RF Pulse Design

Multi-dimensional Excitation II

M229 Advanced Topics in MRI

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2018.04.12

Class Business

- Homework 1 will be due on 4/26
- Office hours
  - Instructors: Fri 10-12 noon
    TAs: Thursday 3-5pm
  - Emails beforehand would be helpful
- Papers and Slides

Today's Topics

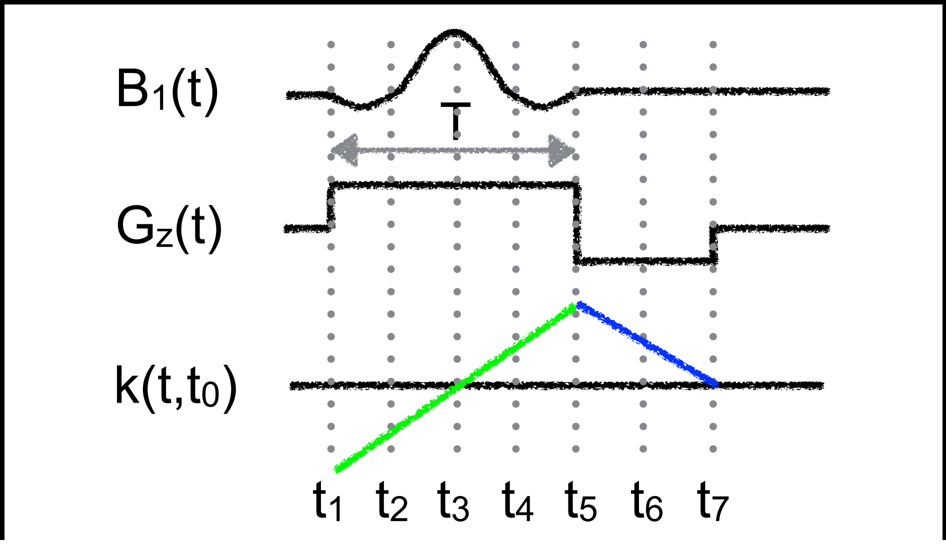
- Recap of excitation k-space
- 2D excitation pulses
  - 2D EPI pulse design
  - Spatial-spectral pulse design
- Matlab exercise

Summary for Excitation k-space

Small-Tip Approximation

$$M_{xy}(t,\vec{r}) = i\gamma M_0 \int_0^t B_1(s) e^{i2\pi \vec{k}(s,t)\cdot\vec{r}} ds$$

$$\vec{k}(s,t) = -\frac{\gamma}{2\pi}\int_s^t \vec{G}(\tau)d\tau$$



Small-Tip-Angle Solution as a k-space Integral

$$M_{xy}(t,\vec{r}) = iM_0 \int_{\vec{k}} p(\vec{k}) e^{i2\pi\vec{k}\cdot\vec{r}} d\vec{k}$$

$$p(\vec{k}) = W(\vec{k})S(\vec{k})$$

$$W(\vec{k}) = \frac{\gamma B_1(s)}{|k'(s,t)|}$$

k-space weighting

$$S(\vec{k}) = \int_{-\infty}^{t} {}^{3}\delta(\vec{k}(s,t) - \vec{k})|k'(s,t)|ds$$

k-space sampling

2D Pulse Design

$$M_{xy}(t,\vec{r}) = iM_0 \int_{\vec{k}} W(\vec{k})S(\vec{k})e^{i2\pi\vec{k}\cdot\vec{r}}d\vec{k}$$

1. Choose a k-space trajectory
2. Choose a weighting function
3. Design the RF pulse

$$B_1(s) = \frac{1}{2\pi}|\vec{G}(s)|W(\vec{k})$$

2D Spatial Pulse Design

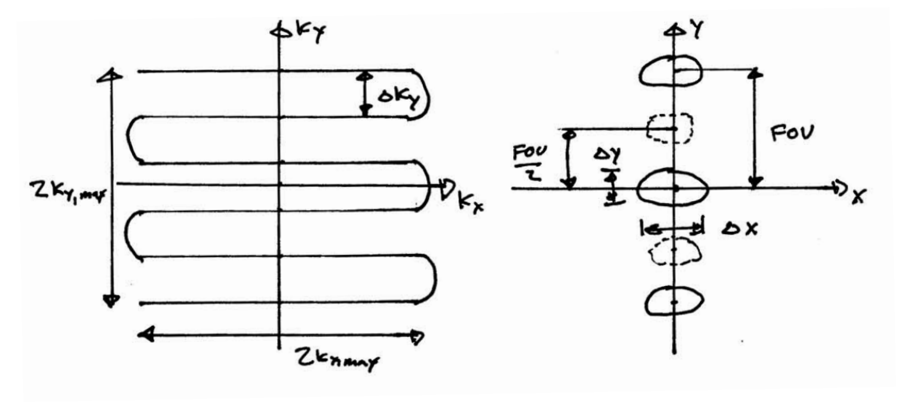
- EPI
  - Non-isotropic resolution
  - Sidelobes in one dimension
  - Spectral-spatial pulses

- Spiral
  - Unity aspect ratio
  - Minimum length
  - Circular sidelobe

2D EPI Pulse Design

Designing EPI k-space Trajectory

- Ideally, an EPI trajectory scans a 2D raster in k-space



Resolution? / FOV?

