RF Pulse Design

Multi-dimensional Excitation II

Matlab Exercise

M229 Advanced Topics in MRI

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Class Business

- Homework 2 will be out today (due on 5/7)
- Jiahao Lin is TA for HW2
  - Friday 2-3pm
  - Or, send an email to him (JiahaoLin@mednet.ucla.edu)

Today’s Topics

- Excitation k-space interpretation
- 2D EPI pulse design
- MATLAB exercise

Excitation k-space Interpretation

Small Tip Approximation

$$M_{xy}(t, z) = i\gamma M_0 \int_0^t B_1(s) e^{\underline{-i\omega(z)(t-s)}} ds$$

$$\boxed{\omega(z) = \gamma G_z z \Rightarrow \omega(\vec{r}, t) = \gamma \vec{G}(t) \vec{r}}$$

$$\Downarrow$$

$$M_{xy}(t, \vec{r}) = i\gamma M_0 \int_0^t B_1(s) e^{-i\gamma \int_s^t \vec{G}(\tau) d\tau \cdot \vec{r}} ds$$

Small Tip Approximation

$$M_{xy}(t,\vec{r}) = i\gamma M_0 \int_0^t B_1(s) e^{\underline{-i\gamma \int_s^t \vec{G}(\tau)d\tau\cdot\vec{r}}} ds$$

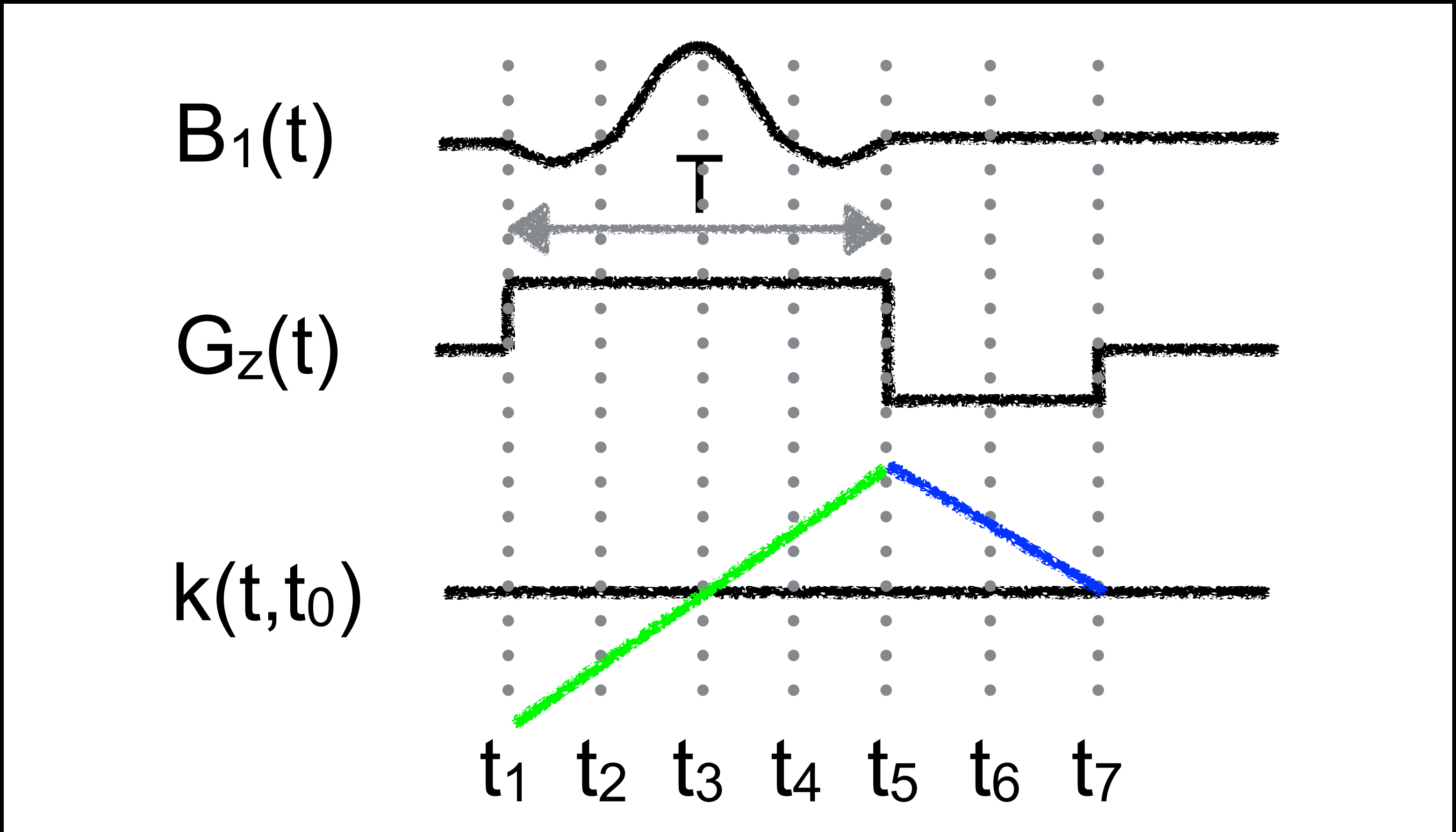
Let us define: $\boxed{\vec{k}(s,t) = -\frac{\gamma}{2\pi}\int_s^t \vec{G}(\tau)d\tau}$

