

RF Pulse Design

Multi-dimensional Excitation II

M229 Advanced Topics in MRI

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Class Business

- Homework 2 will be due on 4/26
- Office hours
 - Instructors: Fri 10-12 noon
 - TAs: Wed 3-5pm
 - Emails beforehand would be helpful
- Papers and Slides

Today's Topics

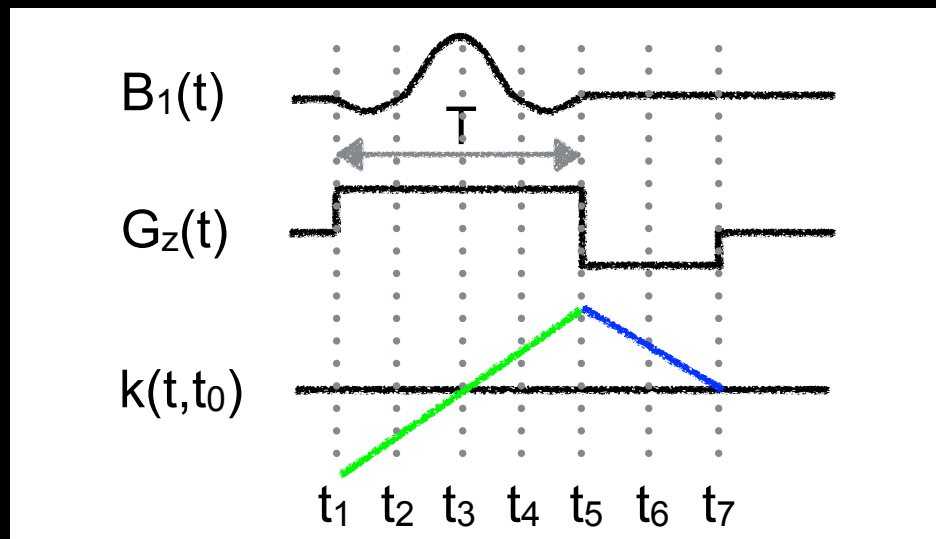
- Recap of excitation k-space
- 2D excitation pulses
 - 2D EPI pulse design
 - Spatial-spectral pulse design
- Matlab exercise

