Pulse Programming Bootcamp
Day 1: Imaging Sequence Elements

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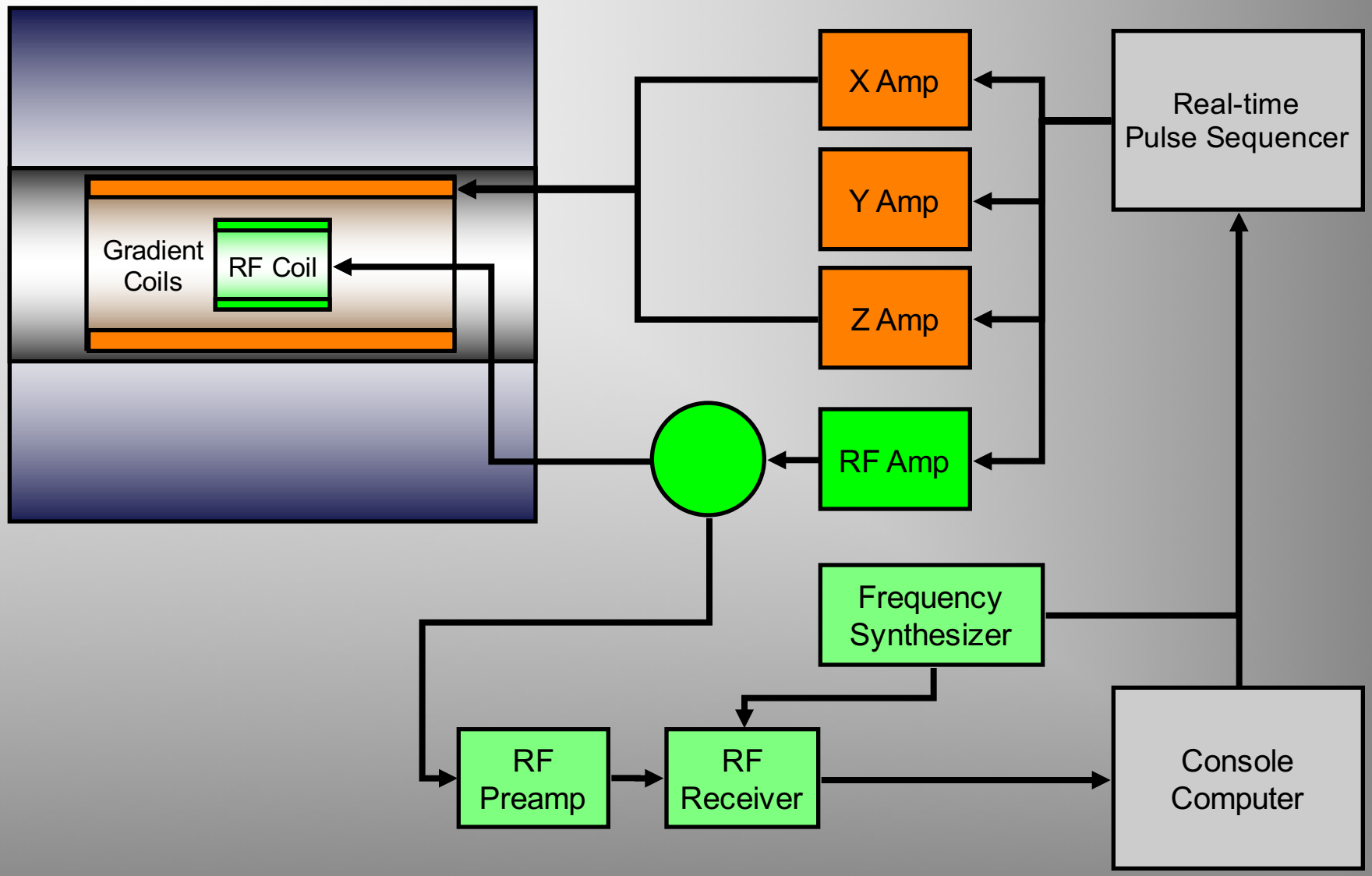
Pulse Programming Bootcamp 2005