$$\Downarrow$$

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

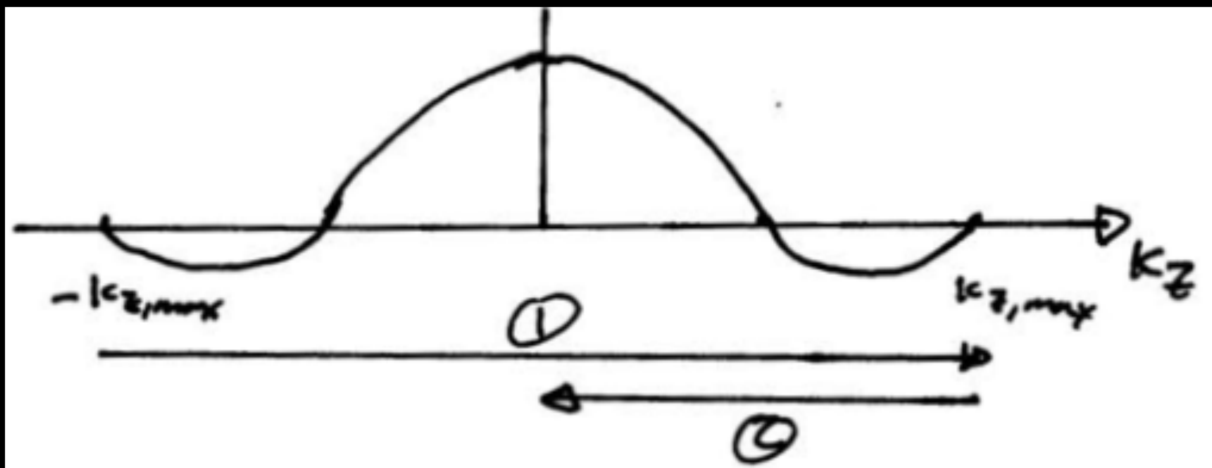
One-Dimensional Example

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



Consider the value of **k** at s = t_1, t_2, … t_7

One-Dimensional Example



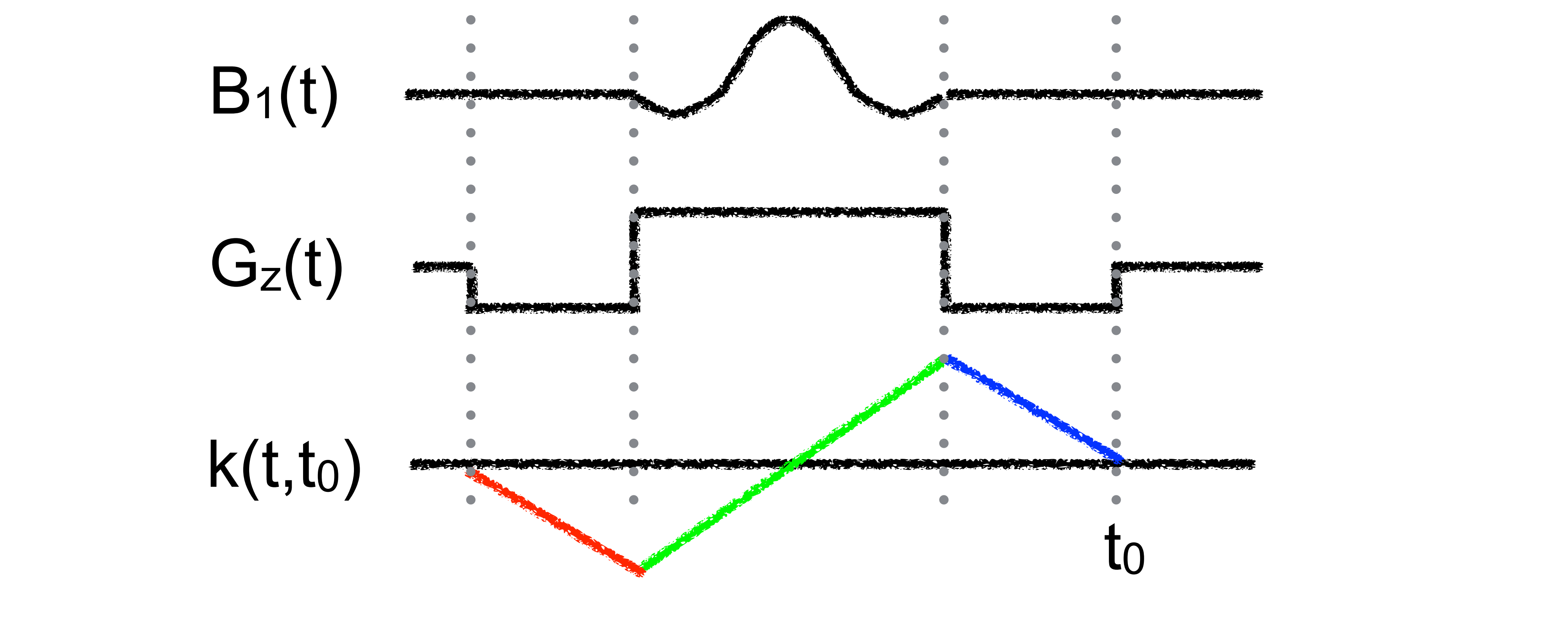
$$k_{z,max} = \frac{T}{2}\frac{\gamma}{2\pi}G_z$$

- This gives magnetization at $t = t_0$, the end of the pulse
- Looks like you scan across k-space, then return to origin

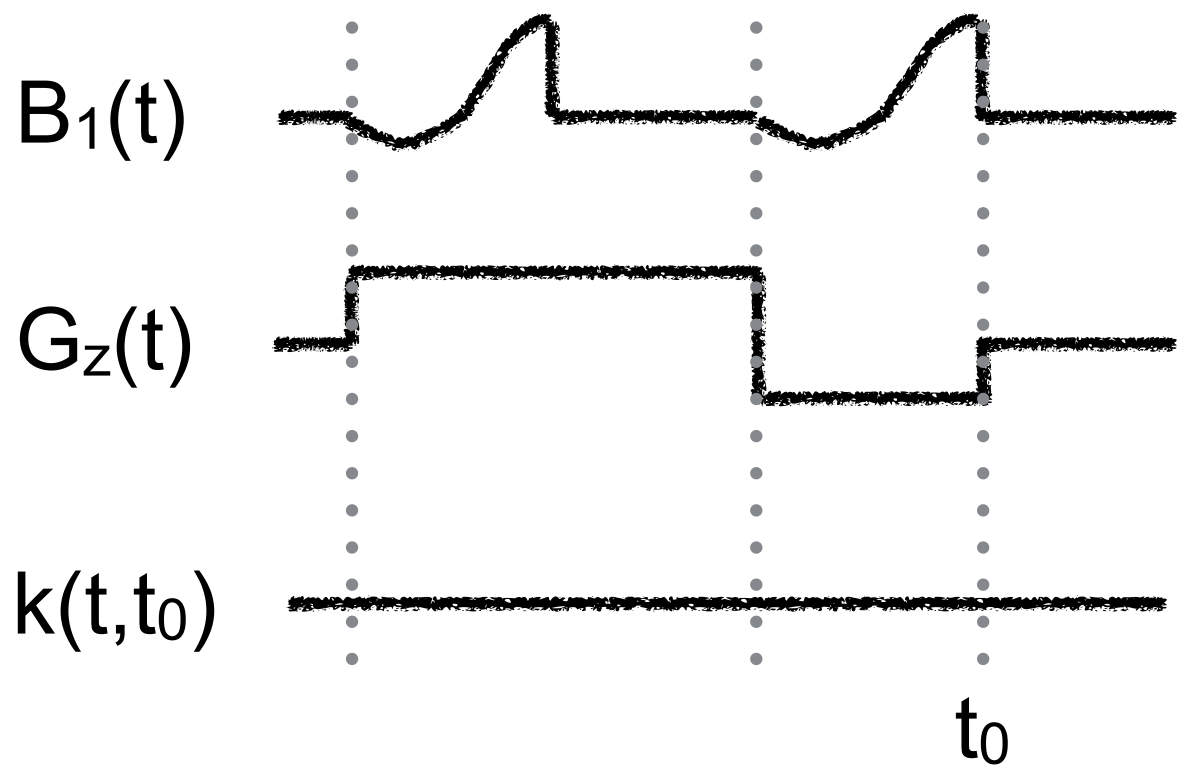
Evolution of Magnetization During Pulse

- RF pulse goes in at DC ($k_z = 0$)
- Gradients move previously applied weighting around
- Think of the RF as “writing” an analog waveform in k-space
- Same idea applies to reception