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

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

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

$$W(\vec{k}) = \frac{\gamma B_1(s)}{|k'(s,t)|} \quad k\text{-space weighting}$$

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

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

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

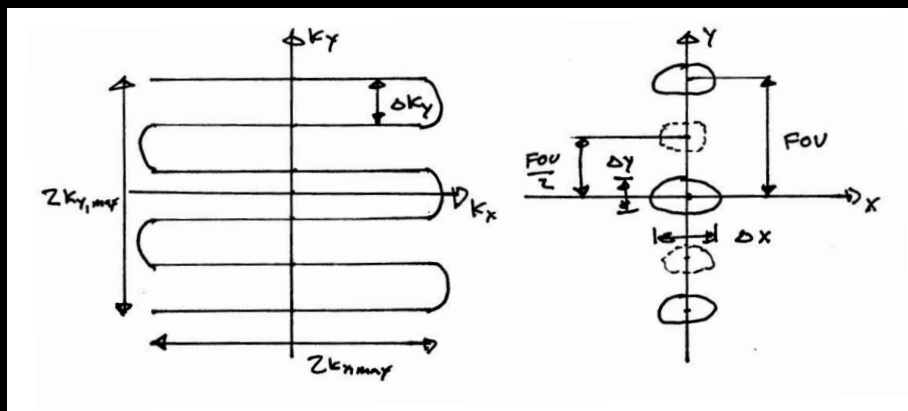
2D Spatial Pulse Design

- 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



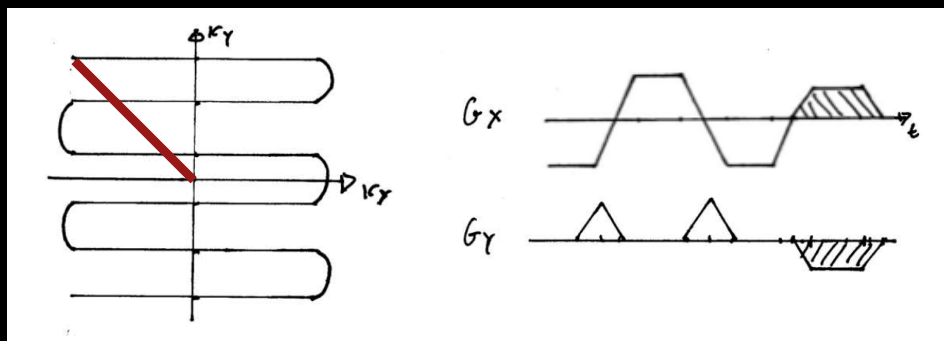
Resolution? / FOV?

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

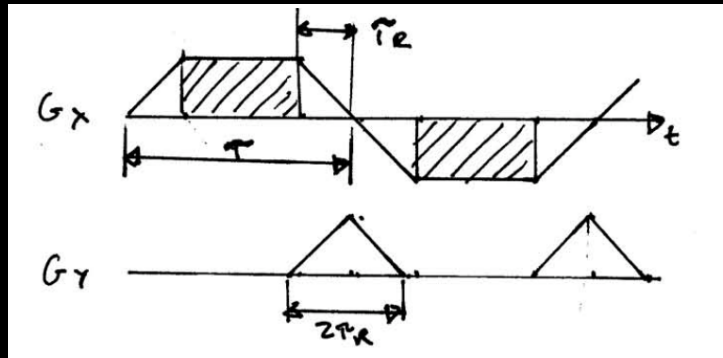
Designing EPI k-space Trajectory

- 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 ...

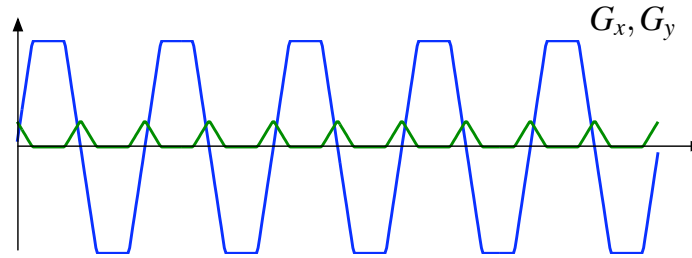
Designing EPI Gradients

- 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

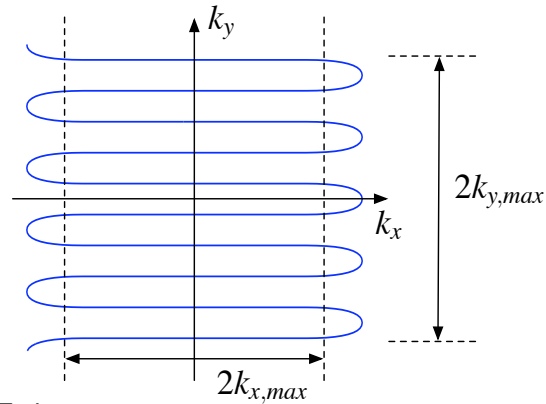
Blipped EPI

- 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

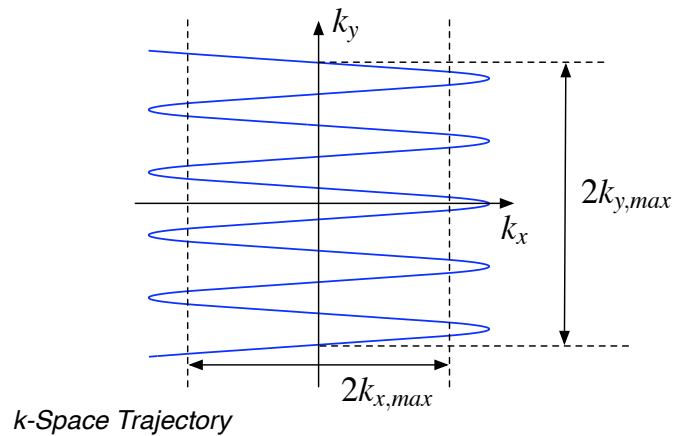
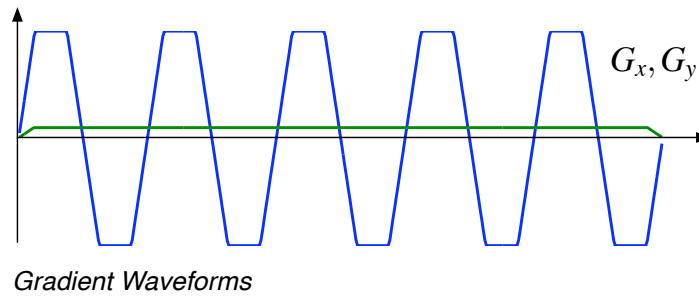


