Localized MR Spectroscopy

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Localized MR Spectroscopy

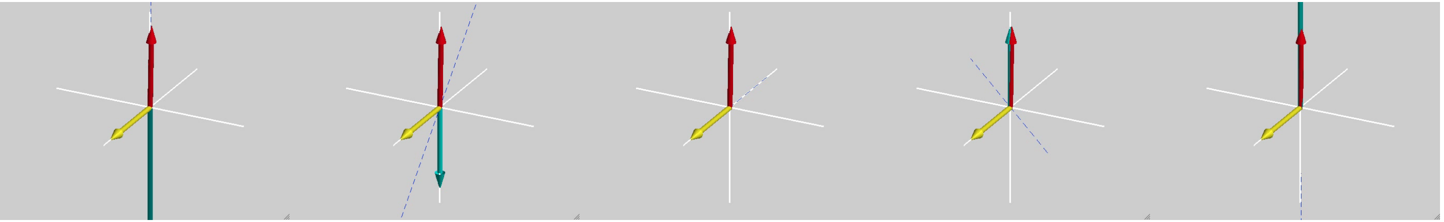
- Specialized methods required for in vivo MRS
- Considerations:
  - Spatial localization: Where is signal coming from?
  - Spectral excitation: Excite resonances of interest
  - Fat and Water Suppression: Usually these are nuisance signals

Outline

- RF pulse refresher
- Spectral Selection
- Spatial Localization
  - Three pulse localization
  - Spatial saturation
- Fast Spectroscopic Imaging
- Spectral-spatial RF pulses

Off-resonance Excitation

$\Delta B \ll -B_1$ $\Delta B \approx -B_1$ $\Delta B = 0$ $\Delta B \approx B_1$ $\Delta B \gg B_1$

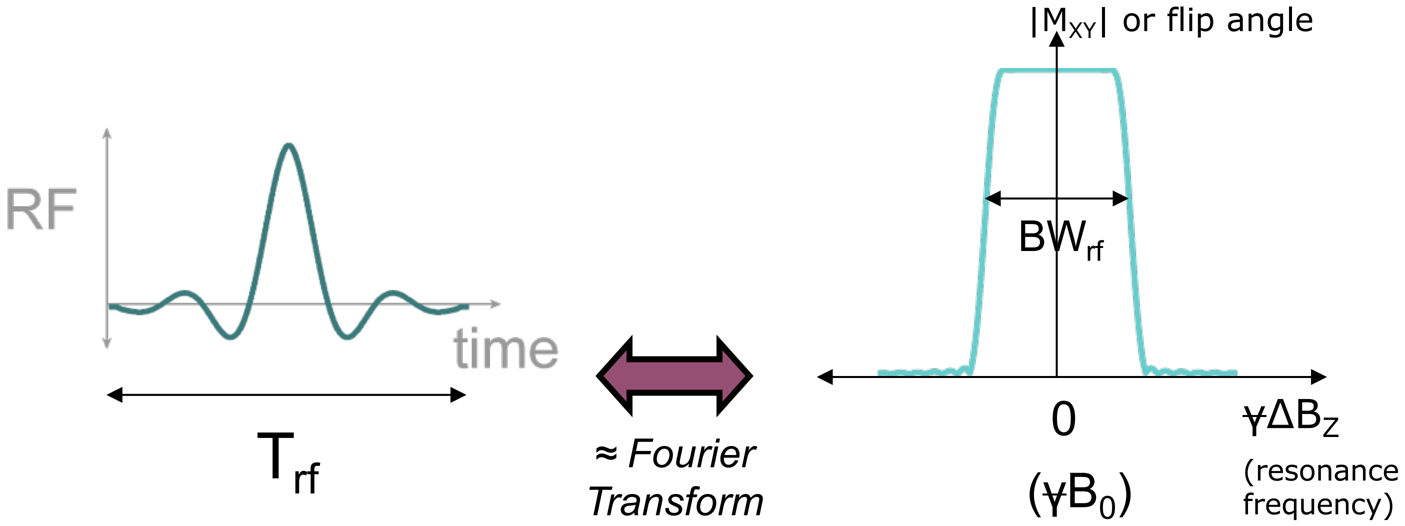


ΔB – green: Change in magnetic field, due to chemical shift, B0 inhomogeneities, and magnetic field gradients
B_1 – yellow: RF field
M – red: Net Magnetization