Caltech Brain Imaging Center

California Institute of Technology

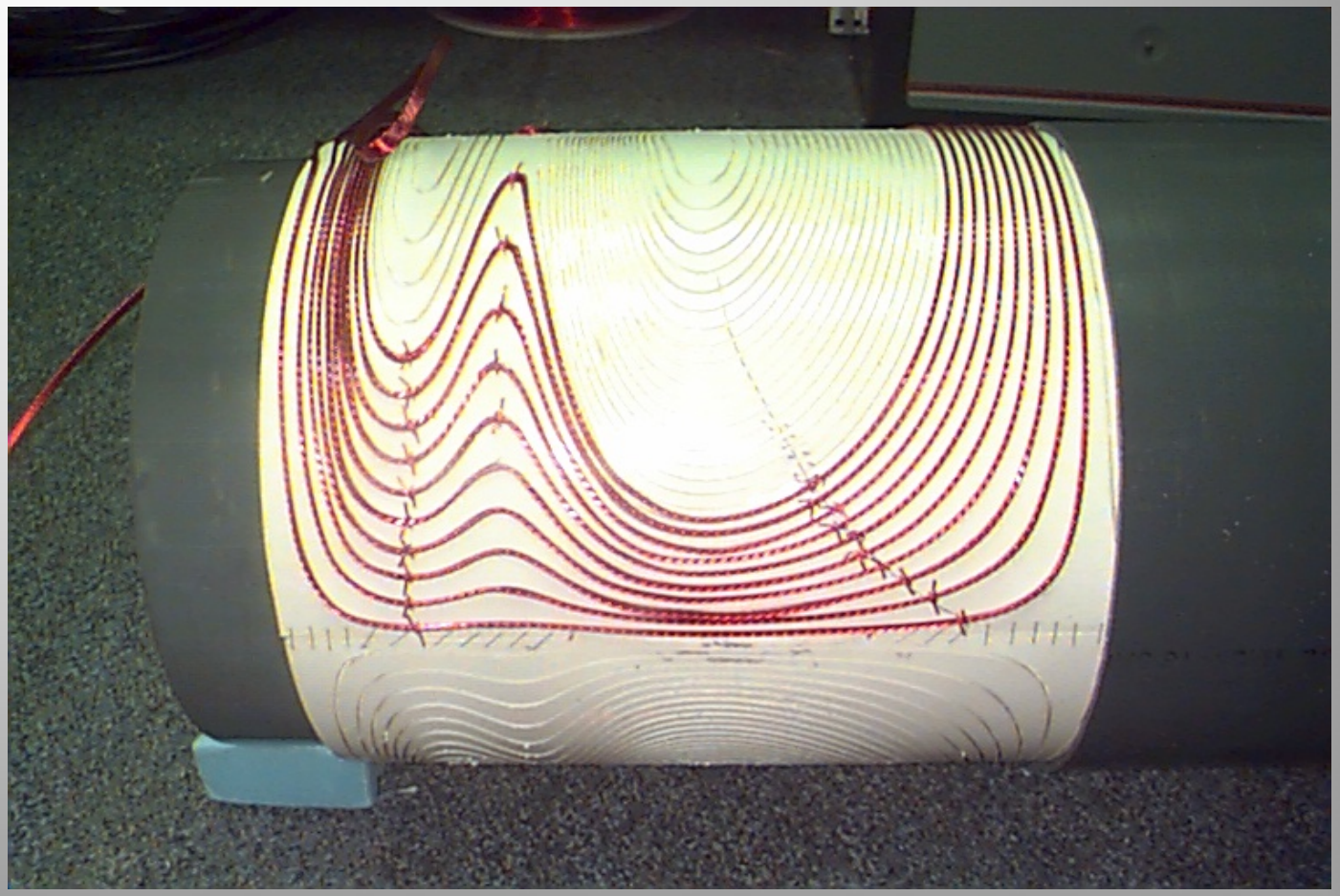
MRI Hardware

MRI Hardware Schematic



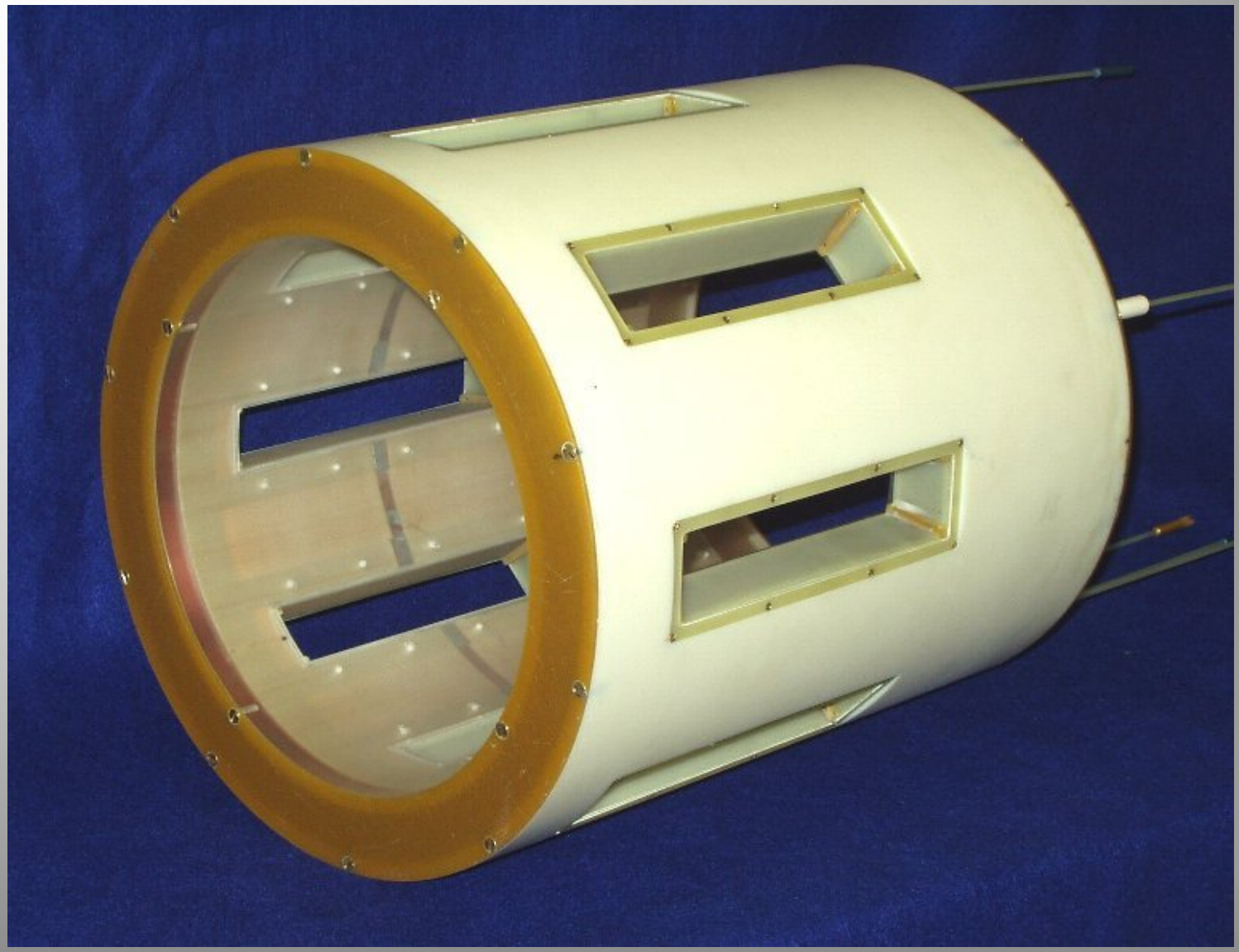
Magnet Solenoid

Gradient Coils

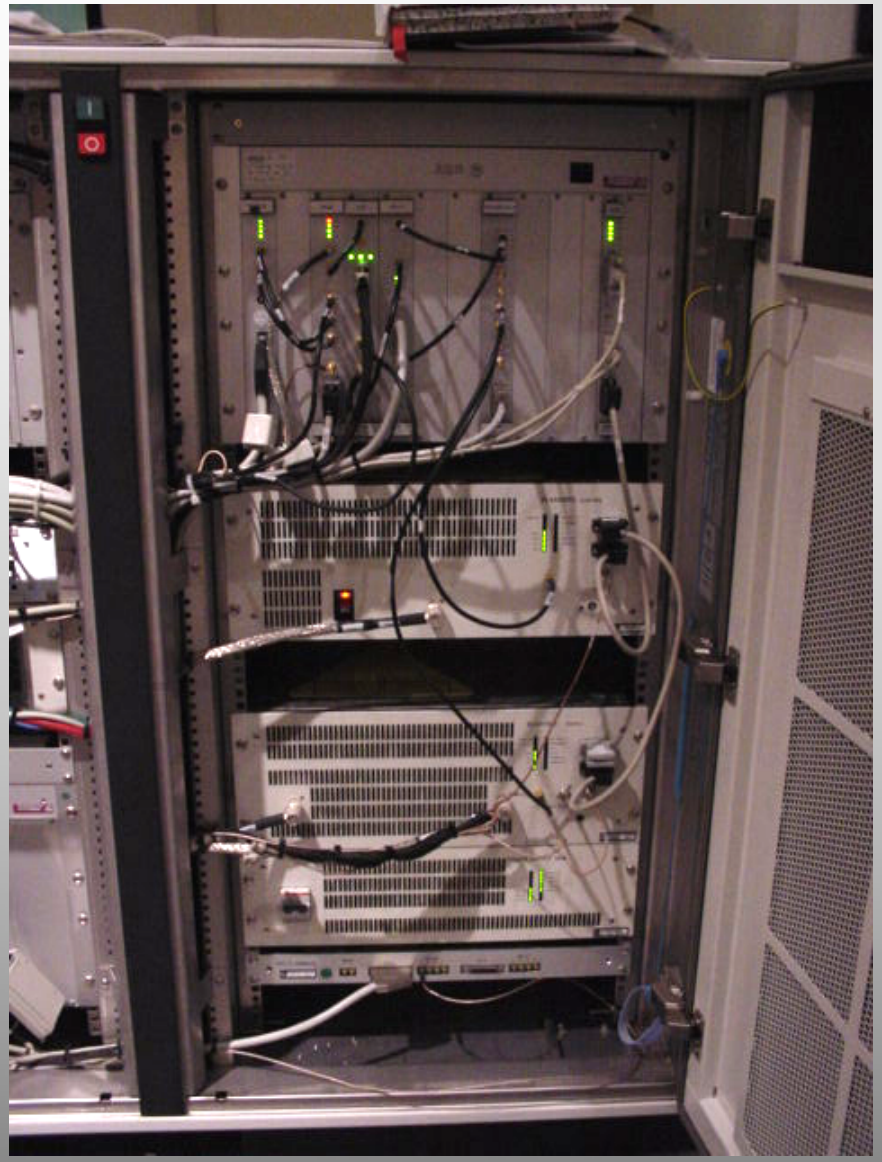


Chronik B, **Rutt BK:** Constrained Length Minimum Inductance Gradient Coil Design. Magnetic Resonance in Medicine. 39 :270-278, 1998

RF Coils



System Electronics



Pulse Sequence Programs

Example Pulse Sequence Code

Microsoft Development Environment [design] - parsRelations.c

File Edit View Debug Tools Window Help

parsRelations.c

```
/*****************************************************************
 * TR relations
 *****************************************************************/

void BIC_FLASH_TR_Rels( void )
{
  int dim;
  double TotalTime;

  DB_MSG(("-->BIC_FLASH_TR_Rels\n"));

  TotalTime = 0.0;

  if( PVM_ErrorDetected == Yes )
  {
    UT_ReportError("FLASH-backbone: In function call!");
    return;
  }

  BIC_FLASH_MinTR();

  /*****************************************************************
   * Calculate Total Scan Time and Set for Scan Editor
   *****************************************************************/

  dim = PTB_GetSpatDim();

  /* Include segment loop */
  if (dim > 1)
    TotalTime = (int)(PVM_RepetitionTime * PVM_Matrix[1] * PVM_AntiAlias[1])
    * PVM_NAverages;

  /* Include 3D phase encoding loop */
  if (dim > 2)
    TotalTime *= PVM_Matrix[2] * PVM_AntiAlias[2];

  /* Include experiment repetitions */
  TotalTime *= PVM_NRepetitions;

  /* Update scan time string with total time */
  UT_ScanTimeStr(PVM_ScanTimeStr,TotalTime);

  ParxRelsShowInEditor("PVM_ScanTimeStr");
```