k-Space Trajectory

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

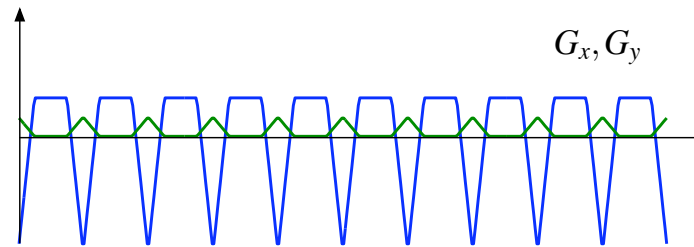
Continuous EPI



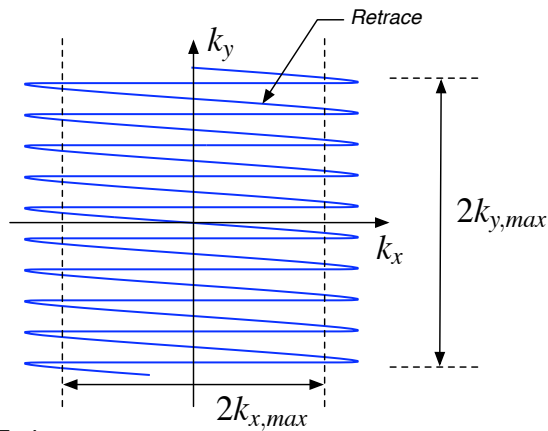
Flyback EPI

- 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 $B_1(t)$

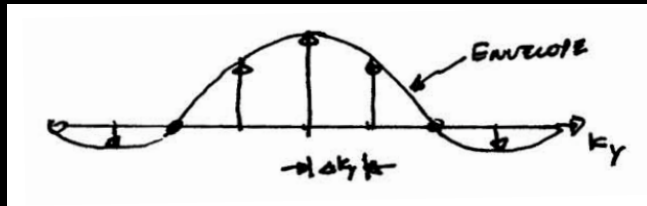
Separable, Product Design

- Assume,

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

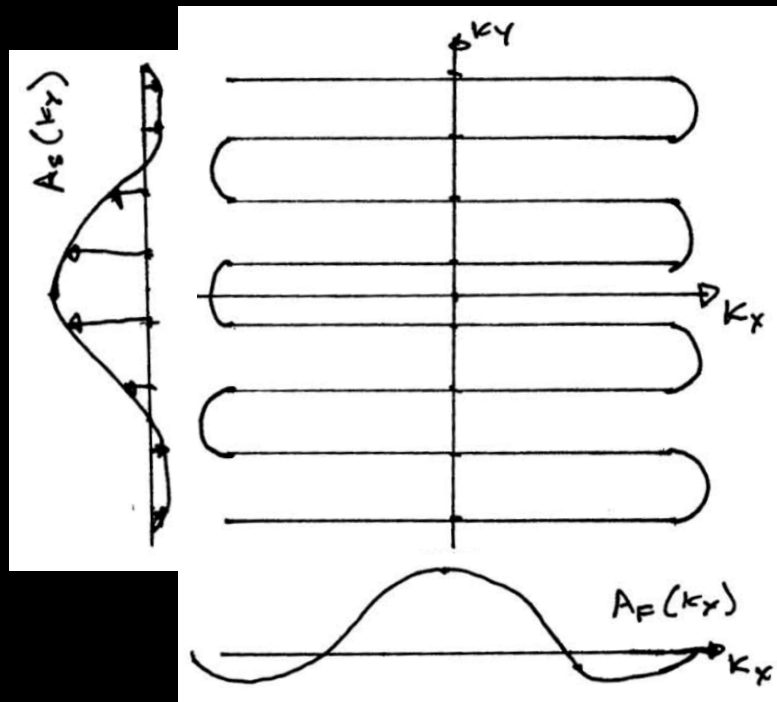
$A_S(k_y)$: weighting in the slow, blipped direction