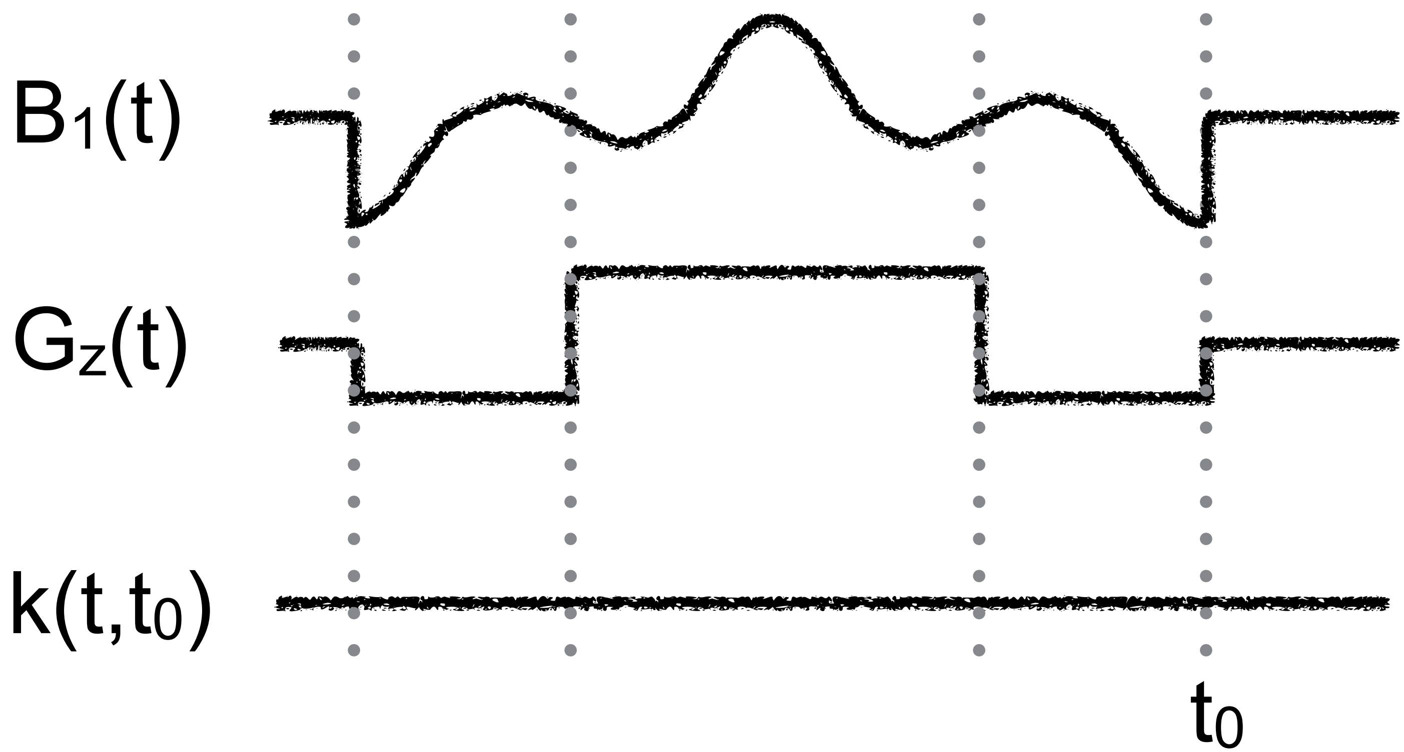
Other 1D Examples



Other 1D Examples



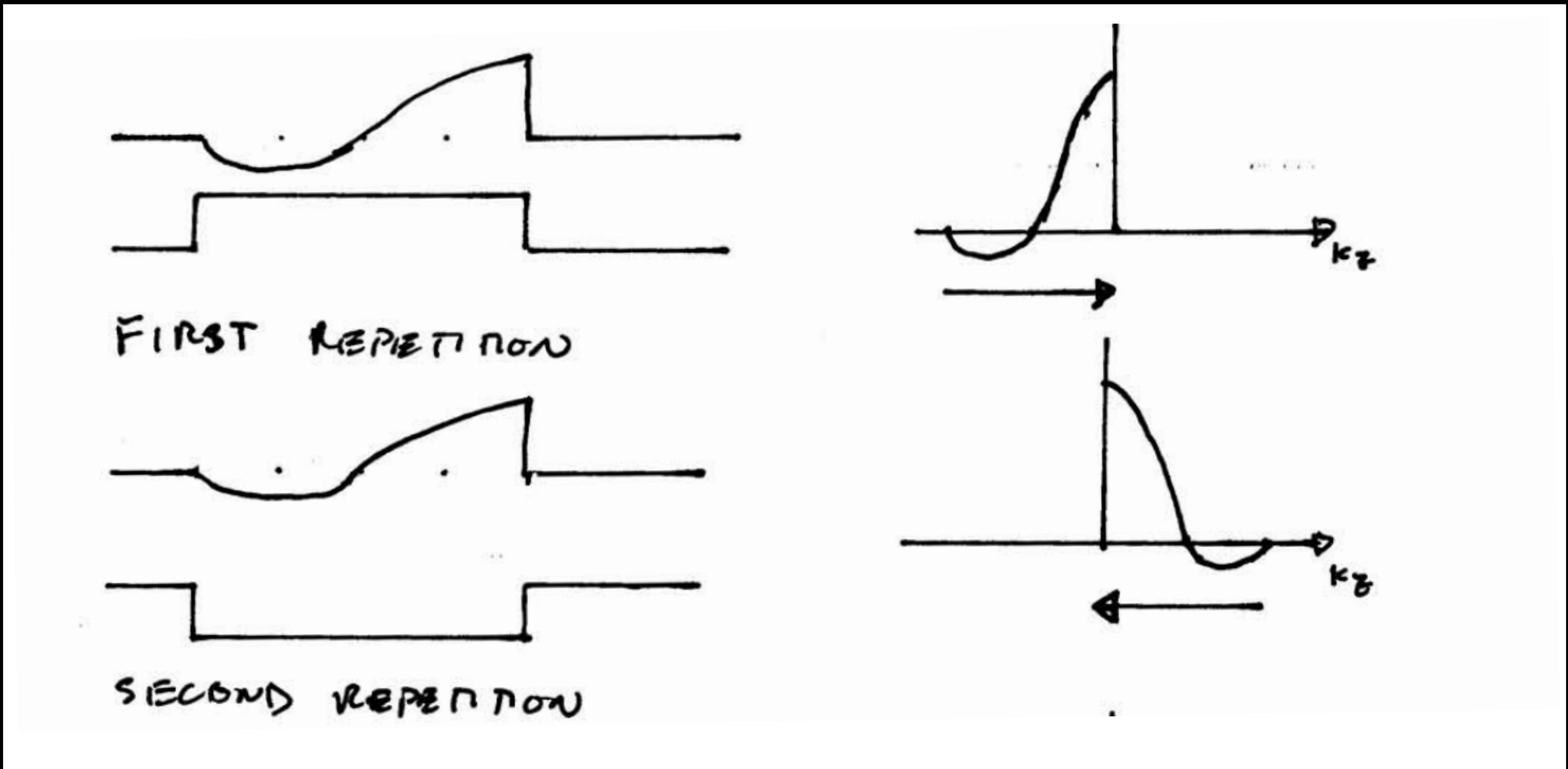
Other 1D Examples



Multiple Excitations

- Most acquisition methods require several repetitions to make an image
  - e.g., 128 phase encodes
- Data is combined to reconstruct an image
- Same idea works for excitation!