Ready Ln 424 Col 1 Ch 1 INS

Microsoft Development Environment [design] - bic_flash.txt

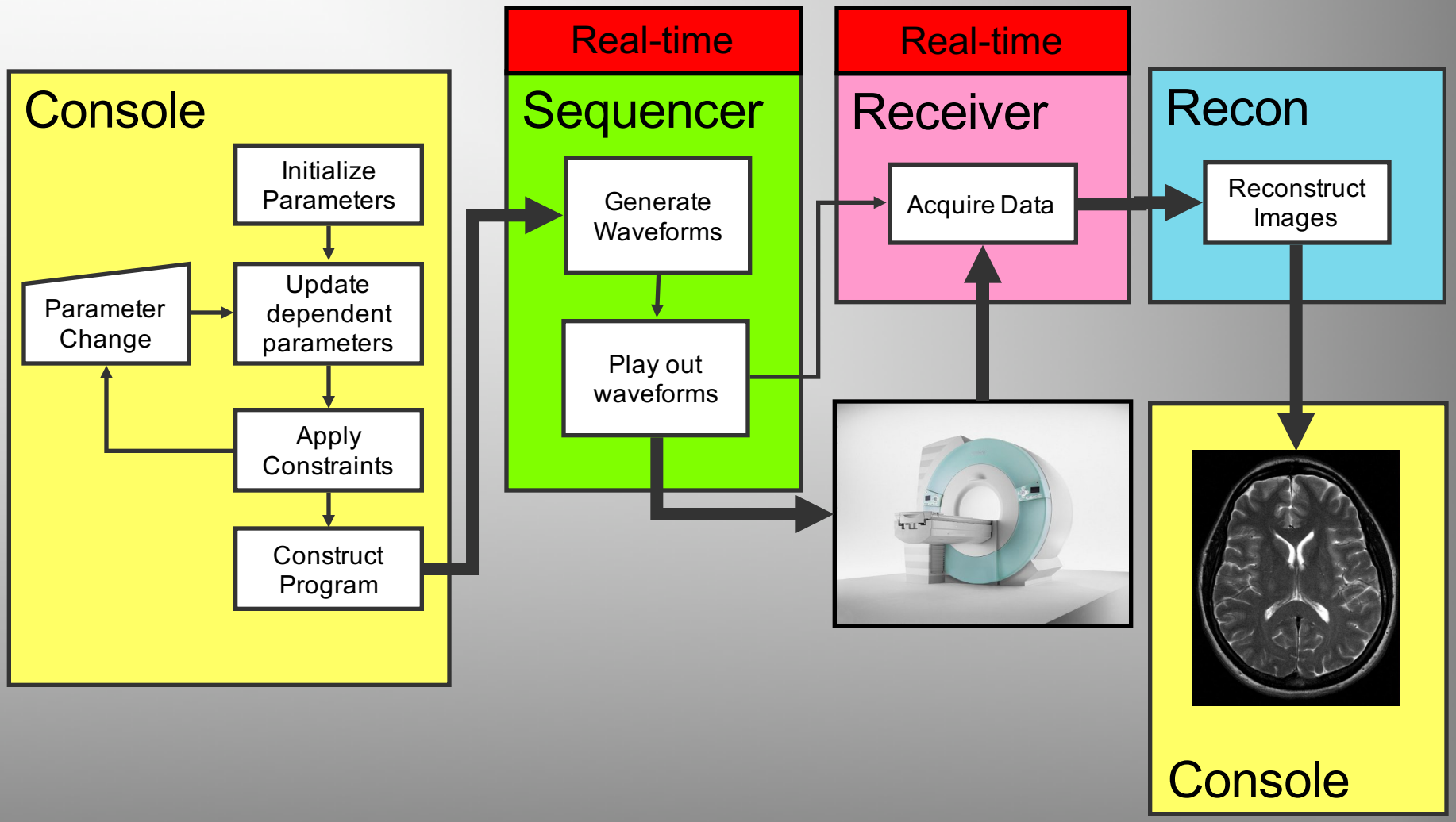
File Edit View Debug Tools Window Help

bic_flash.txt

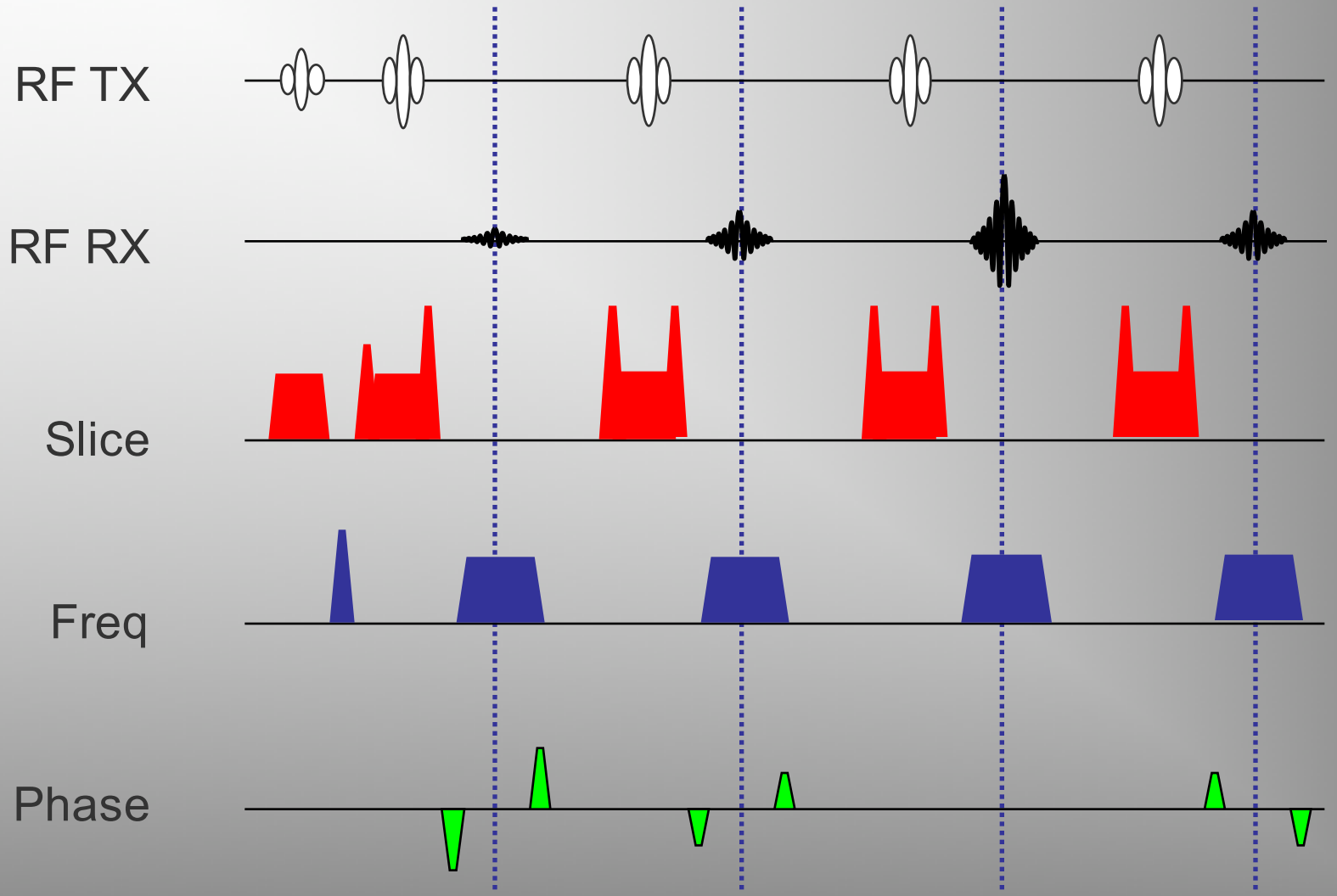
```
;----------------------------------------------------------------
; START OF MAIN SEQUENCE
;----------------------------------------------------------------

start,      10u

;----------------------------------------------------------------
; Slice loop start
;----------------------------------------------------------------

slice,      10u fq8b:f1

#include <TriggerPerSlice.mod>

;----------------------------------------------------------------
; Magnetization preparation modules
;----------------------------------------------------------------

prep,       10u

#include <SatSlices.mod>
#include <FatSup.mod>

; Set transmit frequency from list

    10u fq1:f1

;----------------------------------------------------------------
; Slice selection
;----------------------------------------------------------------

    d3  grad{(0)|(0)|(t0)}
        d8  gatepulse 1
    p0:sp0  ph0

if (BIC_FLASH_UseMinTE == No)
{
    d4  groff           ; Switch of gradients
    d2              ; Allow variable TE
}

;----------------------------------------------------------------
; Read dephase, phase encode and slice rephase
```

Ready Ln 1 Col 1 Ch 1 INS

Pulse Program Flow



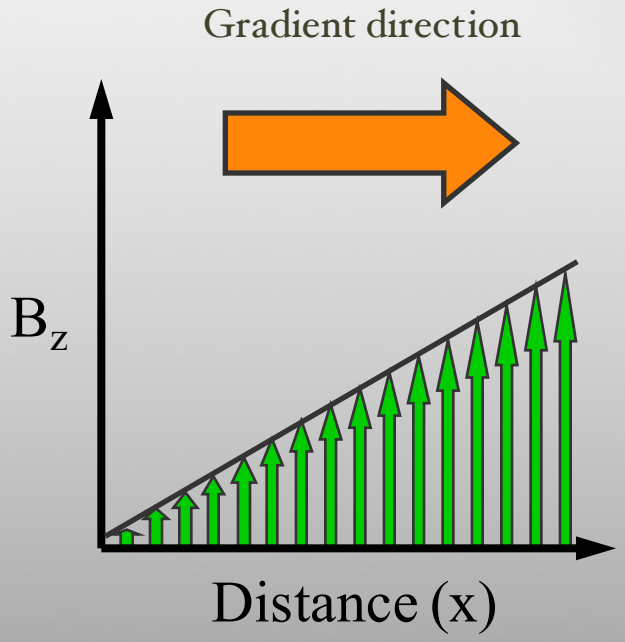
Pulse Sequence Diagrams



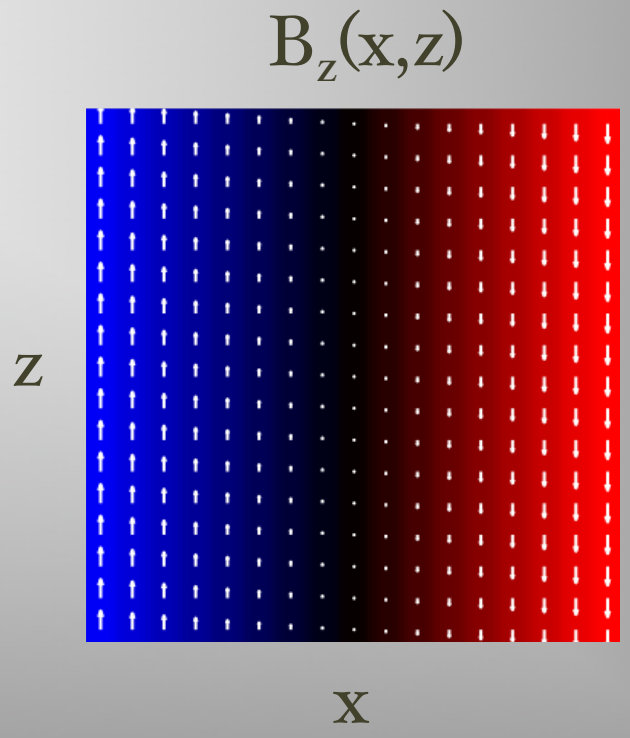
Gradient Pulses

Linear Magnetic Field Gradients

One-Dimensional



Two-Dimensional



$$\frac{\partial B_z}{\partial x} = G_x$$

$$\frac{\partial B_z}{\partial y} = 0$$

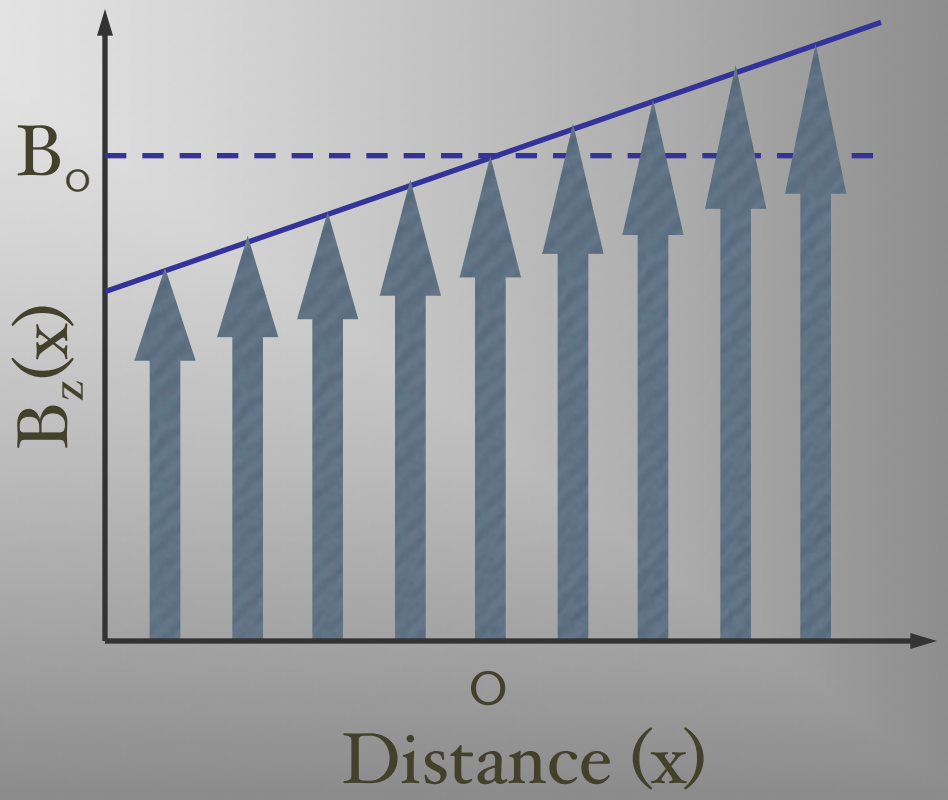
$$\frac{\partial B_z}{\partial z} = 0$$

Deviation from B_o typically very small (~0.1%)