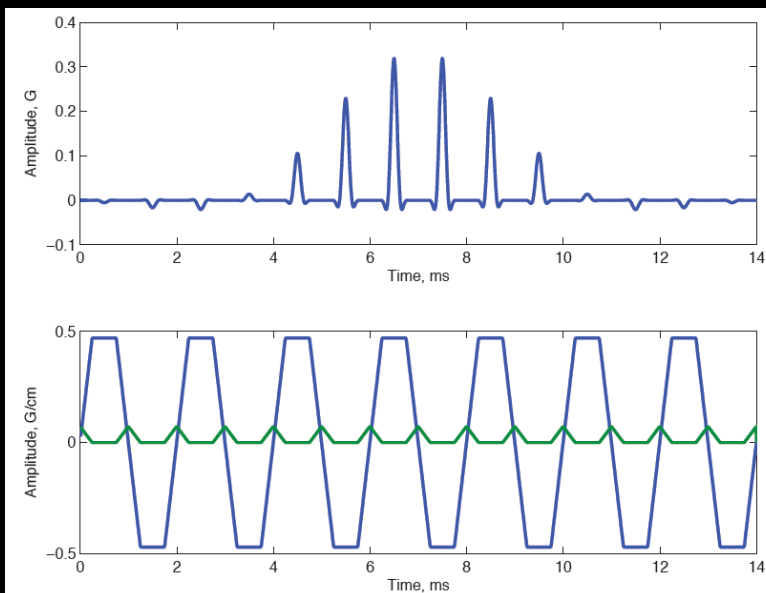
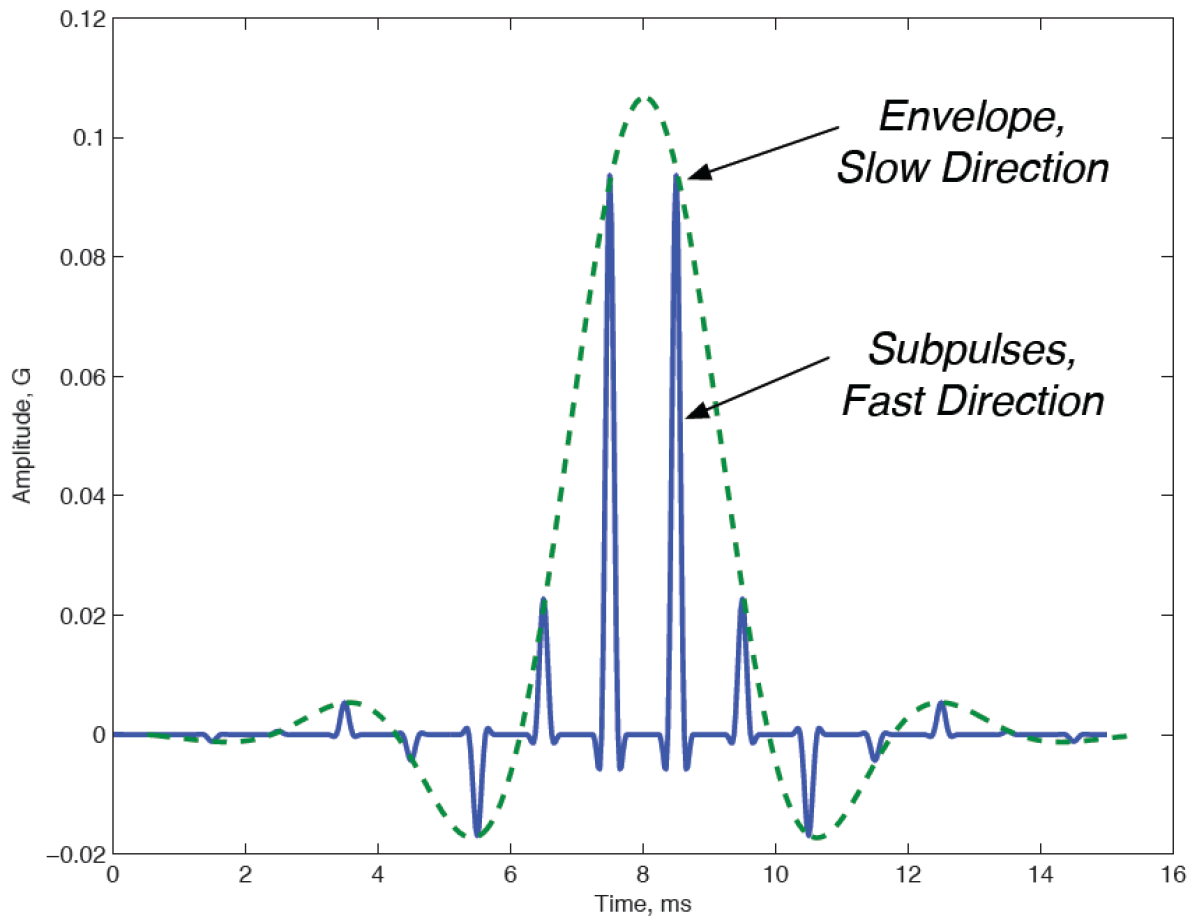
$A_F(k_x)$: weighting in the fast oscillating direction



