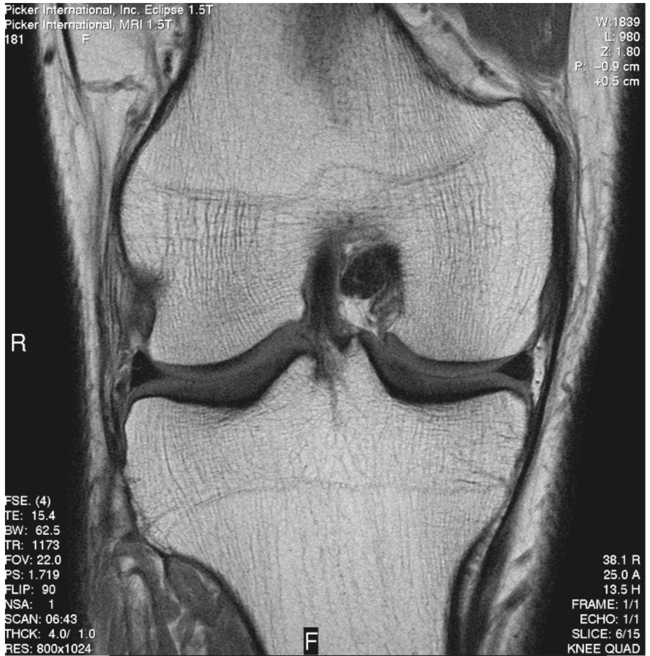


Fast Spin Echo

- **Multiple Echoes within the same TR**
- **Each echo individually phase encoded**
- **Each echo fills one line of K space**
- **ETL (echo train length = number of echoes/shot)**
- **Effective TE**
- **Scan Time Calculation**
  - **TR x (number of PE) / ETL**

FSE examples

T1w SE	T2w FSE
•TR 500msec	•TR 3000msec
•512 PE lines	•512 PE lines
•4mins	•3mins



Proton DensityFSE
•TR 1200mec
•1024 PE lines
•6 mins

MRI has great flexibility

- Image in any plane
- Image anatomy
- Flow (angiography, perfusion)
- Microscopic motion (water diffusion)
- Brain Function (fMRI)
- Use with contrast agents to increase sensitivity to disease

Fat suppression

Questions?