Every RF pulse is spectrally-selective

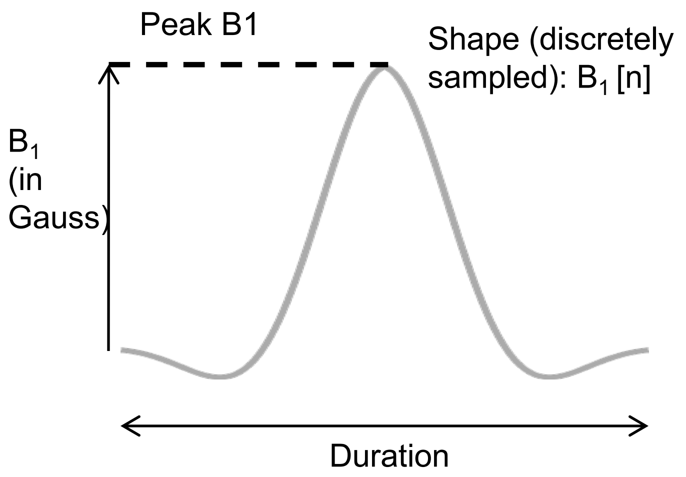
Courtesy Miki Lustig, UC Berkeley

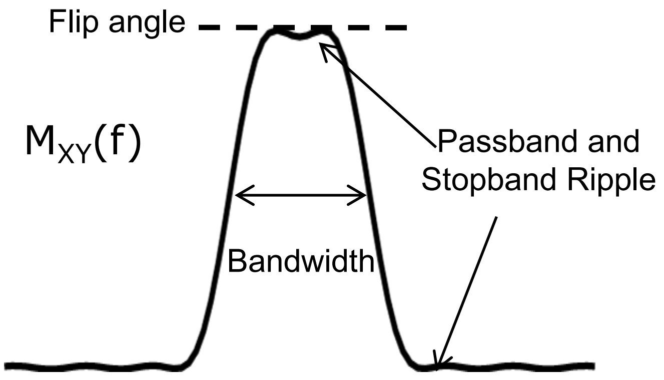
RF Pulse Profile



- Example: sinc-shaped pulse leads to ≈rect-shaped pulse profile
  - Fourier Transform relationship for small flip angles < 30º, use Bloch simulation or SLR transform for large flip angles
- Profile characterized by the "Bandwidth"
- Pulse is inherently selective in off-resonance frequency, which is a combination of chemical shift, B0 inhomogeneity and magnetic field gradients

RF Pulse Parameters





<u>Other important parameters</u>:

Total power, for Specific Absorbtion Rate (SAR) calculations: $SAR \propto \int |B_1(t)|^2 dt$

Isodelay (when spins are in phase during excitation)

Time-bandwidth (TBW) product = duration x bandwidth

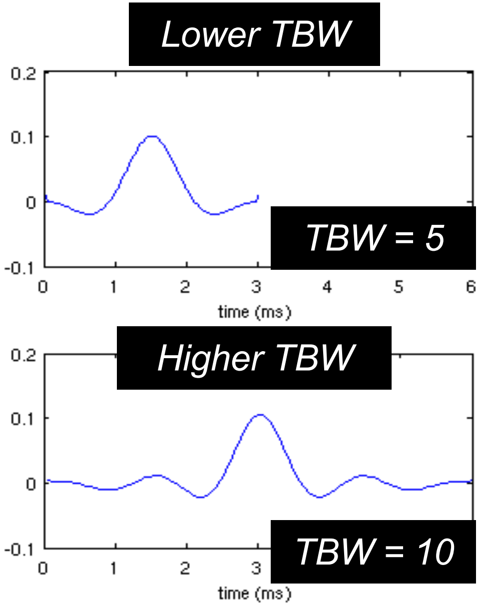
– *useful for characterizing pulse, primary design parameter*

Spectral Selection

- Goals
  - Suppress large, broad fat signal
  - Suppress (or partially suppress) large water signal
  - Spectral editing (eg. lactate, GABA)
- Methods
  - Spectral Excitation
  - Spectral Suppression