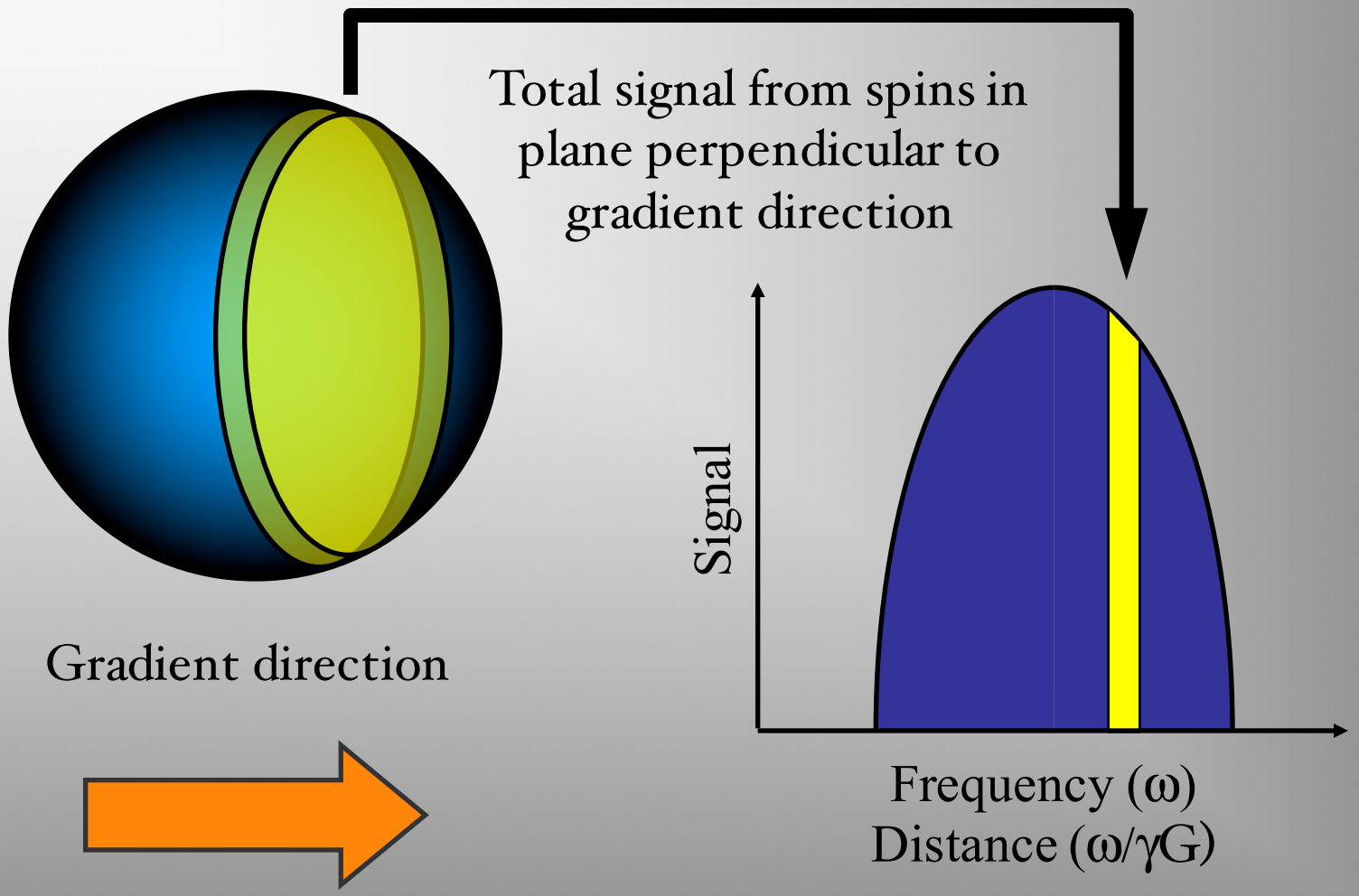
Field Gradients and Magnetization Phase

$$B_z(x) = B_0 + G_x x$$

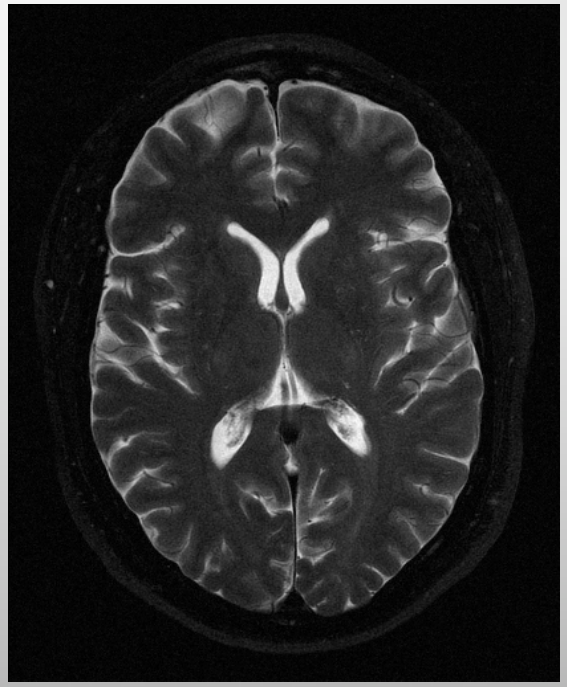
$$\begin{aligned}\phi(x,t) &= \omega(x)t \\ &= \gamma B_z(x)t \\ &= \gamma G_x x t\end{aligned}$$