Designing EPI k-space Trajectory

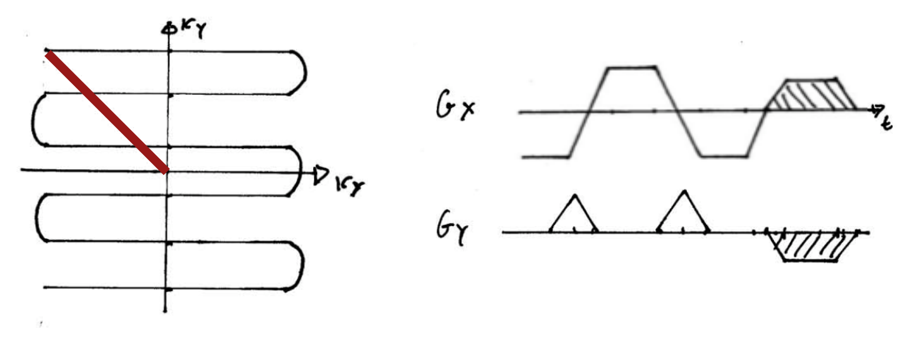
- Resolution: $\Delta x = \frac{TBW}{2k_{x,max}}$ $\Delta y = \frac{TBW}{2k_{y,max}}$
- FOV = $1/\Delta k_y$

$$\Delta k_y = \frac{2k_{y,max}}{L-1}$$

- Ghost FOV = FOV/2
  - Eddy currents & delays produce this

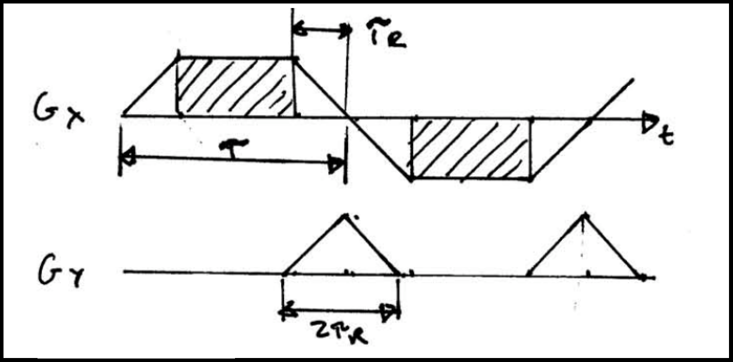
Designing EPI k-space Trajectory

- Refocusing gradients
  - Returns to origin at the end of pulse



Designing EPI Gradients

- Designing readout lobes and blips
  - Flat-top only design



  - RF only played during flat part (simpler)

To the board ...

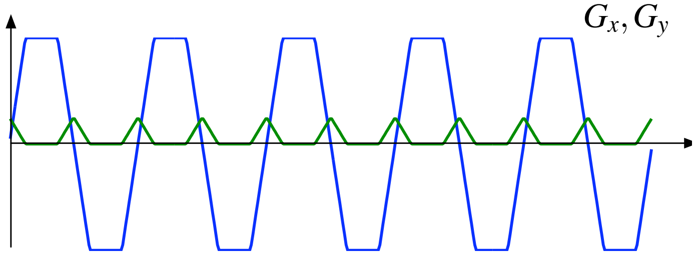
Designing EPI Gradients

- Easy to get k-space coverage in k_y
- Hard to get k-space coverage in k_x
- We can get more k-space coverage by
    - making blips narrower
    - playing RF during part of ramps

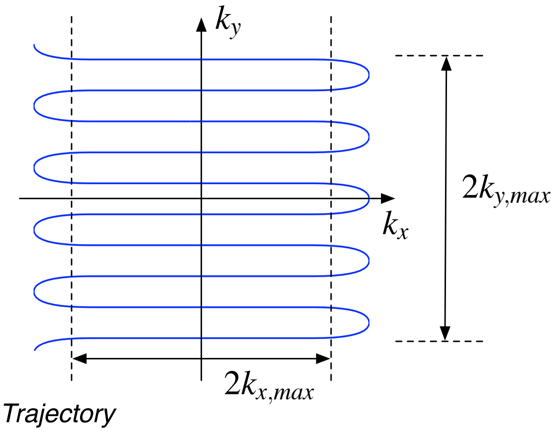
Blipped EPI

- Rectilinear scan of k-space
- Most efficient EPI trajectory
- Common choice for spatial pulses
- Sensitive to eddy currents and gradient delays

Blipped EPI



Gradient Waveforms

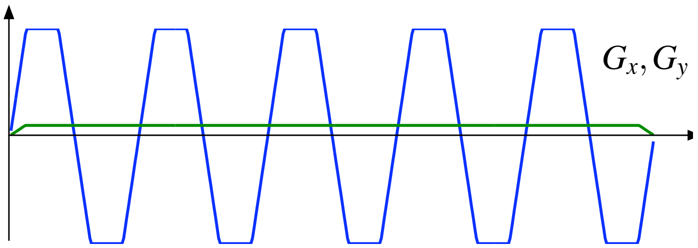


k-Space Trajectory

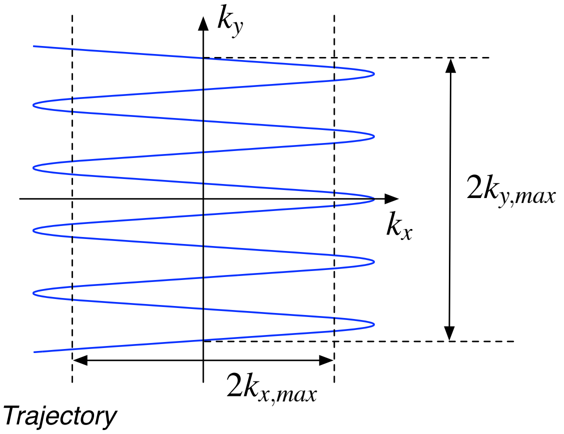
Continuous EPI

- Non-uniform k-space coverage
- Need to oversample to avoid side lobes
  - Less efficient than blipped
- Sensitive to eddy currents and gradient delays
  - Only choice for spectral-spatial pulses

Continuous EPI



Gradient Waveforms

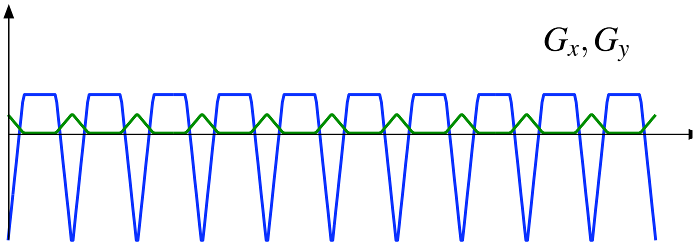


k-Space Trajectory

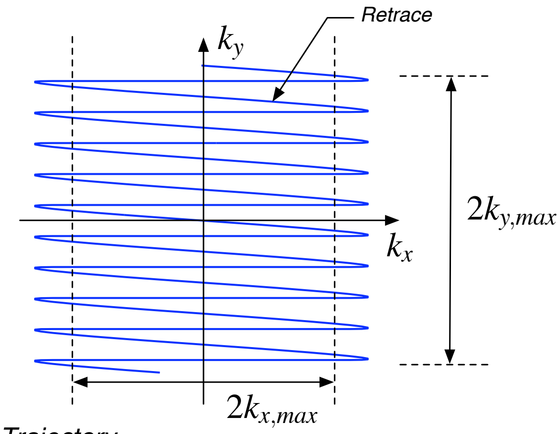
Flyback EPI

- Can be blipped or continuous
- Less efficient since retraces not used (depends on gradient system)
- Almost completely immune to eddy currents and gradient delays