Simple 1D Example



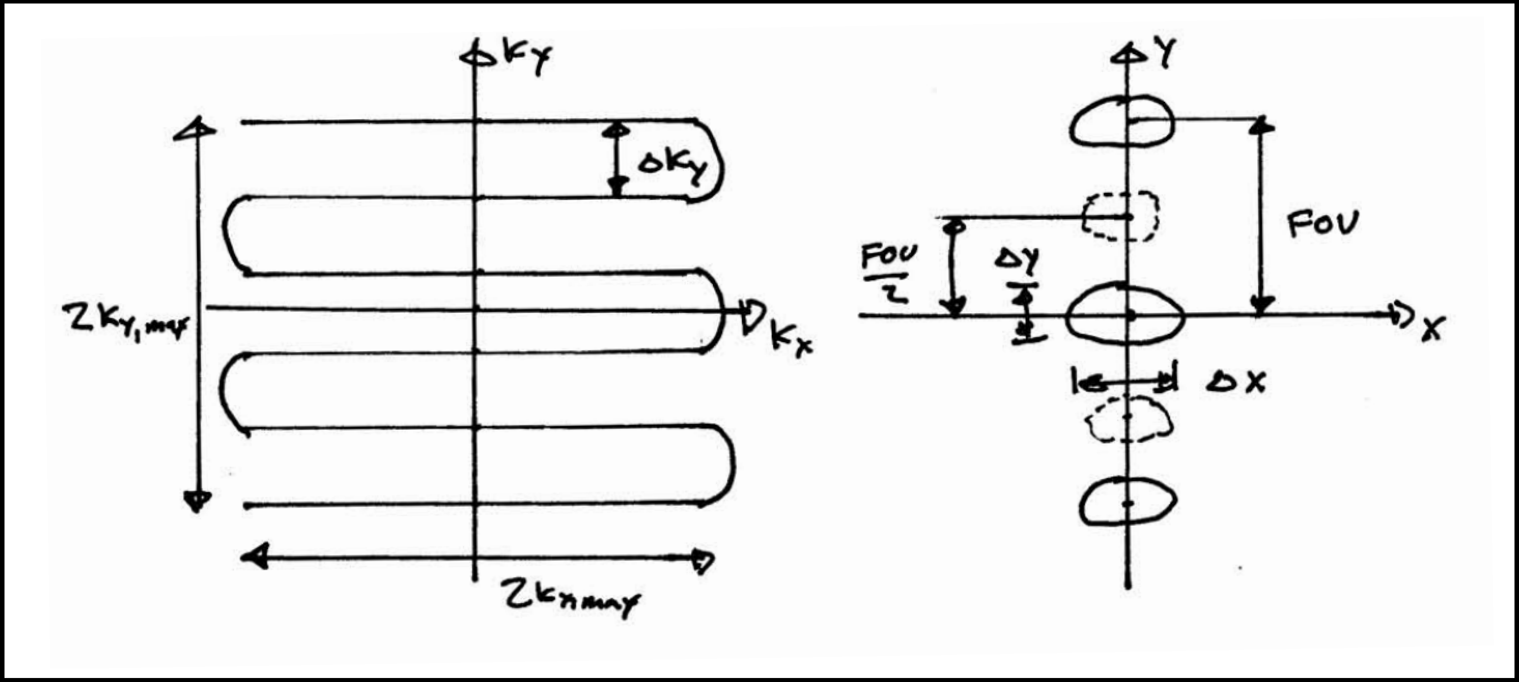
Sum the data from two acquisitions

Same profile as slice selective pulse, but zero echo time

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

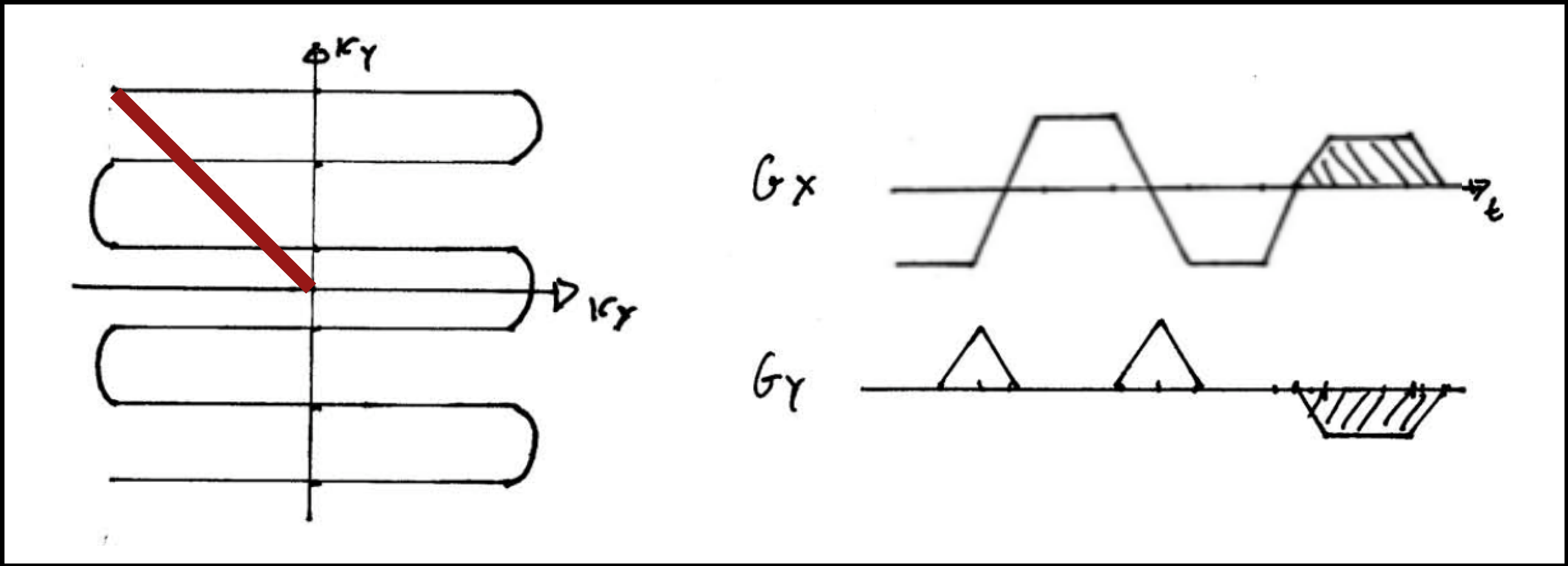
- Resolution: $\Delta x = \frac{TBW}{2k_{x,max}}$ $\Delta y = \frac{TBW}{2k_{y,max}}$
- FOV = $1/\Delta k_y$