Frequency Encoding



Frequency Encoding Bandwidth

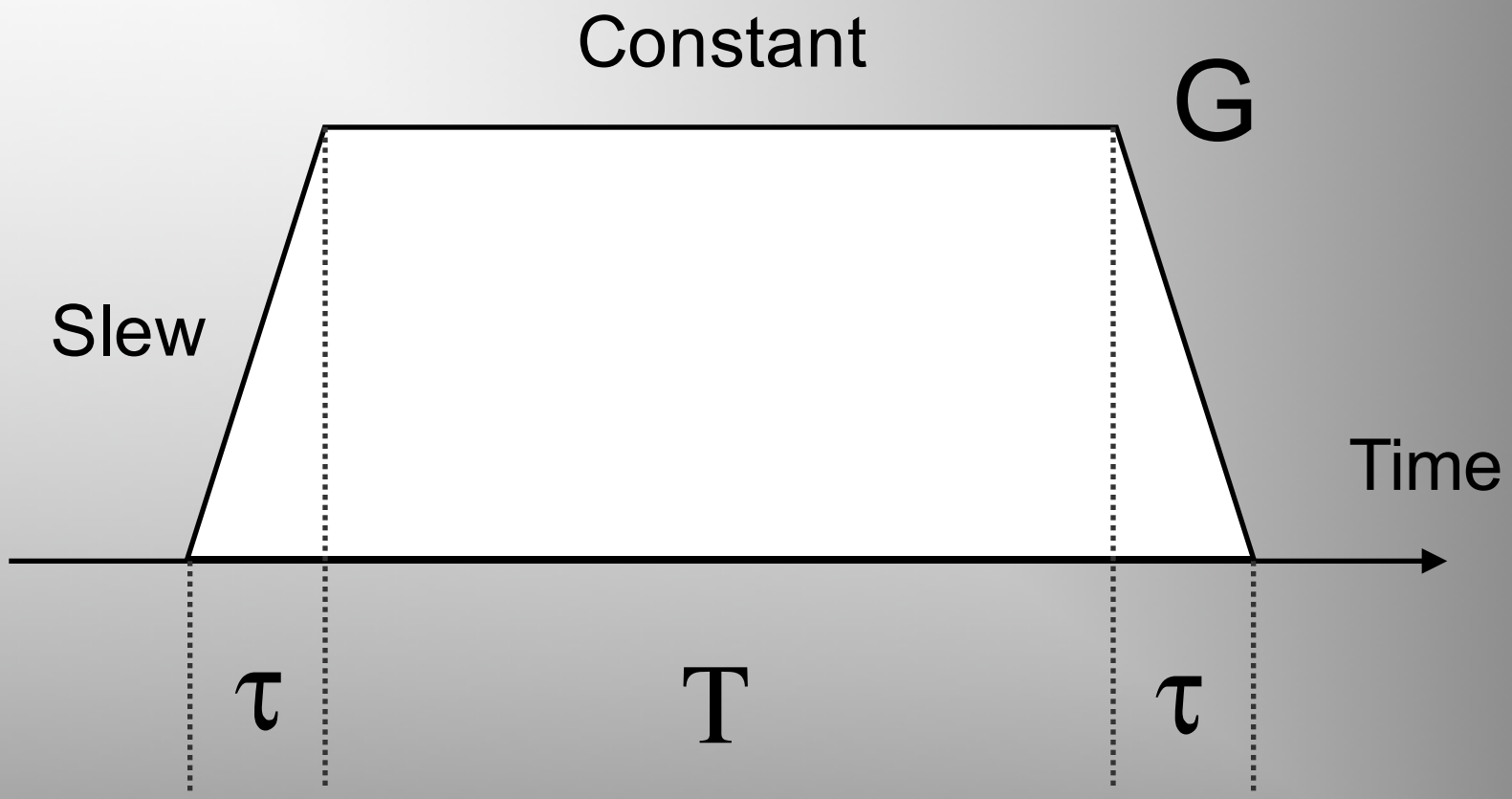


$$BW = \gamma G_x FOV_x$$

$$[Hz] = \left[\frac{Hz}{G}\right]\left[\frac{G}{cm}\right][cm]$$

$$B_z = B_0 + G_x x$$

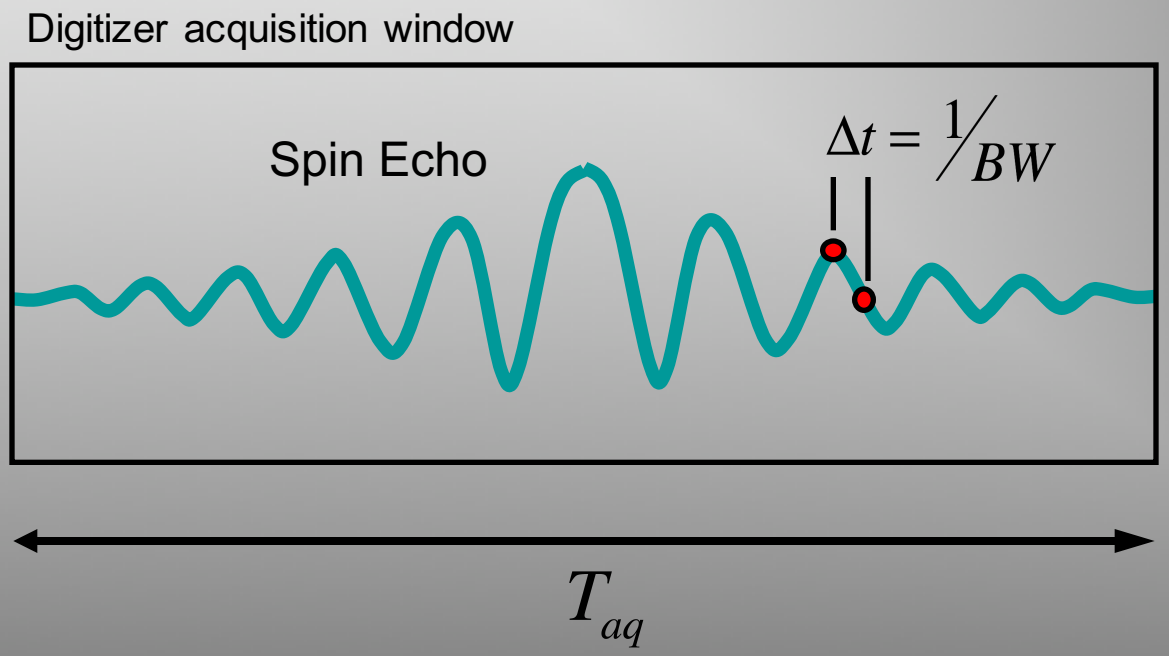
Real Gradient Pulses



Frequency Encoding Bandwidth and Noise

SNR is proportional to the square-root of the total digitizer acquisition time (c.f. SNR proportional to the square root of the number of signal averages).

$$\frac{S}{N} \propto \sqrt{T_{aq}} = \sqrt{N_x \Delta t} = \sqrt{\frac{N_x}{BW}}$$



Gradient Moments

k-space

k measures phase accumulated per unit distance over a time interval (radians/m) due to a time varying gradient (pulse, waveform, etc).

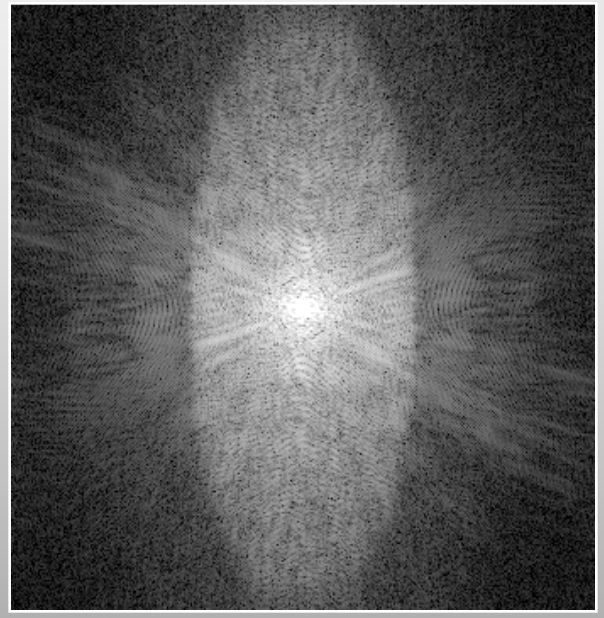
$$\mathbf{k}(t) = \int_0^t dt' \gamma \mathbf{G}(t')$$

k is a vector => k-space can be multidimensional.

The components of **k** (k_x, k_y, etc.) have units of radians/m.

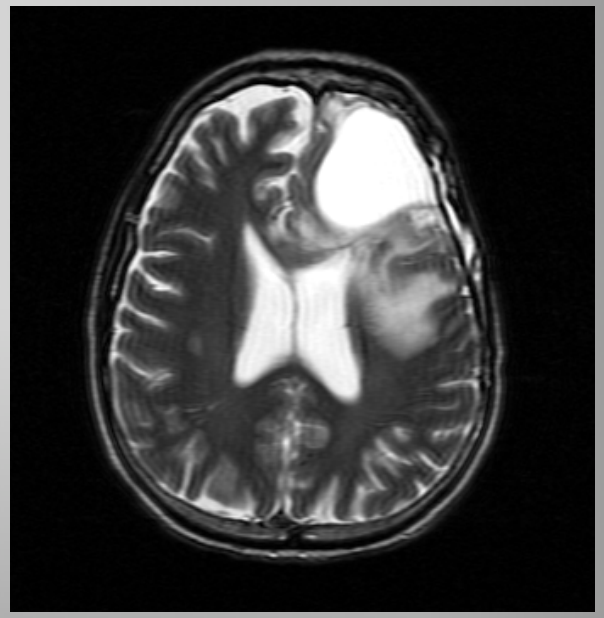
MR Imaging as Diffraction

MRI data is acquired in the inverse space of the final image



k-space

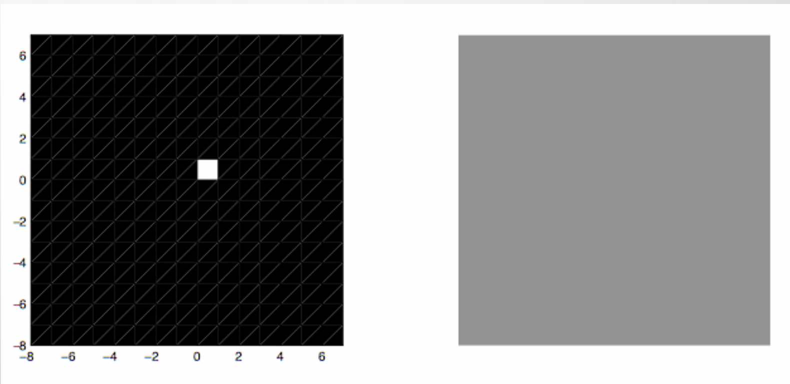
Fourier Transform

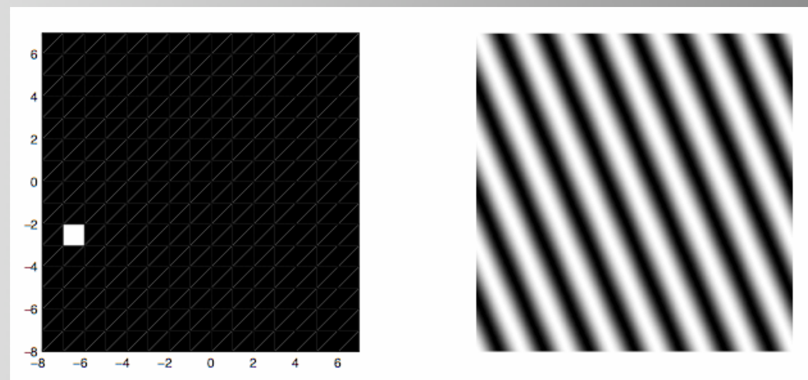


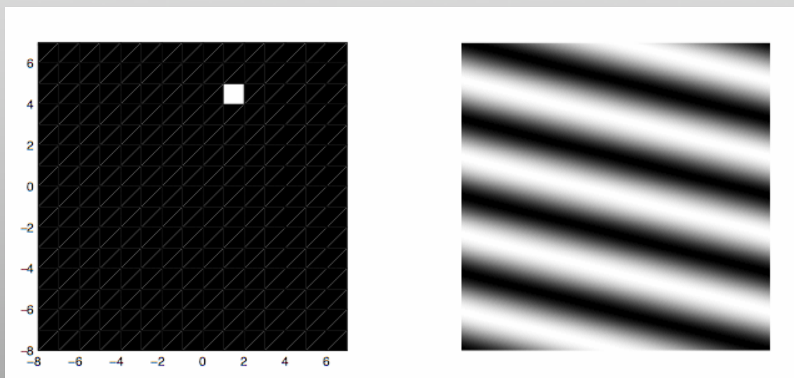
Frequency Encoded Space

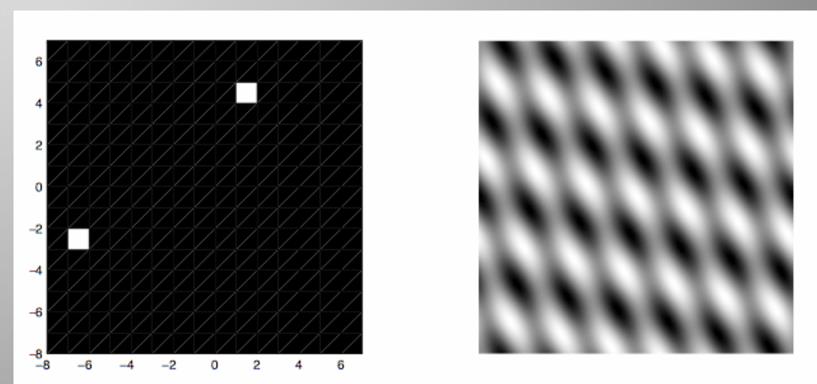
Spatial Frequencies and k-space

k-space Real space





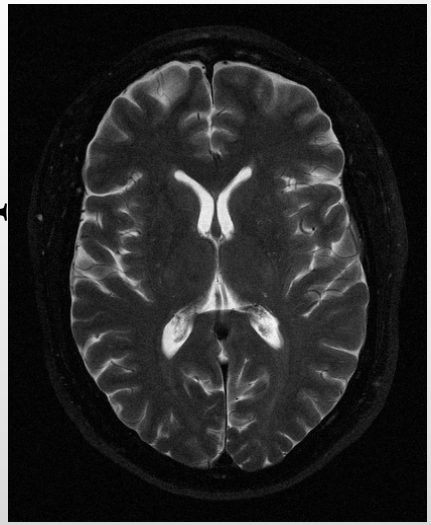


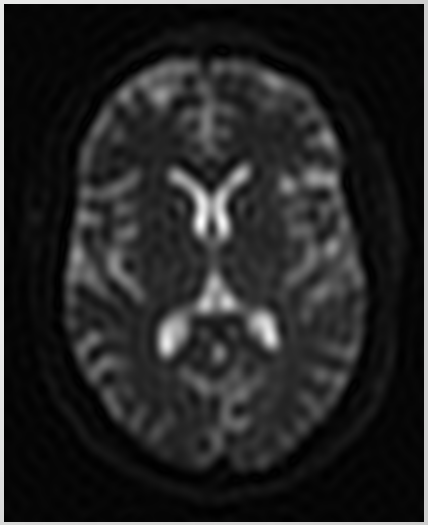


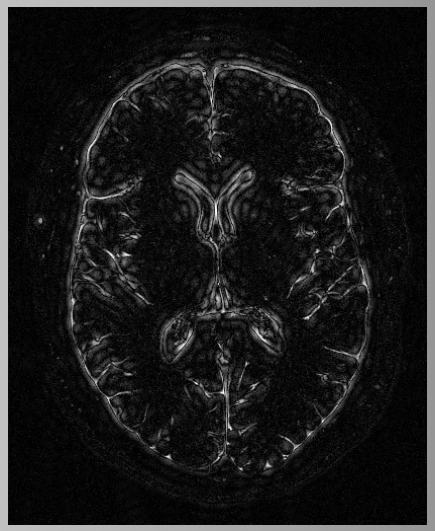
Coordinates in k-space equate to spatial frequency.