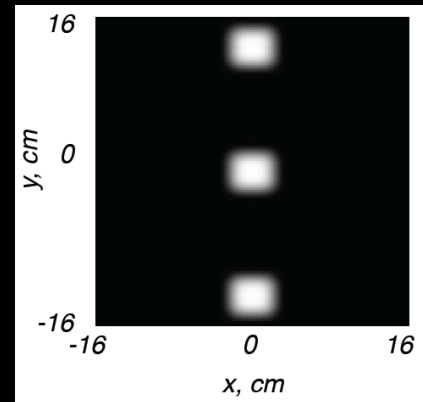
- Each impulse corresponds to a pulse in the fast direction, $A_F(k_x)$

Separable, Product Design





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

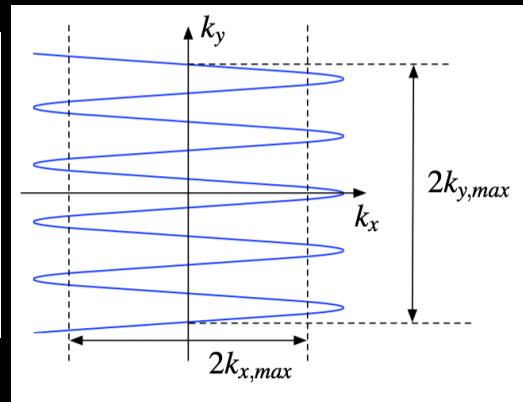
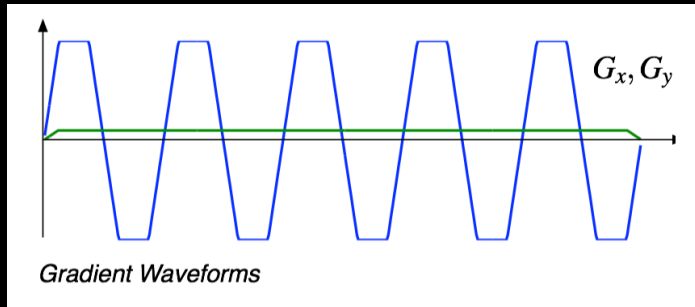


Spectral Spatial Pulse

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 \Rightarrow 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