Flyback EPI



Gradient Waveforms



k-Space Trajectory

Designing 2D EPI Spatial Pulses

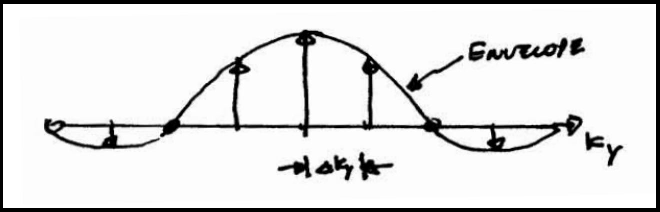
- Two major options
  - General approach, same as 2D spiral pulses
  - Seperable, product design (easier)
- General approach
  - Choose EPI k-space trajectory
  - Design gradient waveforms
  - Design *W(k)*, k-space weighting
  - Design $B_1(t)$

Separable, Product Design

- Assume,

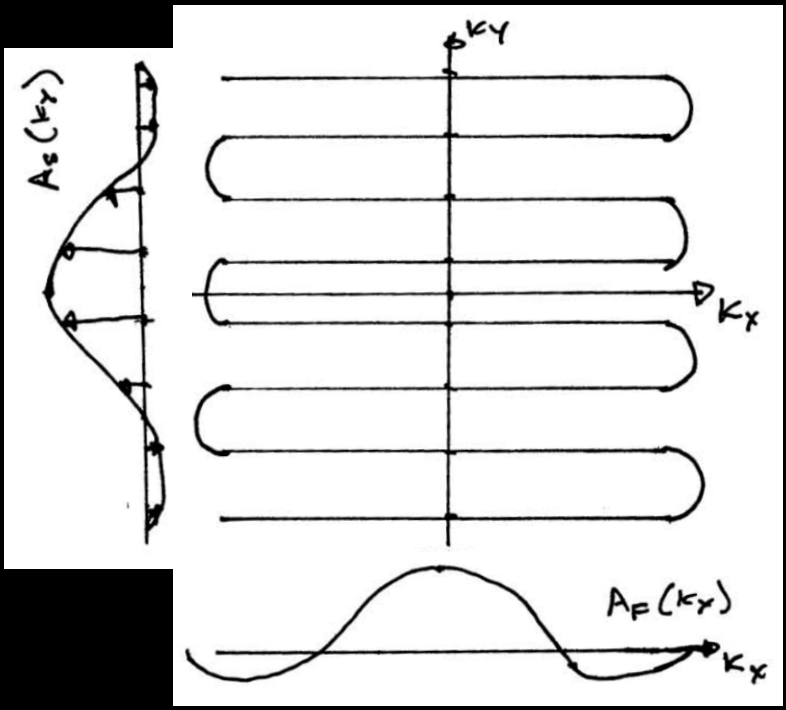
$$W(k_x, k_y) = A_F(k_x) \cdot A_S(k_y)$$

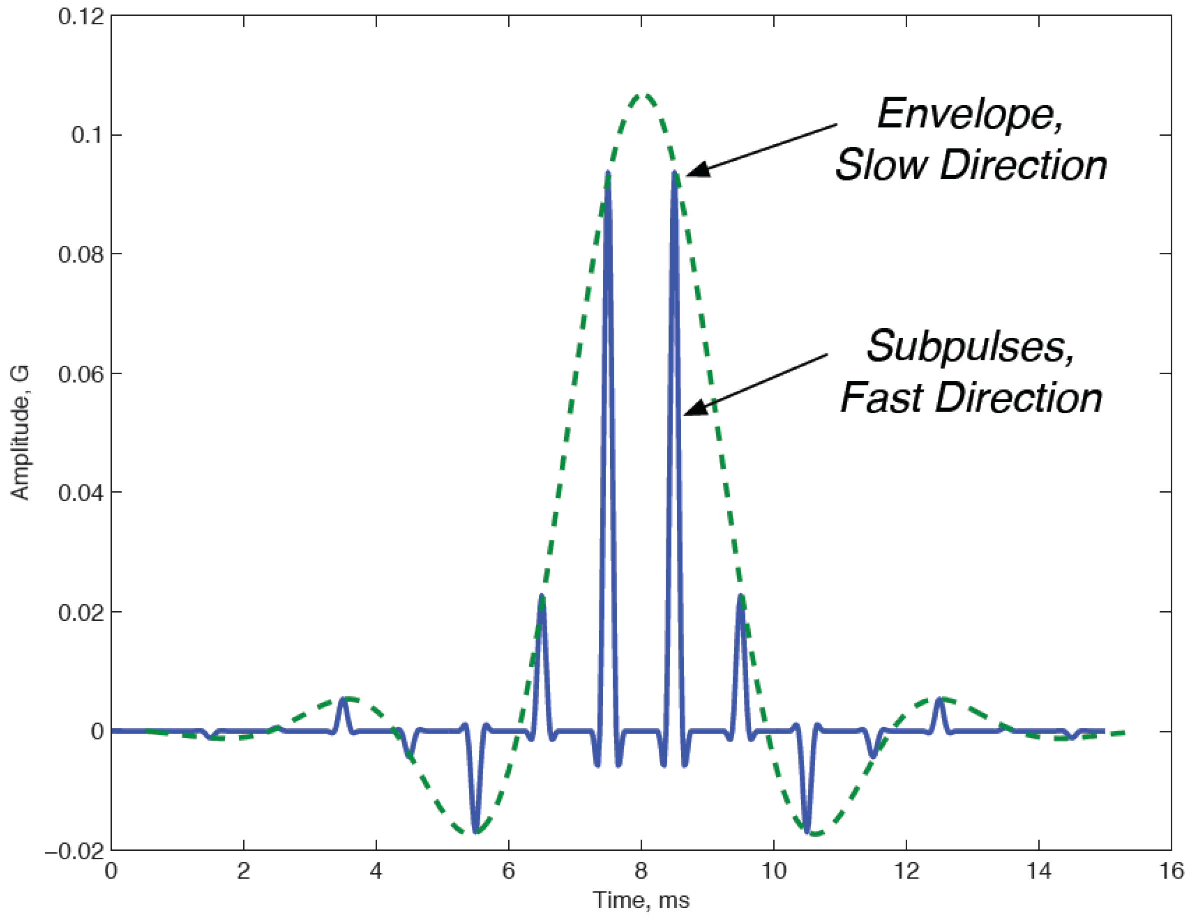
$A_S(k_y)$: weighting in the slow, blipped direction
$A_F(k_x)$: weighting in the fast oscillating direction