k-space Spatial Frequency Regions

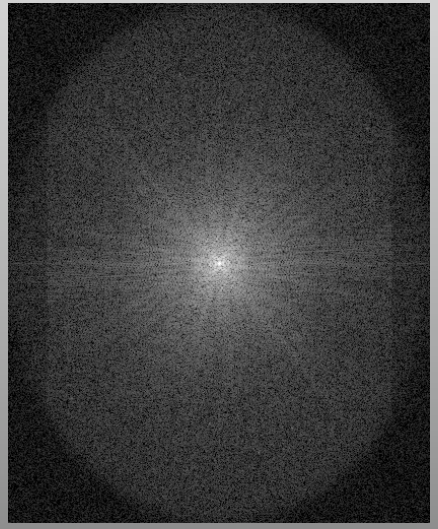
Real Space

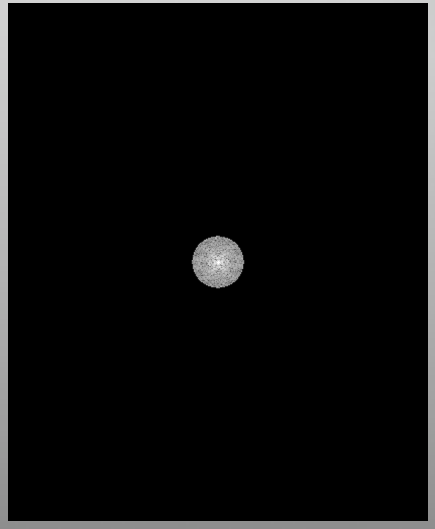


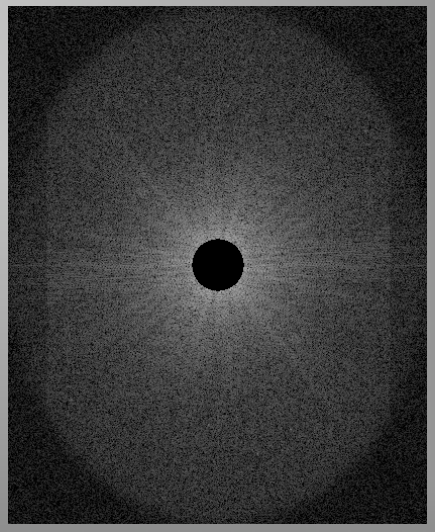




k Space



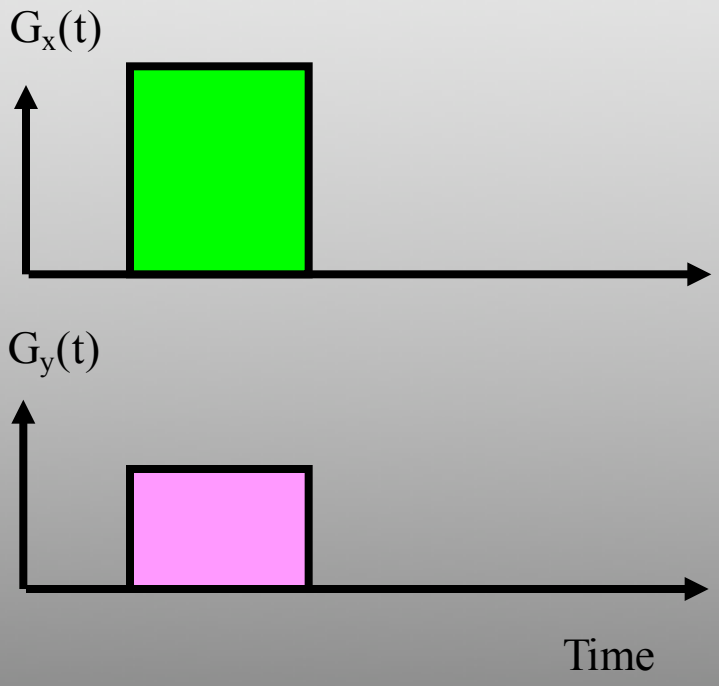


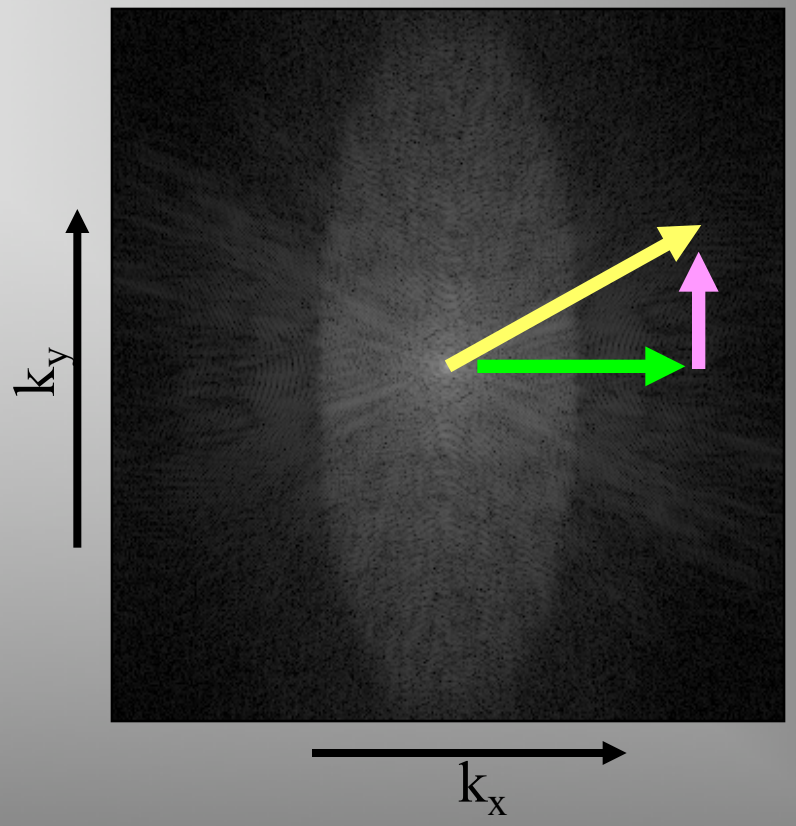


k-space Maneuvers

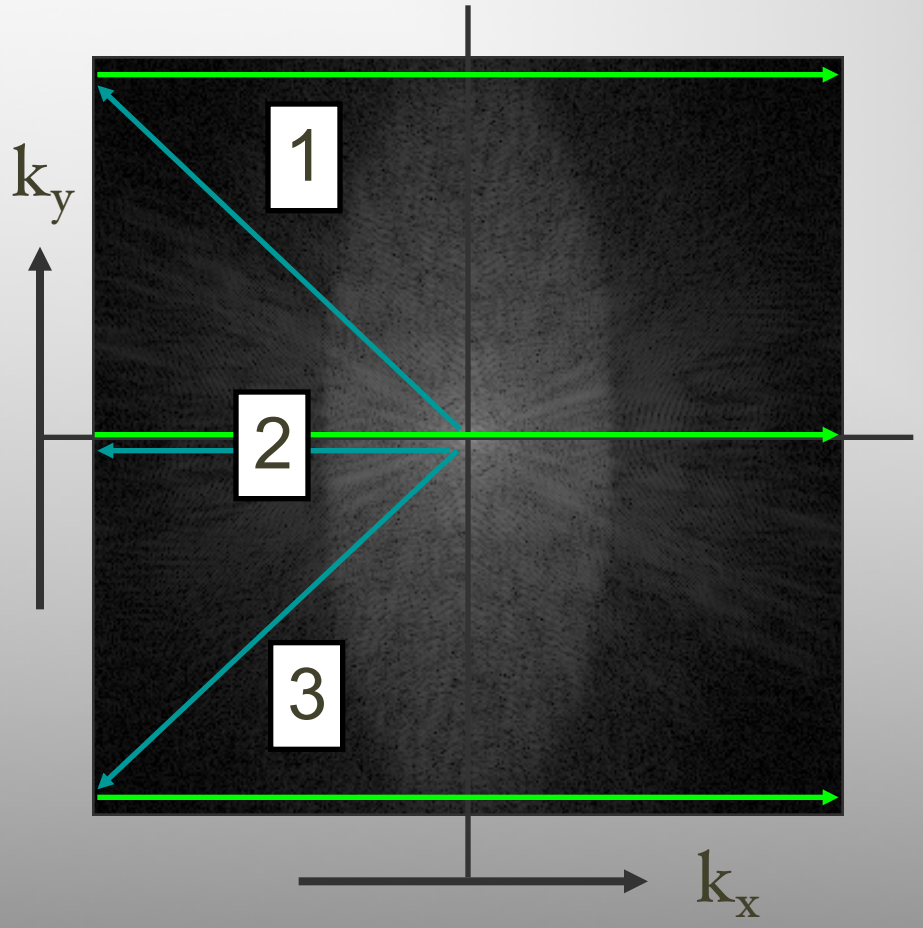
$$\mathbf{k}(t) = \int_0^t dt' \gamma \mathbf{G}(t')$$

Gradient pulses move the spin system in k-space.