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

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

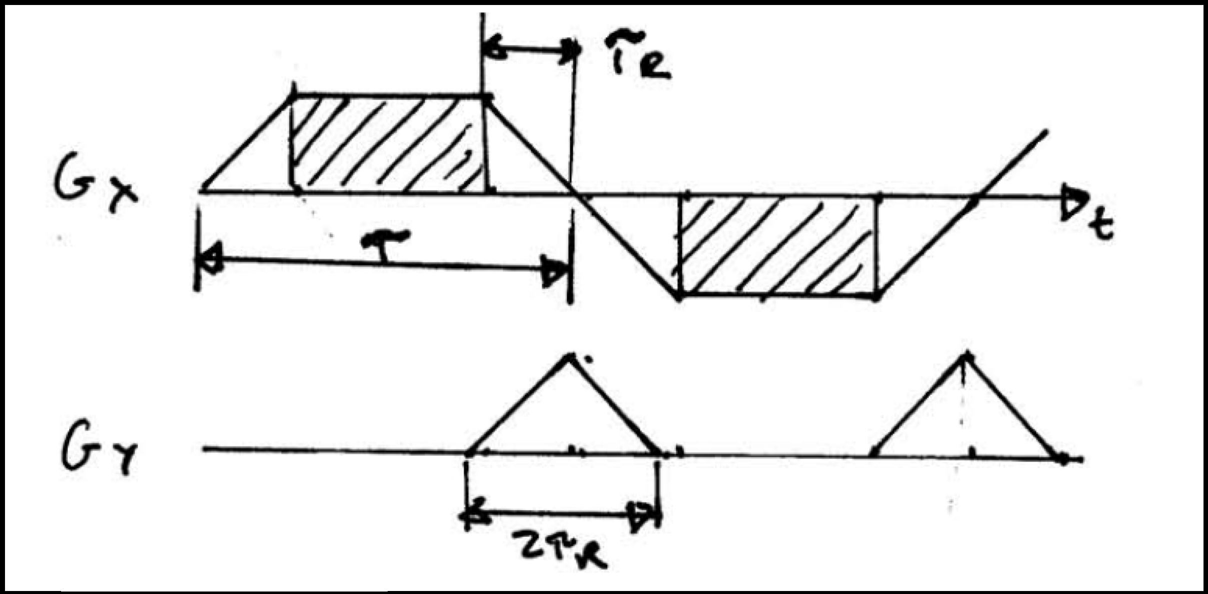
Designing EPI k-space Trajectory

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



Designing EPI Gradients

- Designing <u>readout lobes</u> and <u>blips</u>
  - Flat-top only design



  - RF only played during flat part (simpler)

To the board ...