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



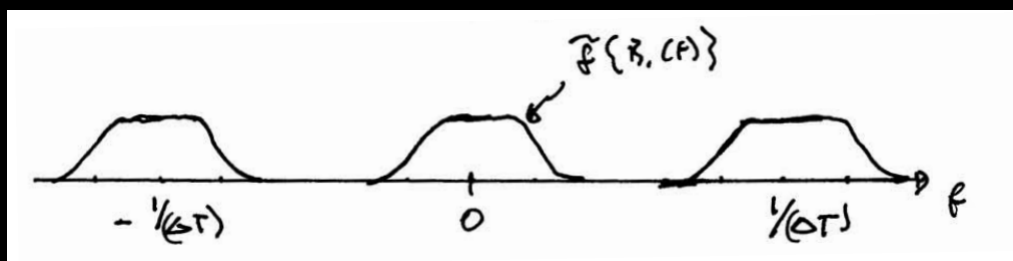
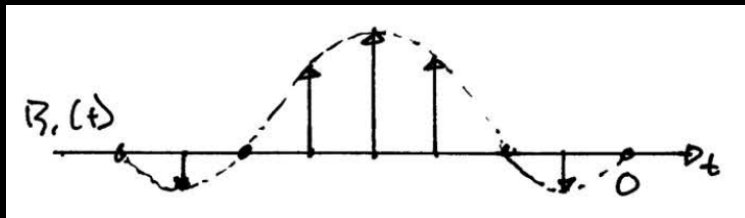
$$M_{xy}(t_0, f) = i\gamma M_0 \int_{-t_0}^0 B_1(k_f) e^{i2\pi f k_f} dk_f$$

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

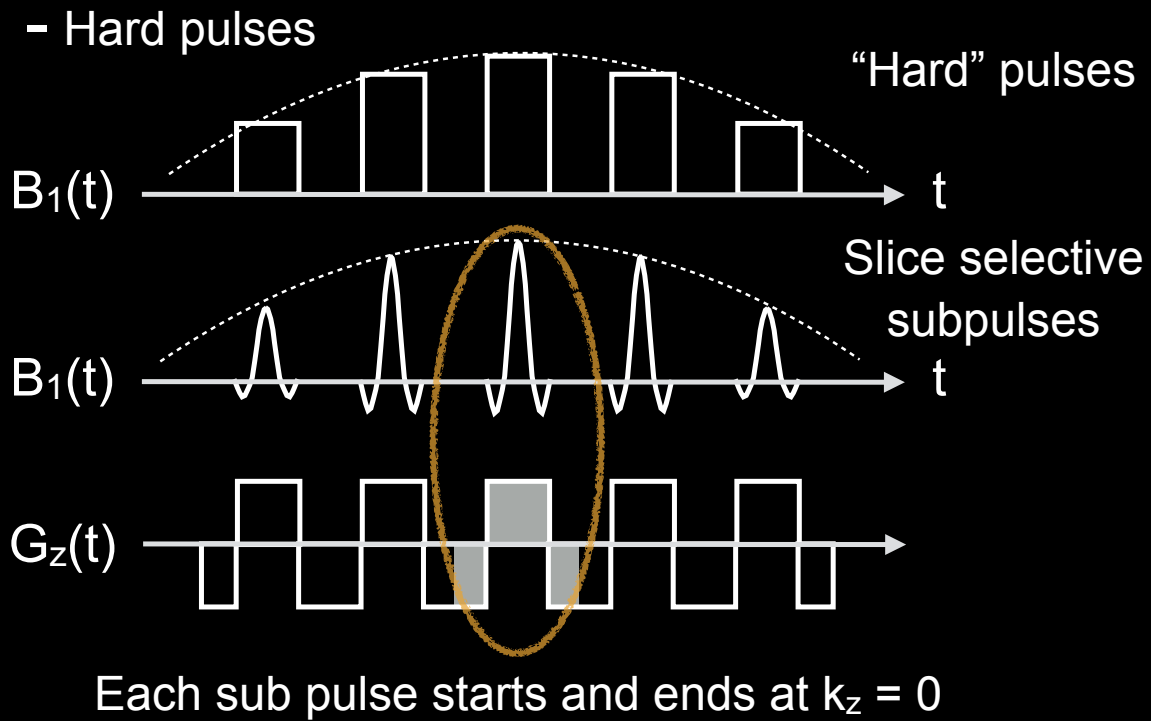
Note that k_f is time!