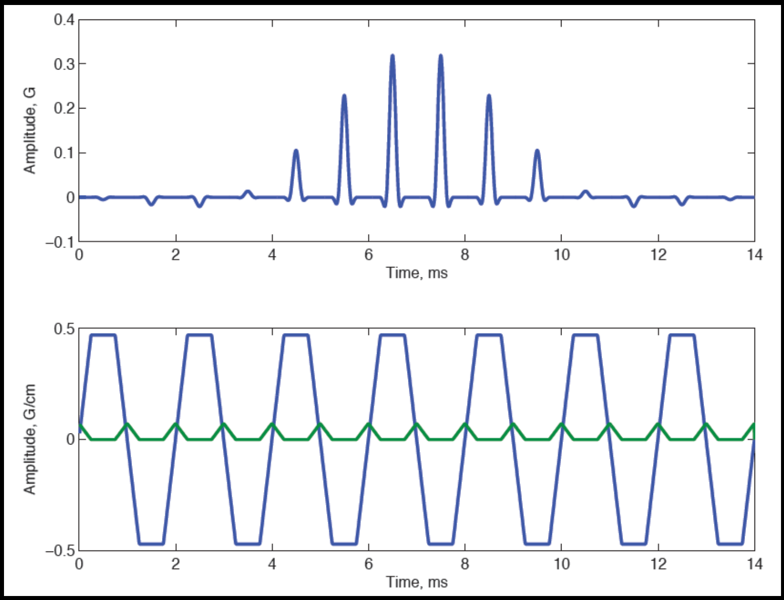


- Each impulse corresponds to a pulse in the fast direction, $A_F(k_x)$

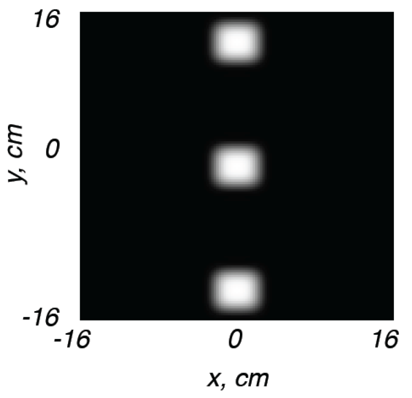
Separable, Product Design







1 ms subpulses
14 subpulses
Flattop only (0.5 ms)
4 cm x 4 cm mainlobe
Sidelobes at +/- 13 cm

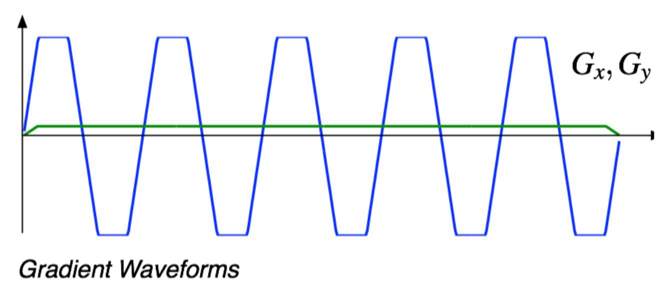


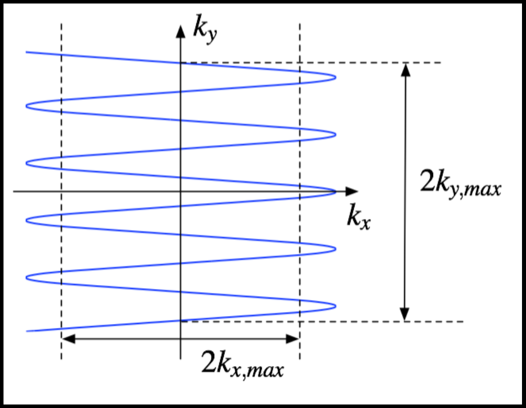
Spectral Spatial Pulse

Spatial-Spectral Pulses

- 2D pulses selective in space and frequency
- Excite a slice at a limited band of frequencies
- Clinical applications
  - High speed imaging (spiral/EPI)
  - Robust lipid suppression
  - Spectroscopic imaging (MRSI)

Basic Idea





- Gy gradient simply establishes a linear relationship between position and frequency
    - Spatial selectivity in y ⇒ Frequency selectivity

Basic Idea

$$M_{xy}(t,\vec{r}) = i\gamma M_0 \int_0^t B_1(s) e^{i2\pi\vec{k}(s,t)\cdot\vec{r}} ds$$

⬇

$$M_{xy}(t,y) = i\gamma M_0 \int_0^t B_1(s) e^{i2\pi k_y(s,t)\cdot y} ds$$

$$\vec{k}(s,t) = -\frac{\gamma}{2\pi}\int_s^t \vec{G}(\tau)d\tau$$

⬇

$$k_y(s,t) = -\frac{\gamma}{2\pi} G_y(t-s)$$

Basic Idea

$$M_{xy}(t, y) = i\gamma M_0 \int_0^t B_1(s) e^{i2\pi \underbrace{\left(\frac{\gamma G_y y}{2\pi}\right)}_{f} \underbrace{(s-t)}_{k_f}} ds$$

$$\Downarrow$$

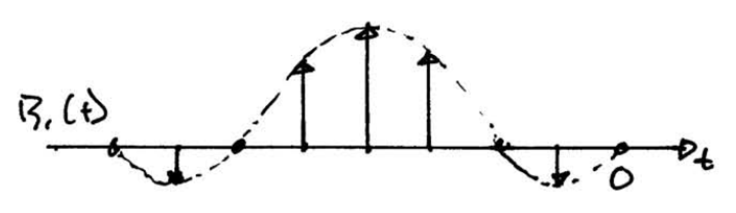
$$M_{xy}(t_0, f) = i\gamma M_0 \int_{-t_0}^{0} B_1(k_f) e^{i2\pi f k_f} dk_f$$