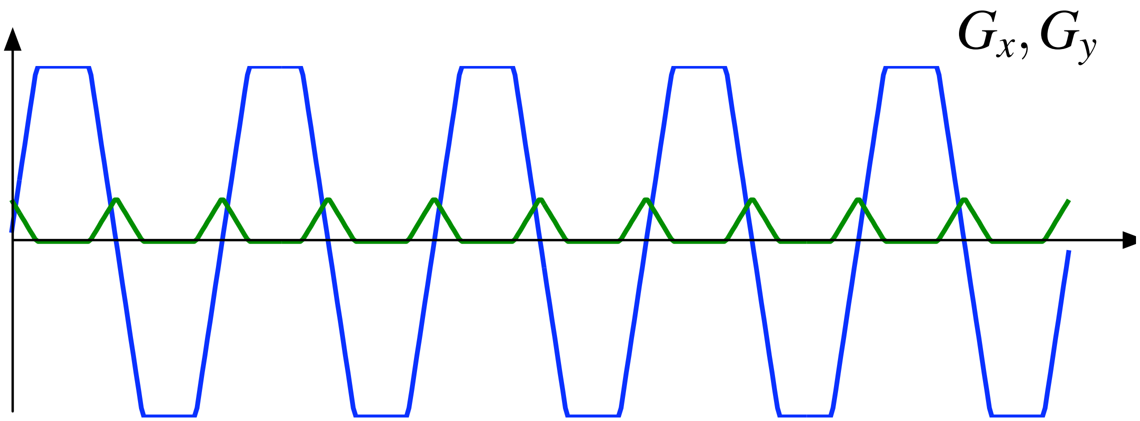
Designing EPI Gradients

- 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

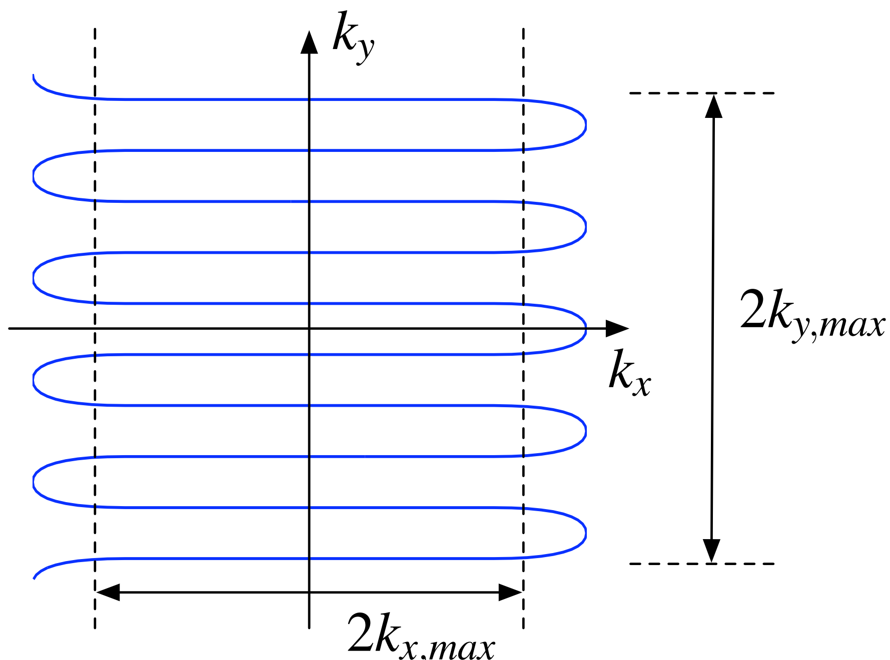
Blipped EPI

- 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

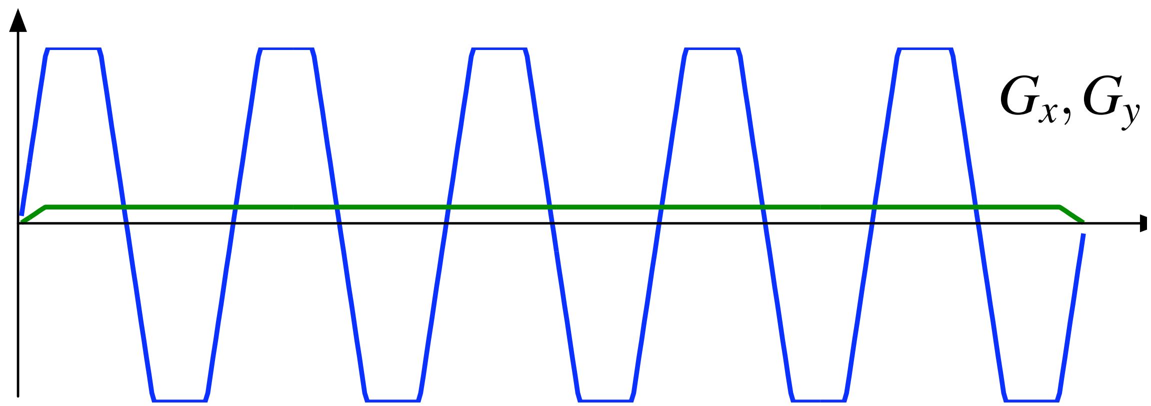


k-Space Trajectory

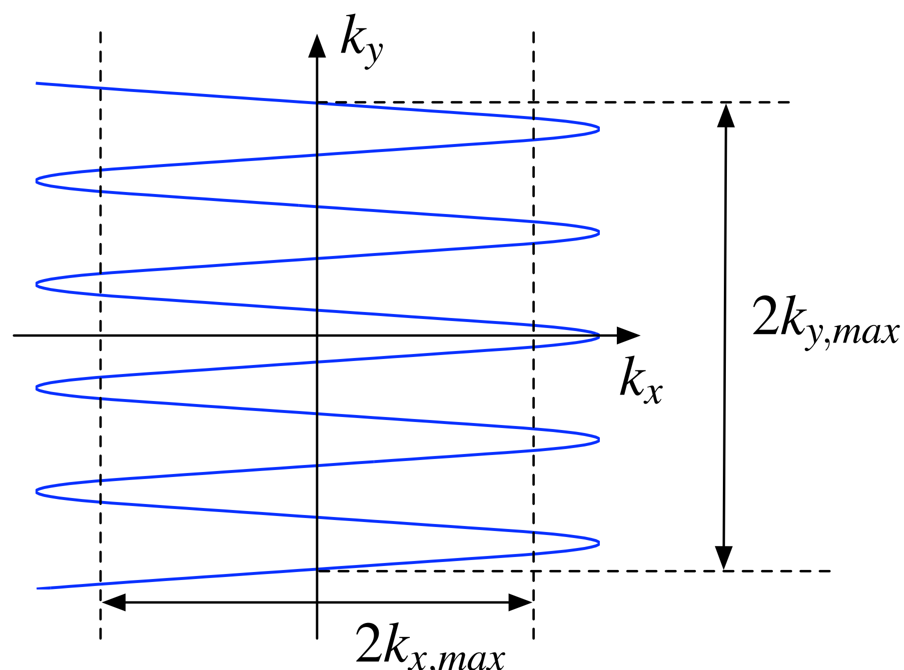
Continuous EPI

- 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

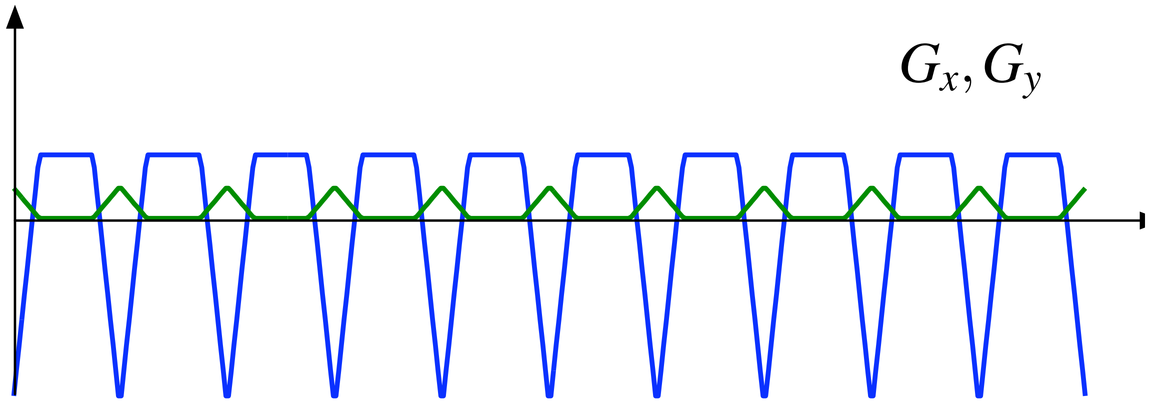


k-Space Trajectory

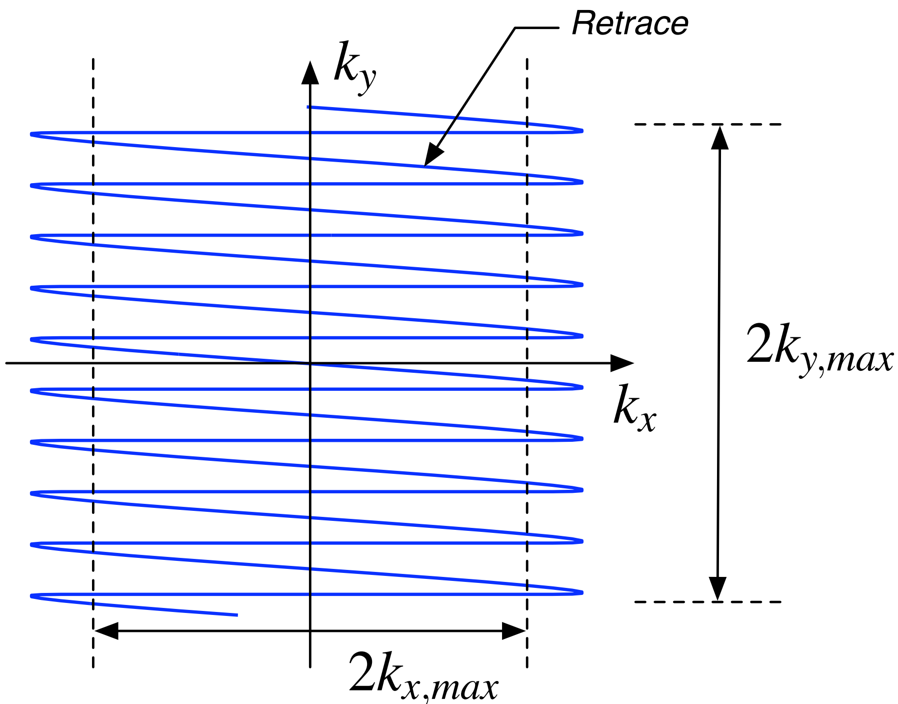
Flyback EPI

- 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

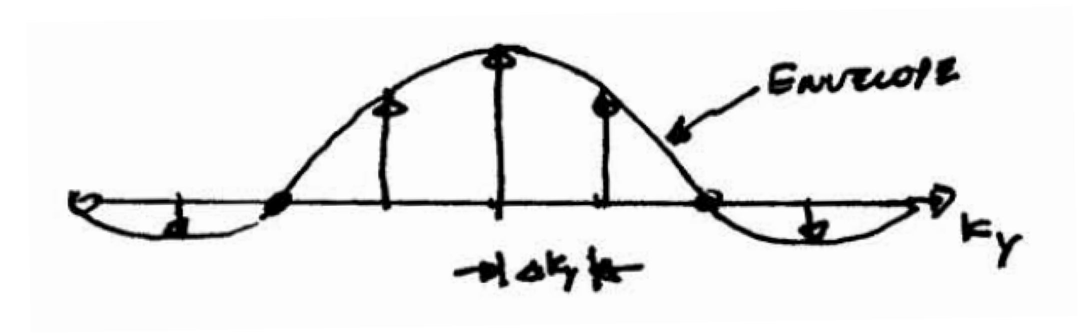
- Two major options
  - General approach, same as 2D spiral pulses
  - Seperable, product design (easier)
- General approach
  - Choose EPI k-space trajectory
  - Design gradient waveforms
  - Design *W(k)*, k-space weighting
  - Design $B_1(t)$