Spectral Pulses

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

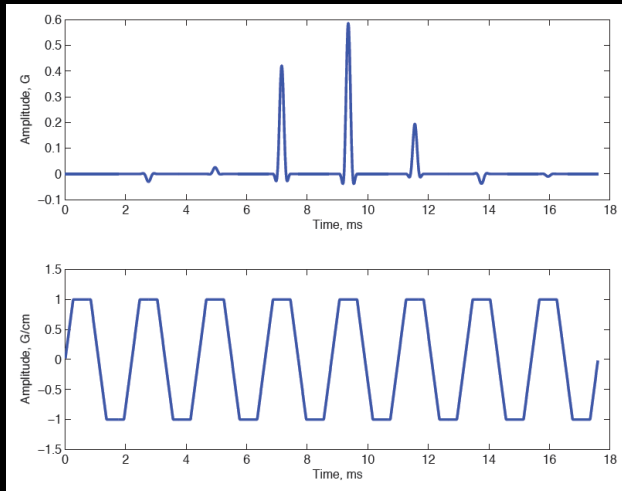


Add Spatial Selectivity to a Spectral Pulse



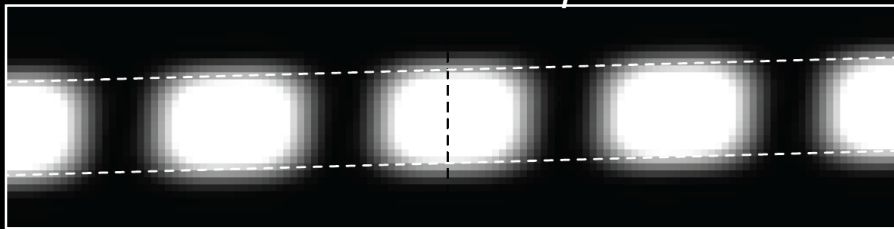
To the board ...