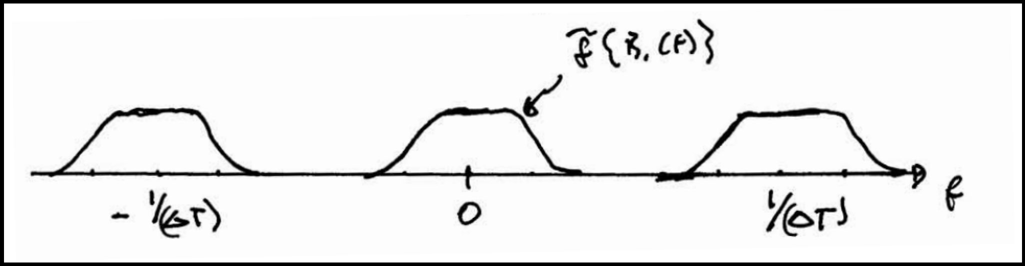
$$M_{xy}(f) = i\gamma M_0 \int_{-\infty}^{0} B_1(k_f) e^{i2\pi f k_f} dk_f$$

Note that k_f is time!

Spectral Pulses

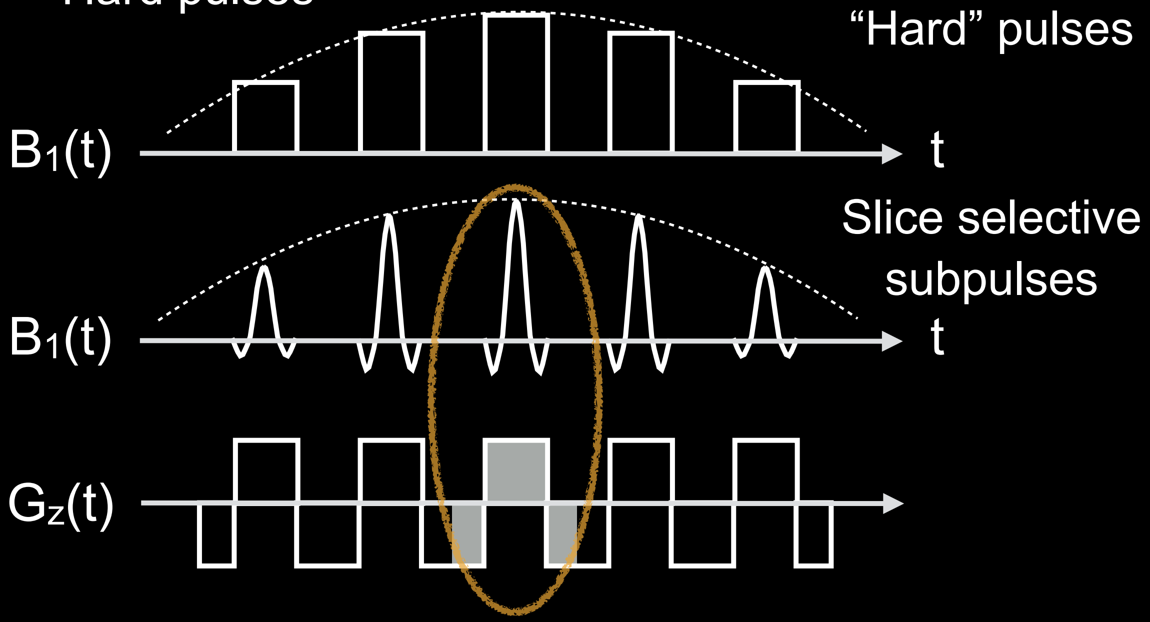
$$M_{xy}(f) = i\gamma M_0 \int_{-\infty}^{0} B_1(t) e^{i2\pi f t} dt$$





Add Spatial Selectivity to a Spectral Pulse

- Hard pulses



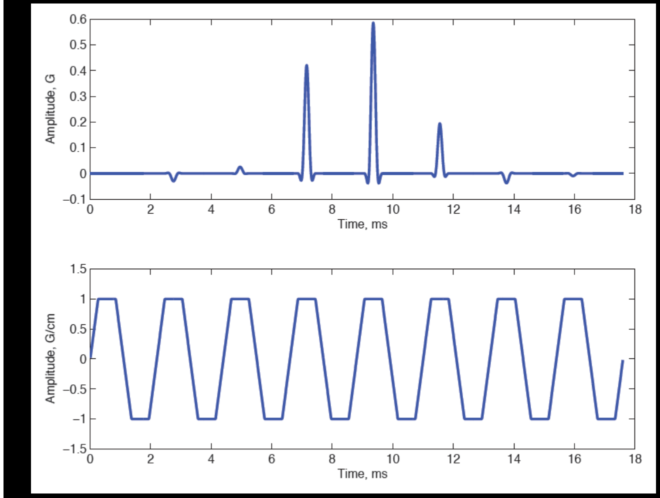
“Hard” pulses

Slice selective subpulses

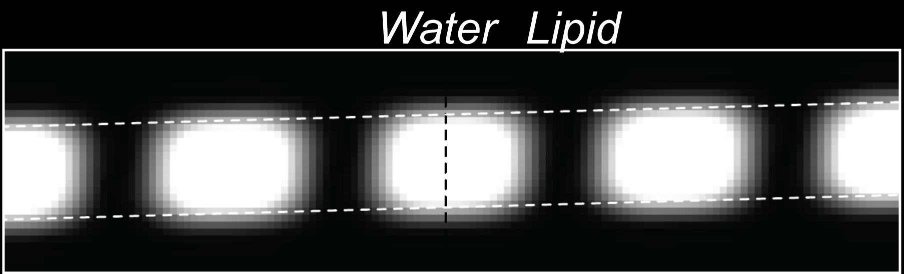
Each sub pulse starts and ends at $k_z = 0$

To the board ...