Separable, Product Design

- Assume,

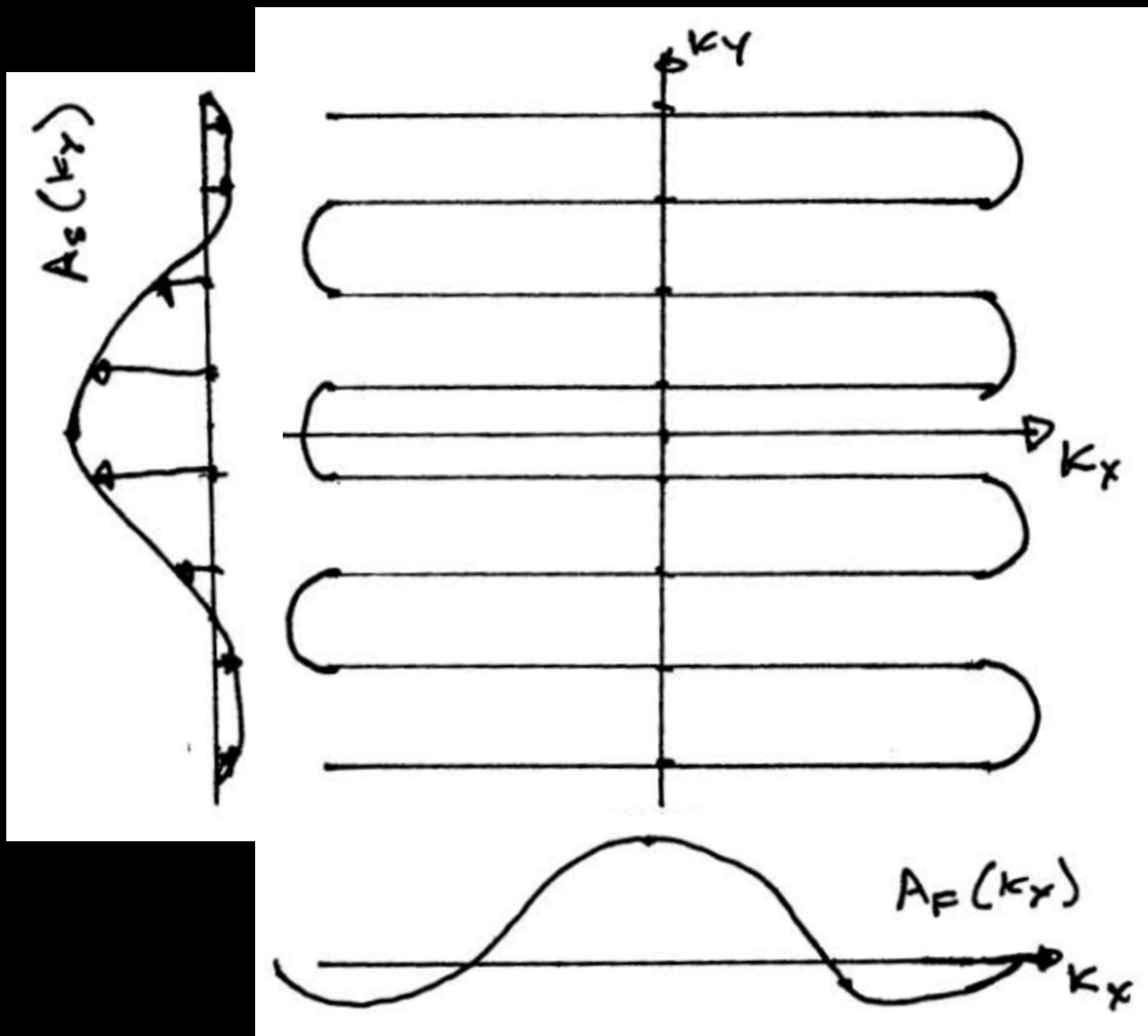
$$W(k_x, k_y) = A_F(k_x) \cdot A_S(k_y)$$

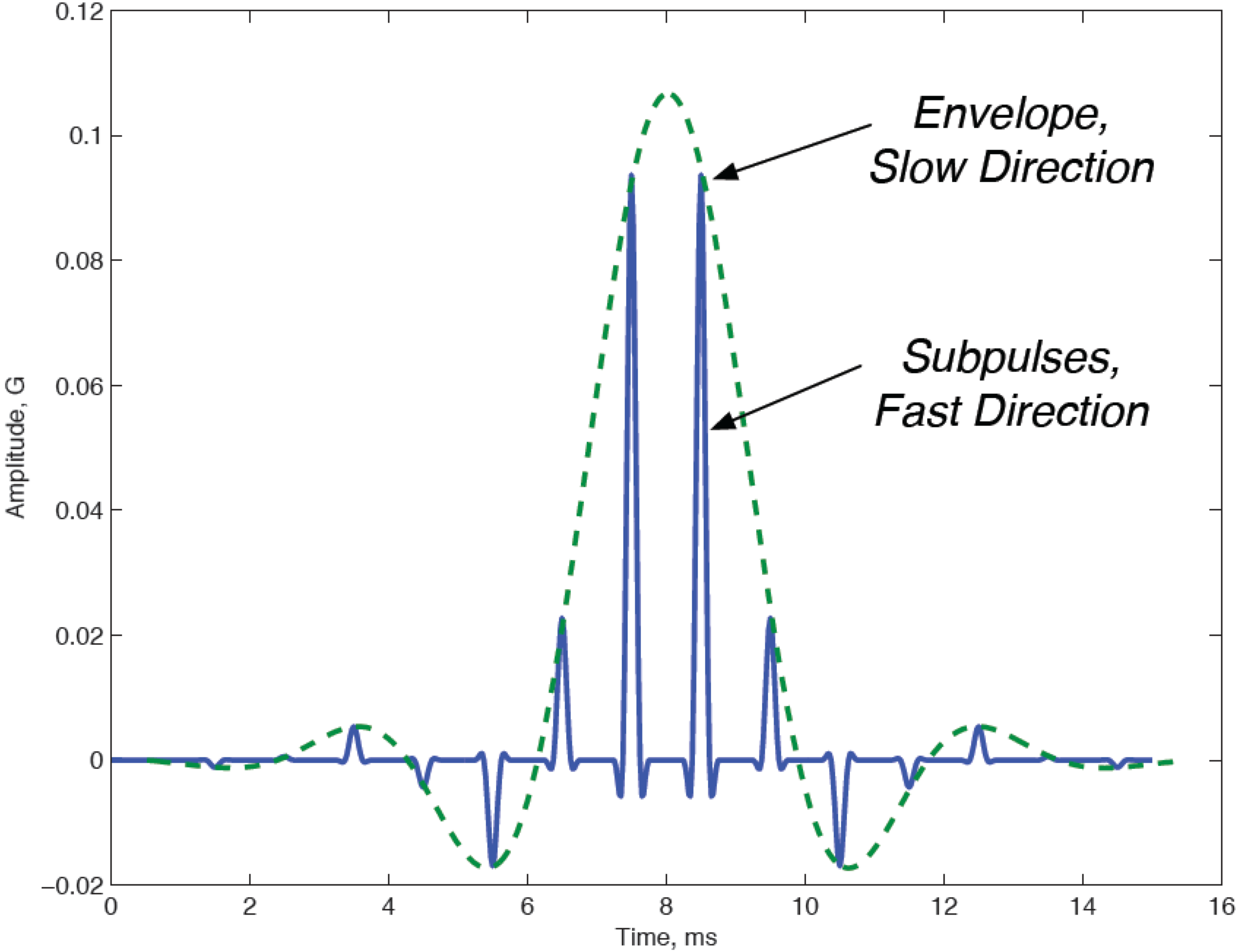
$A_S(k_y)$: weighting in the slow, blipped direction
$A_F(k_x)$: weighting in the fast oscillating direction