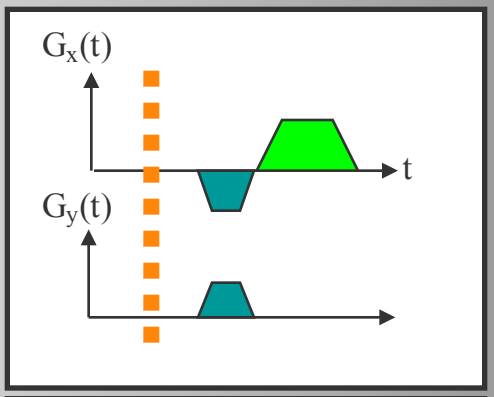




k-space Trajectories



1



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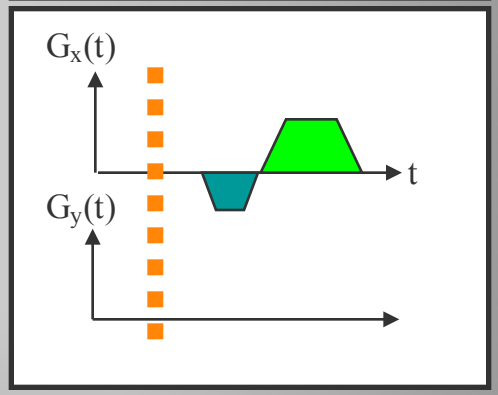

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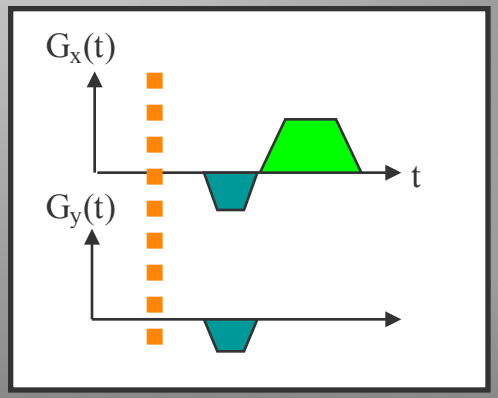
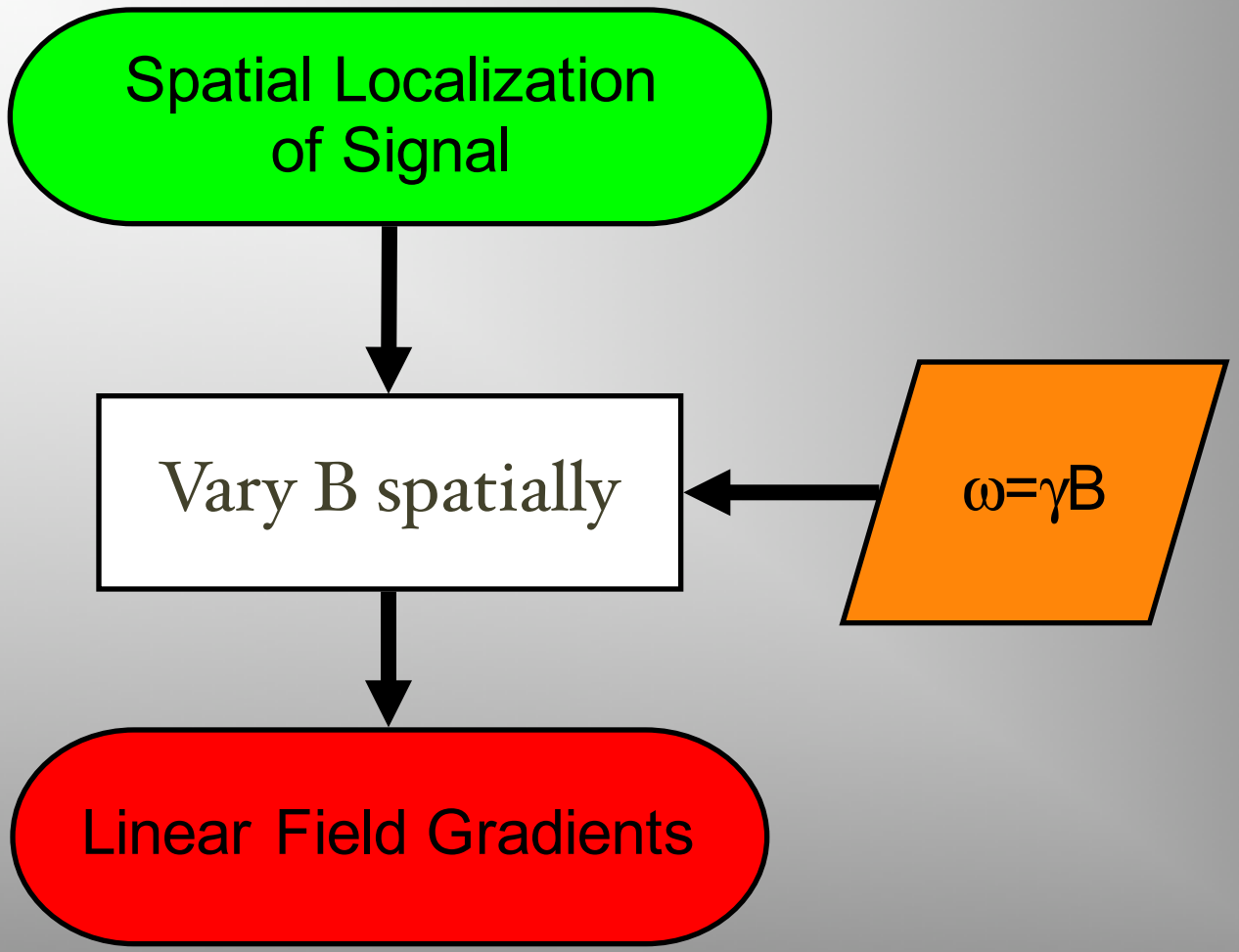


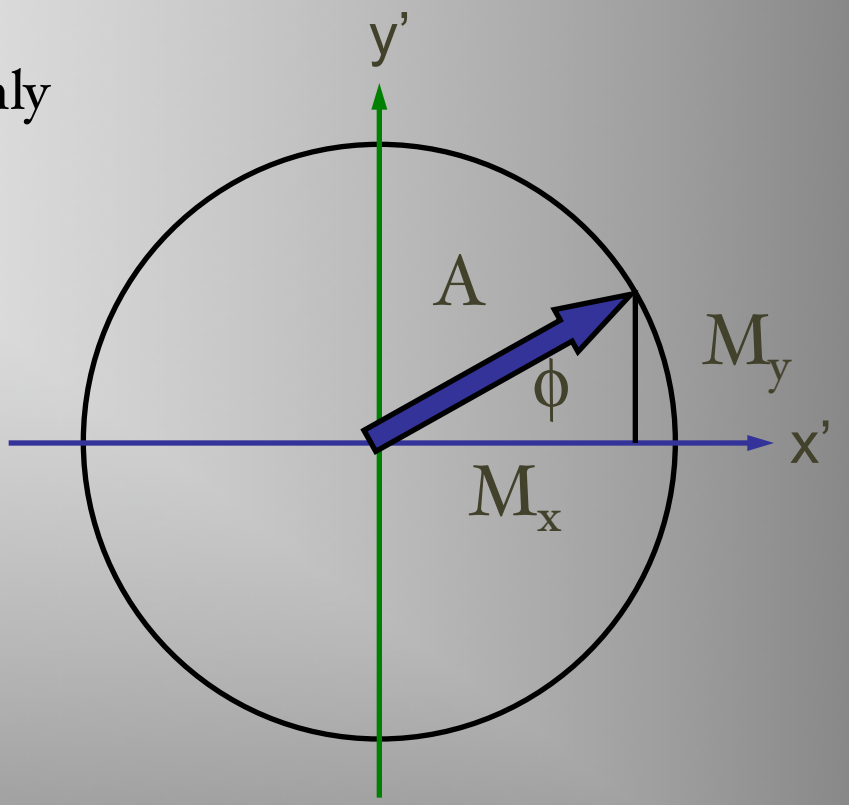
Spatial Encoding



MR Signal as a Complex Quantity

- Both the magnitude and phase of the MR signal are measured.
- Two signal channels are commonly referred to as “real” and “imaginary”.

$$M = Ae^{i\phi}$$
$$= A\cos(\phi) + iA\sin(\phi)$$
$$= M_x + iM_y$$



The Fourier Transform (FT)

The Fourier Transform is an Integral Transform which, for MRI, relates a time varying waveform to the corresponding frequency spectrum.

FORWARD TRANSFORM (time -> frequency)