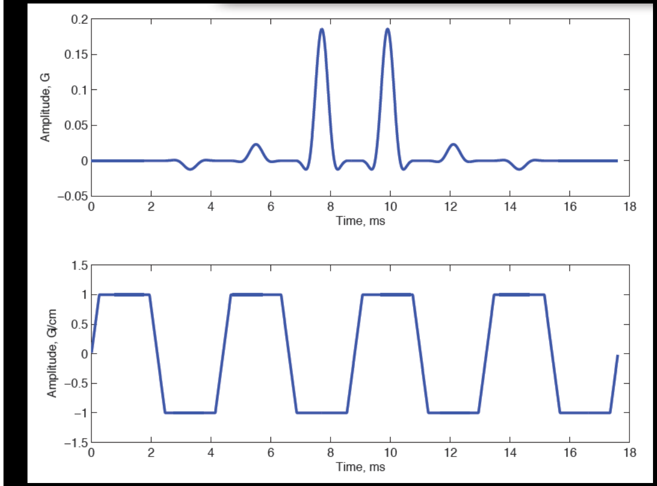
Flyback Design



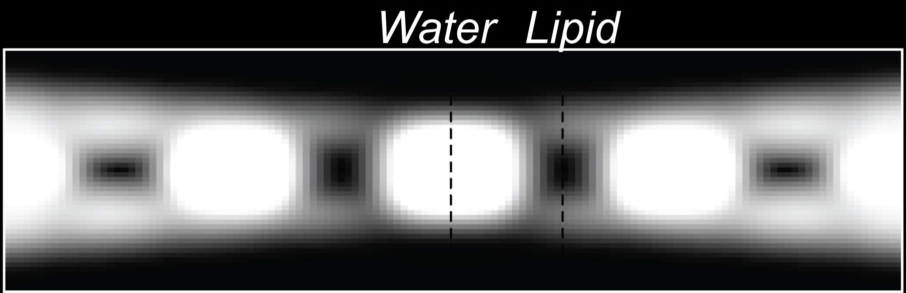
1.1 ms sublobes
8 sublobes
250 Hz spectral passband
15 ms length



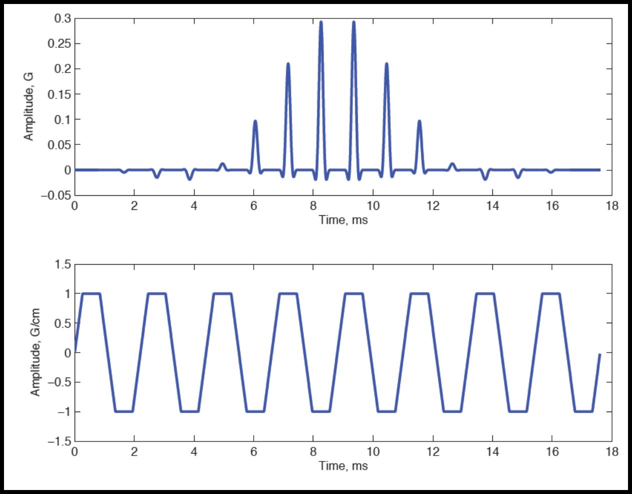
Opposed Null Design



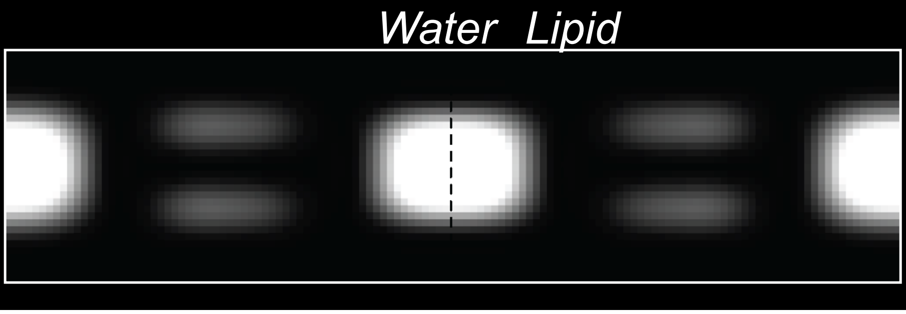
2.2 ms sublobes
8 sublobes
250 Hz spectral passband
13.2 ms length