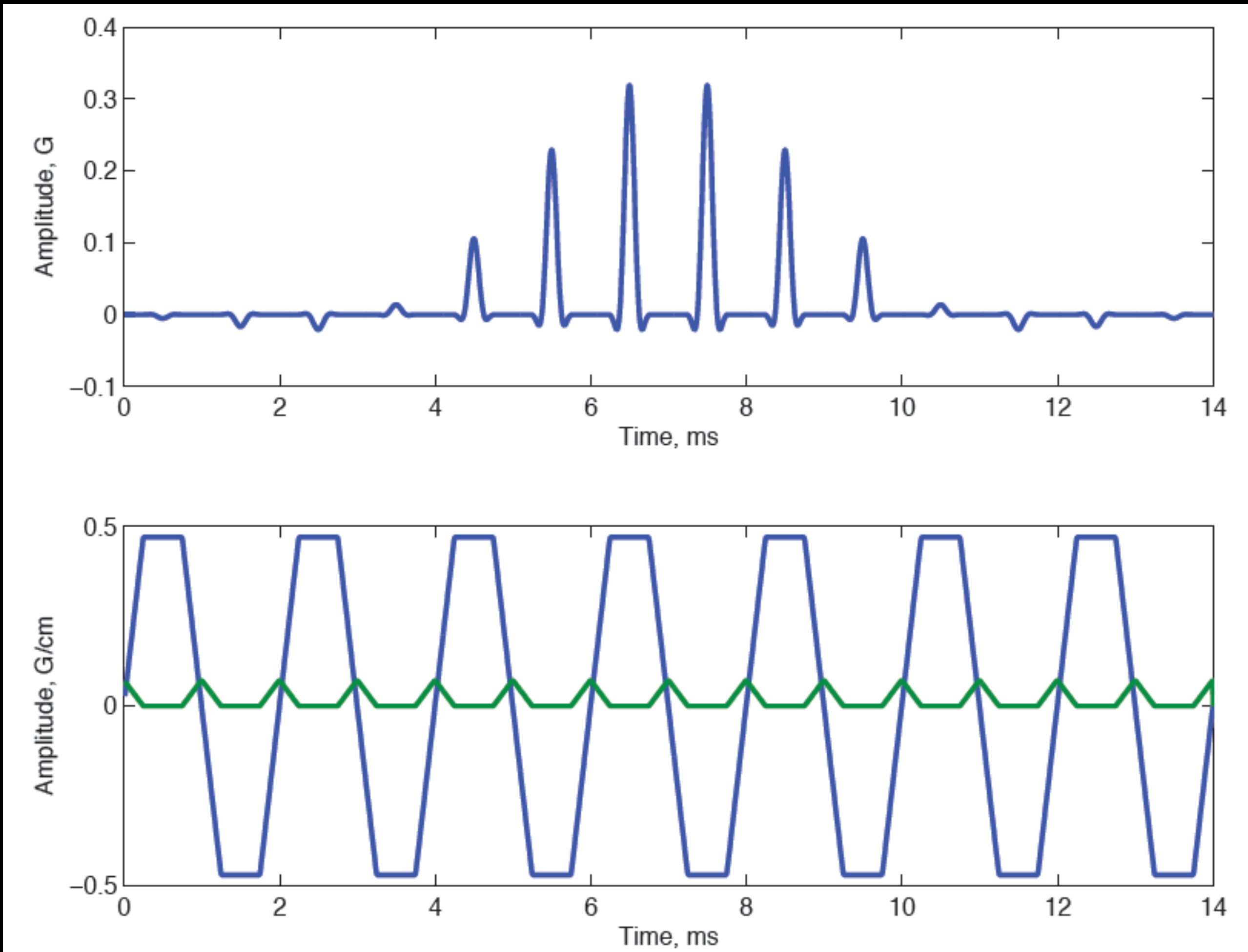
- Each impulse corresponds to a pulse in the fast direction, $A_F(k_x)$

Separable, Product Design

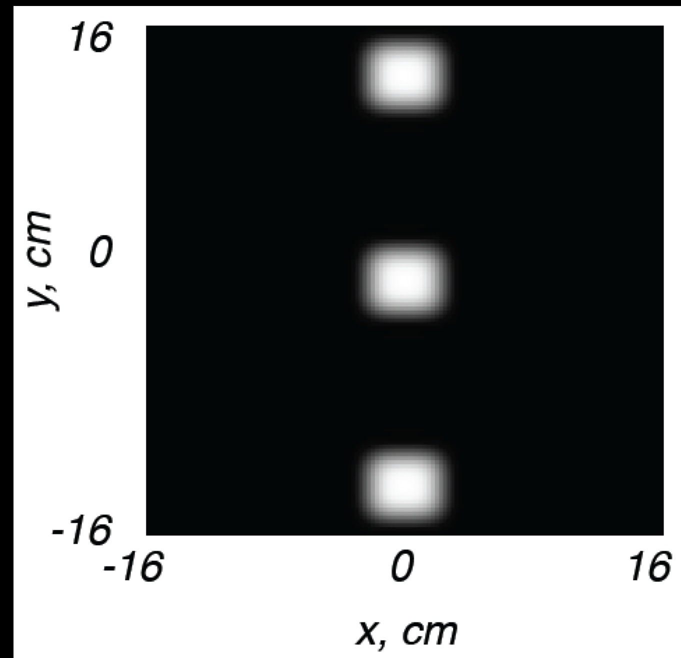




Envelope,
Slow Direction
Subpulses,
Fast Direction
Amplitude, G
Time, ms
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
0
2
4
6
8
10
12
14
16



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



Matlab Exercise

Bloch Simulator

- http://mrsrl.stanford.edu/~brian/blochsim/

```
[mx,my,mz] = bloch(b1,gr,tp,t1,t2,df,dp,mode,mx,my,mz)

Bloch simulation of rotations due to B1, gradient and
off-resonance, including relaxation effects.  At each time
point, the rotation matrix and decay matrix are calculated.
Simulation can simulate the steady-state if the sequence
is applied repeatedly, or the magnetization starting at m0.

INPUT:
        b1 = (Mx1) RF pulse in G.  Can be complex.
        gr = (Mx1,2,or 3) 1,2 or 3-dimensional gradient in G/cm.
        tp = (Mx1) time duration of each b1 and gr point, in seconds,
                        or 1x1 time step if constant for all points
                        or monotonically INCREASING endtime of each
                        interval..
        t1 = T1 relaxation time in seconds.
        t2 = T2 relaxation time in seconds.
        df = (Nx1) Array of off-resonance frequencies (Hz)
        dp = (Px1,2,or 3) Array of spatial positions (cm).
                Width should match width of gr.
        mode= Bitmask mode:
                Bit 0:  0-Simulate from start or M0, 1-Steady State
                Bit 1:  1-Record m at time points.  0-just end time.
```

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
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 = 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;
```

Thanks!

- Next time:
  - Project Discussion
- Homework 2
  - Adiabatic pulse design
  - 2D EPI design

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