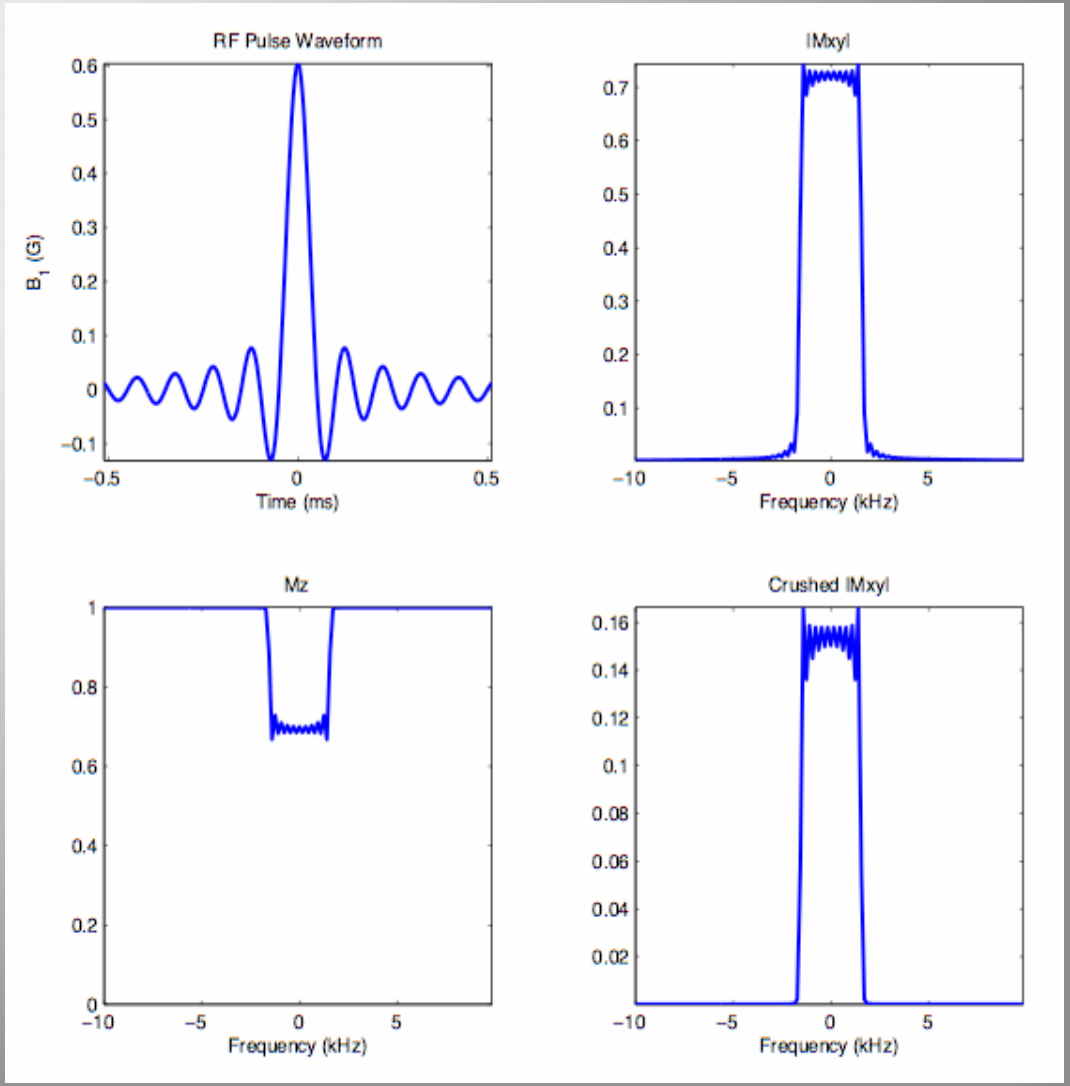
$$\bar{S}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, S(t)\, e^{i\omega t}$$

REVERSE TRANSFORM (frequency -> time)

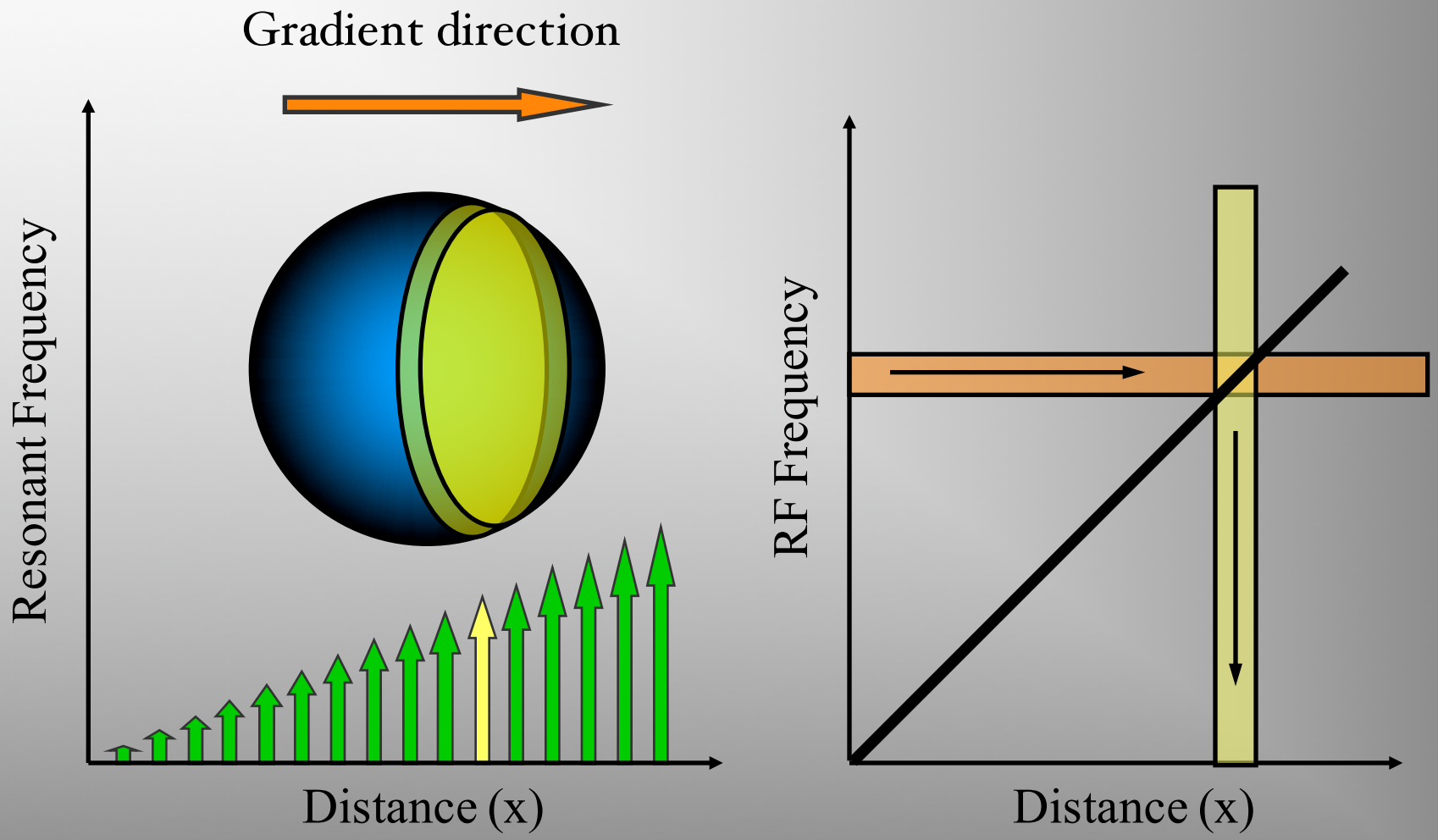
$$S(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, \bar{S}(\omega) e^{-i\omega t}$$

Bandlimited RF Pulses

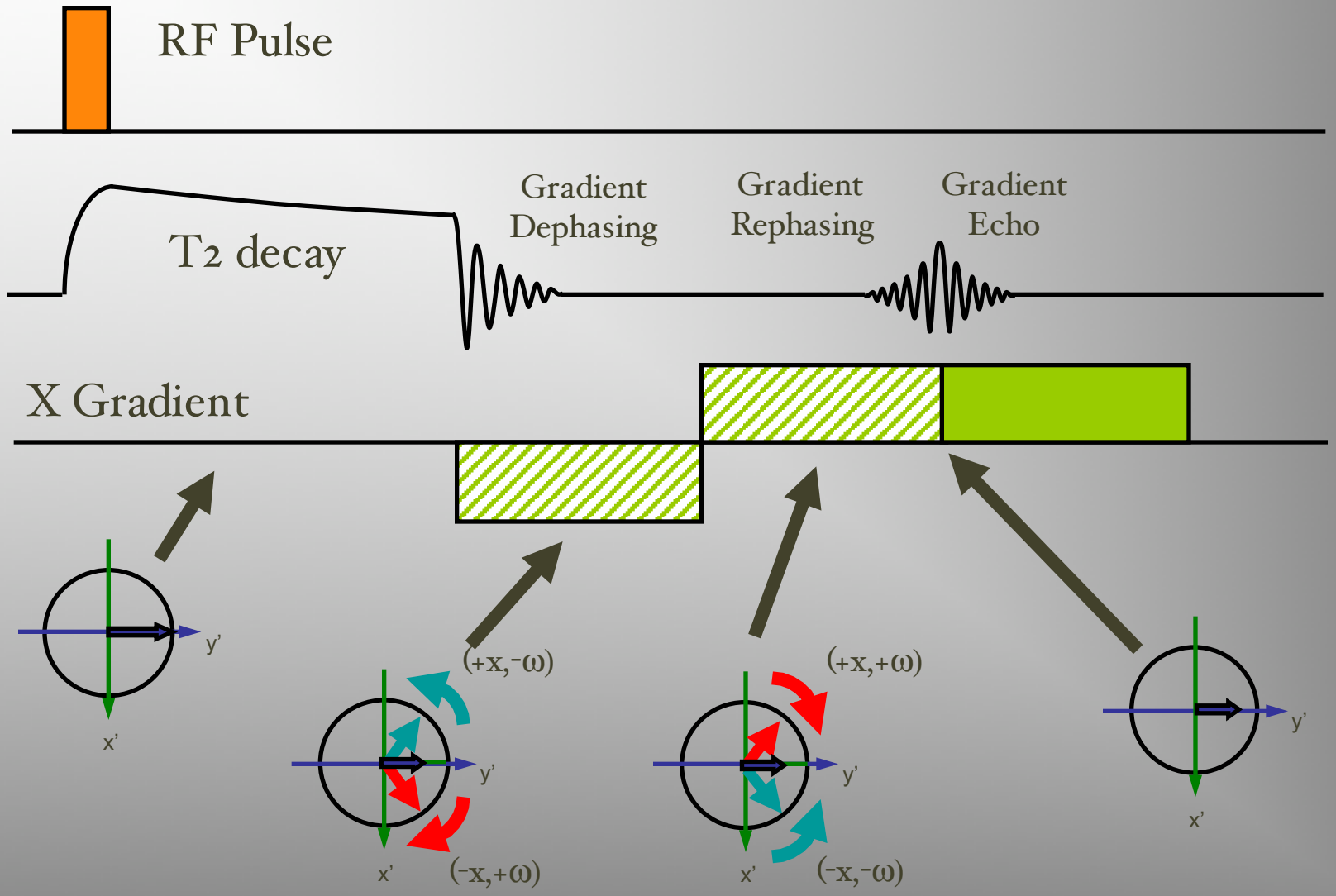
- Pulse waveform modulates Larmor carrier frequency.
- Affects frequency band centered on Larmor frequency.



Slice Selection with Gradients



The Gradient Echo



Construct Full Gradient Echo Sequence

Tomorrow : Pulse Sequences