True Null Design

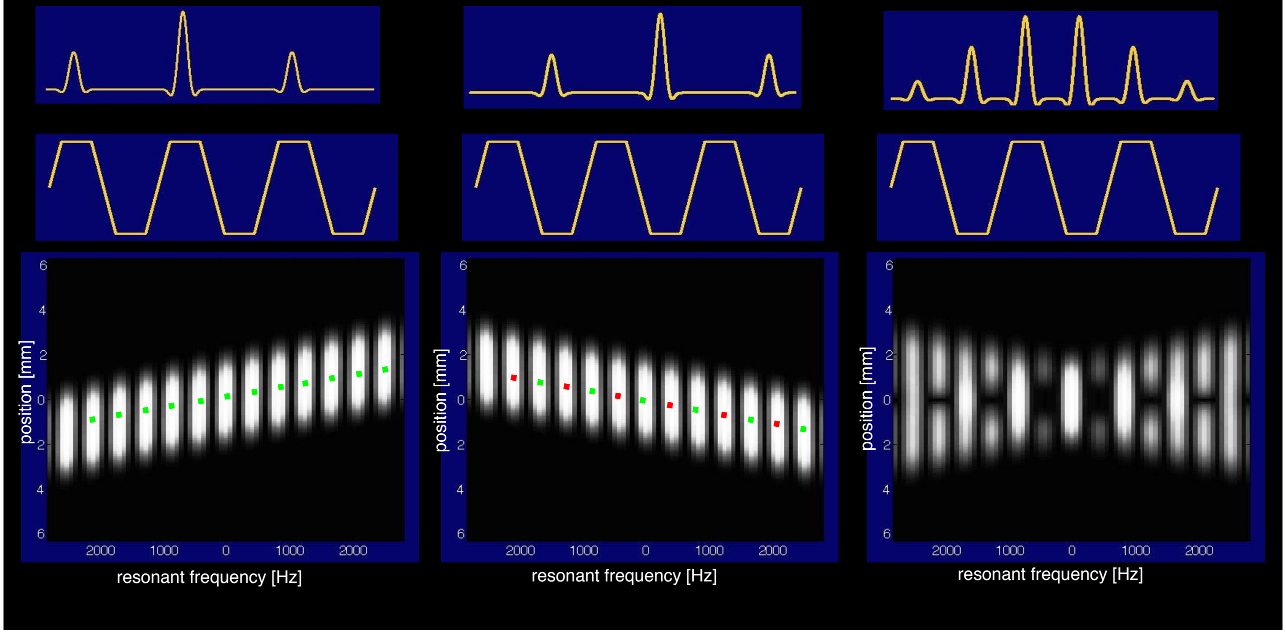


1.1 ms sublobes
16 sublobes
250 Hz spectral passband
15ms length



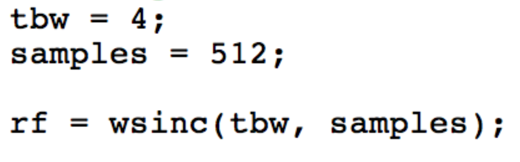
Source of Bipolar Sidelobes

- Interference between excitations from positive and negative gradient lobes



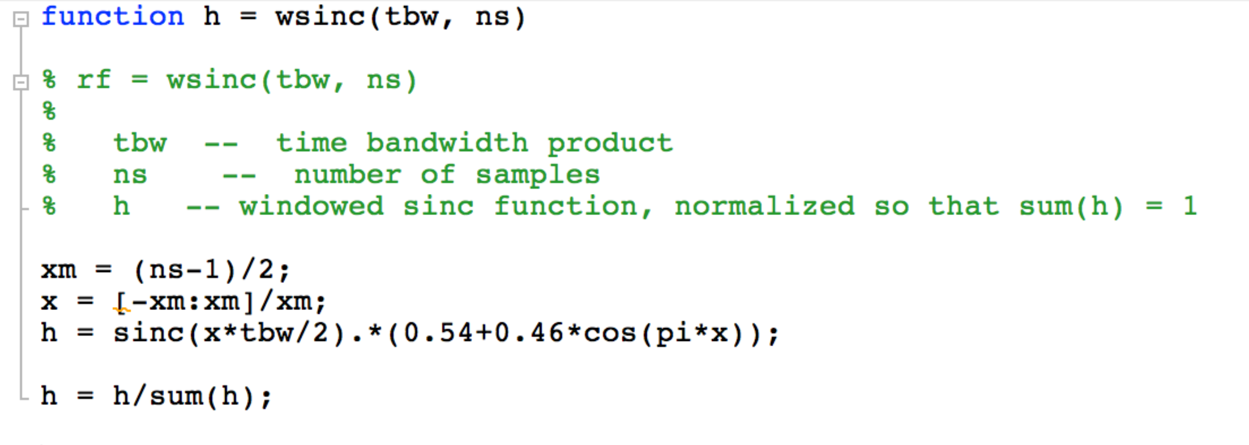
Matlab Exercise

Windowed Sinc RF Pulse



```
%% Design of Windowed Sinc RF Pulses
tbw = 4;
samples = 512;

rf = wsinc(tbw, samples);
```



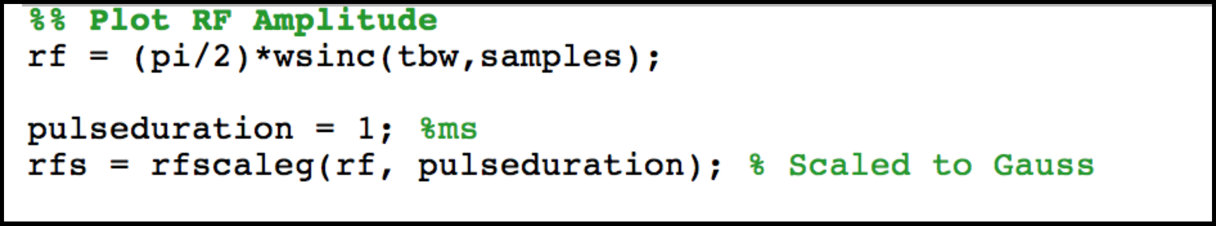
```
function h = wsinc(tbw, ns)

% rf = wsinc(tbw, ns)
%
%   tbw   --   time bandwidth product
%   ns     --   number of samples
%   h    -- windowed sinc function, normalized so that sum(h) = 1

xm = (ns-1)/2;
x = [-xm:xm]/xm;
h = sinc(x*tbw/2).*(0.54+0.46*cos(pi*x));

h = h/sum(h);
```

RF Pulse Scaling



```
%% Plot RF Amplitude
rf = (pi/2)*wsinc(tbw,samples);

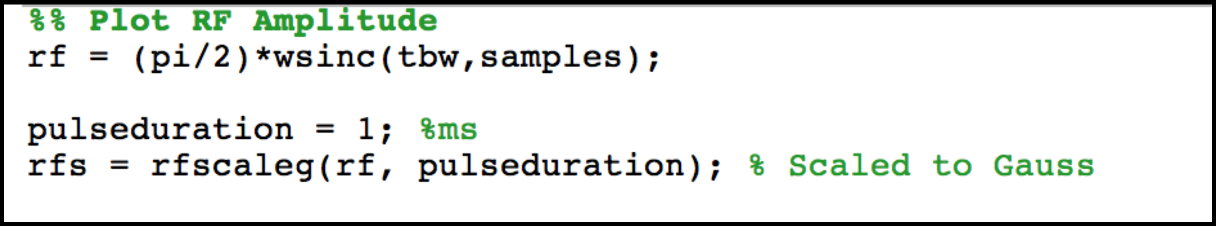
pulseduration = 1; %ms
rfs = rfscaleg(rf, pulseduration); % Scaled to Gauss
```