Flyback Design

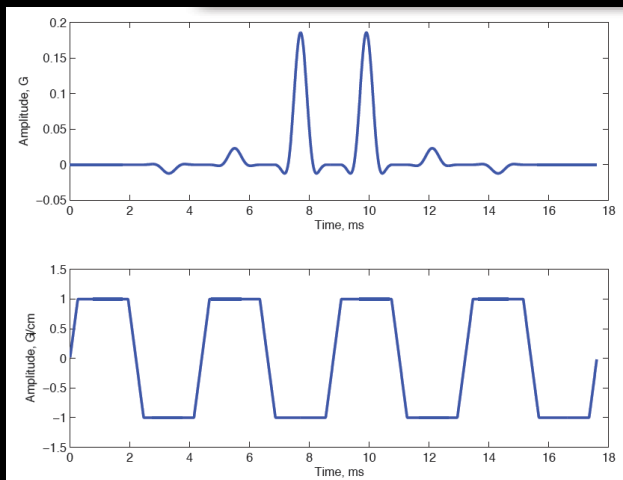


1.1 ms sublobes
8 sublobes
250 Hz spectral passband
15 ms length

Water Lipid

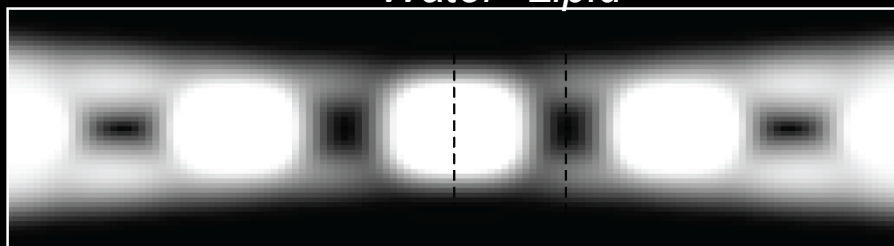


Opposed Null Design

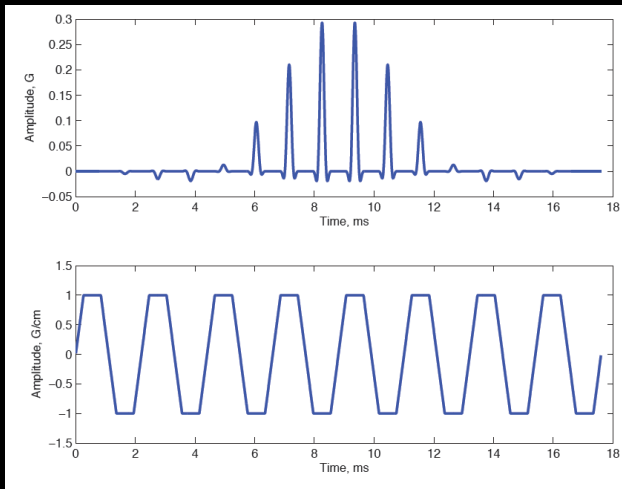


2.2 ms sublobes
8 sublobes
250 Hz spectral passband
13.2 ms length

Water Lipid

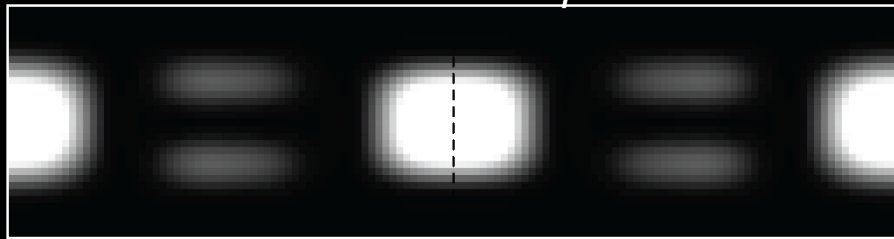


True Null Design



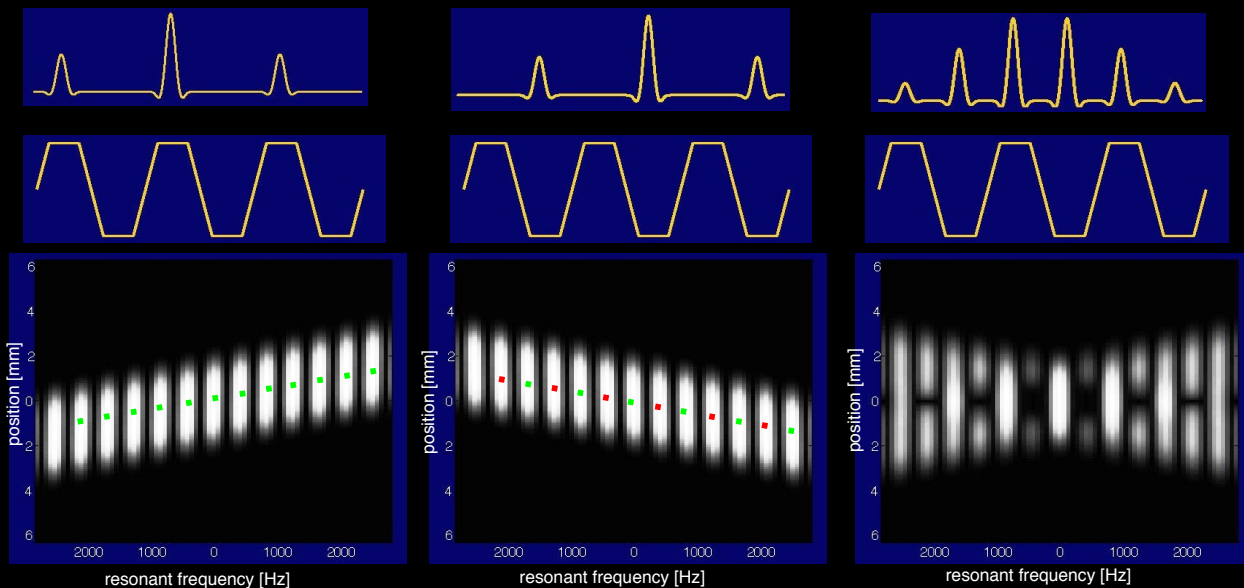
1.1 ms sublobes
16 sublobes
250 Hz spectral passband
15ms length

Water Lipid



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
```

$$\theta = \int_0^{\tau} \gamma B_1(s) ds$$

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

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

RF Pulse Scaling

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

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

```
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 = rfscalerf(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

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

$$\gamma/2\pi = 4.257 \text{ kHz/G}$$

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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