$$\theta = \int_0^T \gamma B_1(s) ds$$

$$\theta_i = \gamma B_1(t_i) \Delta t$$

$$B_1(t_i) = \frac{1}{\gamma \Delta t} \theta_i$$

RF Pulse Scaling



```
%% Plot RF Amplitude
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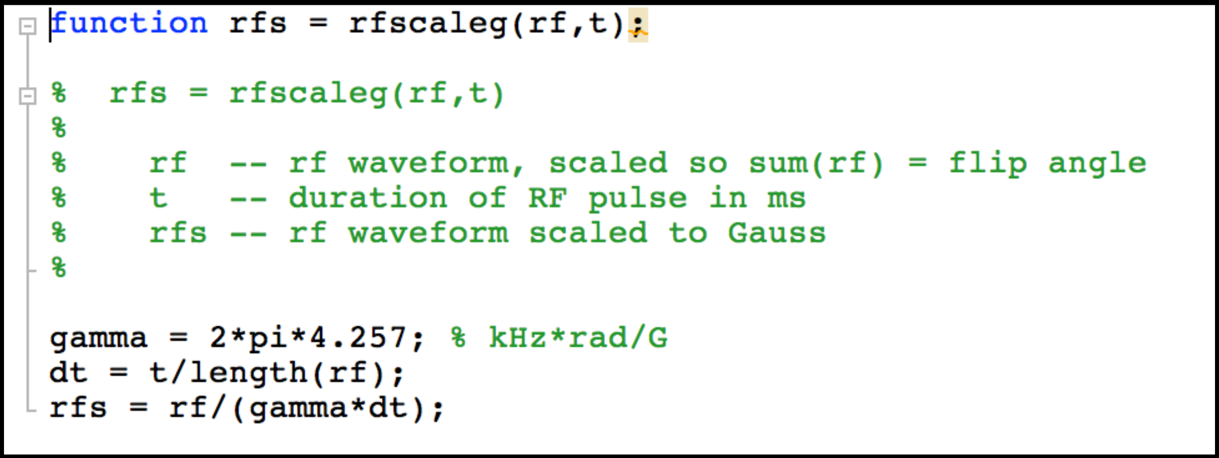
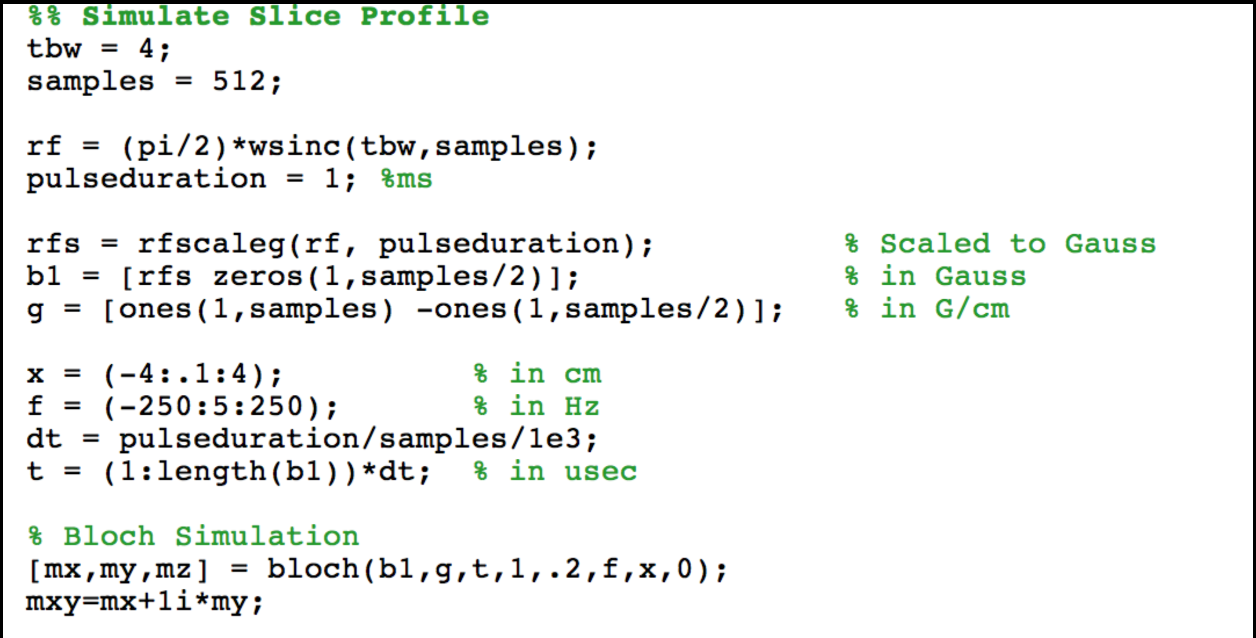


```
function rfs = rfscaleg(rf,t);

%  rfs = rfscaleg(rf,t)
%
%    rf  -- rf waveform, scaled so sum(rf) = flip angle
%    t   -- duration of RF pulse in ms
%    rfs -- rf waveform scaled to Gauss
%

gamma = 2*pi*4.257; % kHz*rad/G
dt = t/length(rf);
rfs = rf/(gamma*dt);
```

Bloch Simulation



```
%% Simulate Slice Profile
tbw = 4;
samples = 512;

rf = (pi/2)*wsinc(tbw,samples);
pulseduration = 1; %ms

rfs = rfscaleg(rf, pulseduration);             % Scaled to Gauss
b1 = [rfs zeros(1,samples/2)];                 % in Gauss
g = [ones(1,samples) -ones(1,samples/2)];      % in G/cm

x = (-4:.1:4);             % in cm
f = (-250:5:250);          % in Hz
dt = pulseduration/samples/1e3;
t = (1:length(b1))*dt;     % in usec

% Bloch Simulation
[mx,my,mz] = bloch(b1,g,t,1,.2,f,x,0);
mxy=mx+1i*my;
```

Slice Thickness

- Pulse duration = 1 ms
- TBW = 4
- G_z = 1 G/cm

$$\Delta z = \frac{BW}{\frac{\gamma}{2\pi} G_z}$$

$\gamma/2\pi$ = 4.257 kHz/G

Summary

- Adiabatic Pulse Design
- 2D Pulse Design
  - Examples:
    - EPI pulse design
    - Spatial-Spectral Pulses
- Matlab Exercise

Thanks!

- Homework 2
  - 2D EPI design
  - SPSP design
- Next time:
  - Pulse sequences

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