Pulse Selectivity

- Described by the Time-Bandwidth (TBW) product:
  - TBW = time x bandwidth
  - Ex: 2 ms pulse with 4 kHz bandwidth has a TBW = 8
- TBW proportional to the pulse selectivity
- TBWs from 2-20 seen in MRI
  - Rule-of-thumb (sinc pulses): TBW = number of zero-crossings

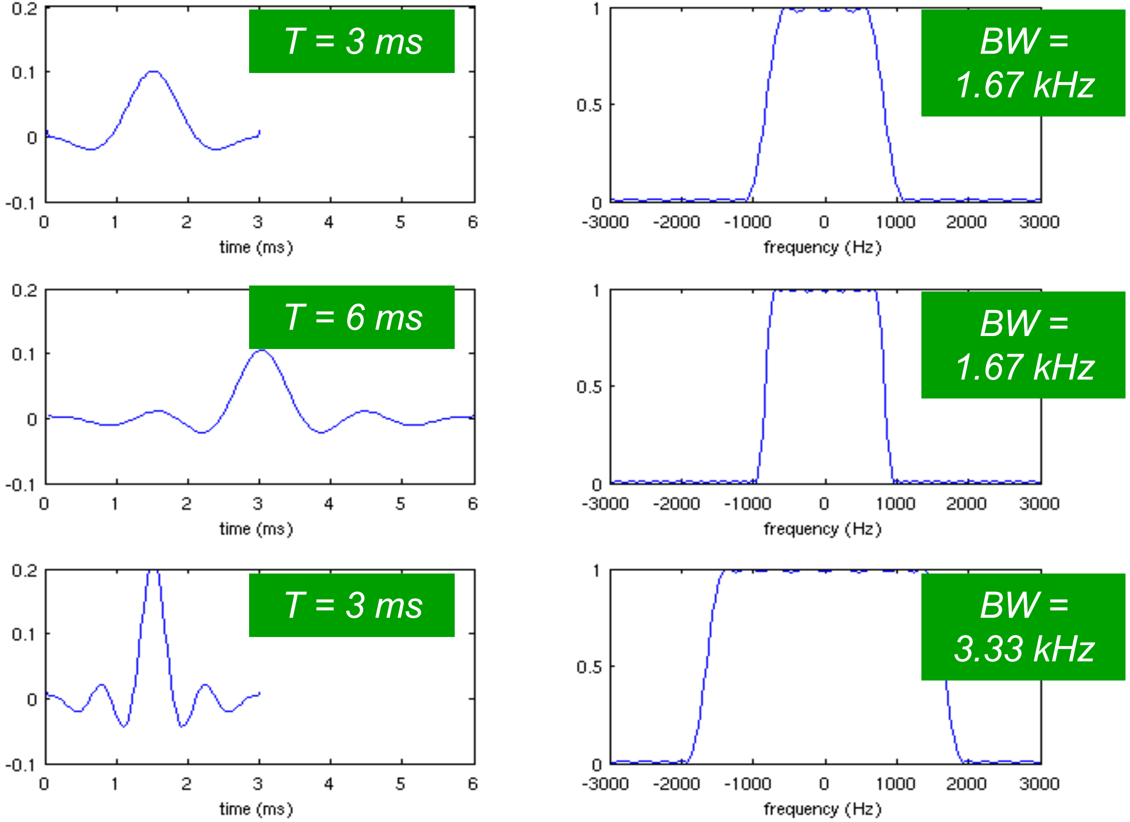


Time-Bandwidth Relationship

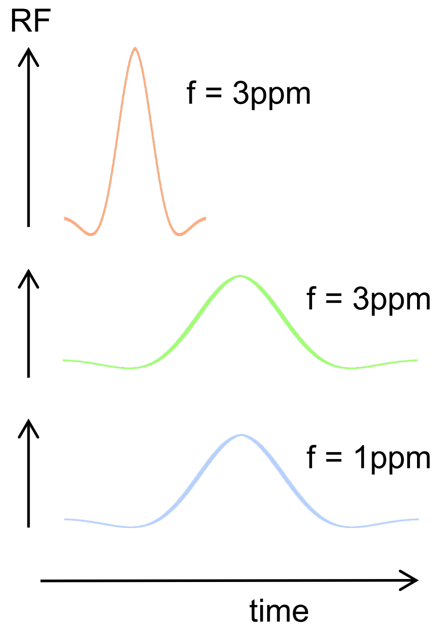
TBW = 5

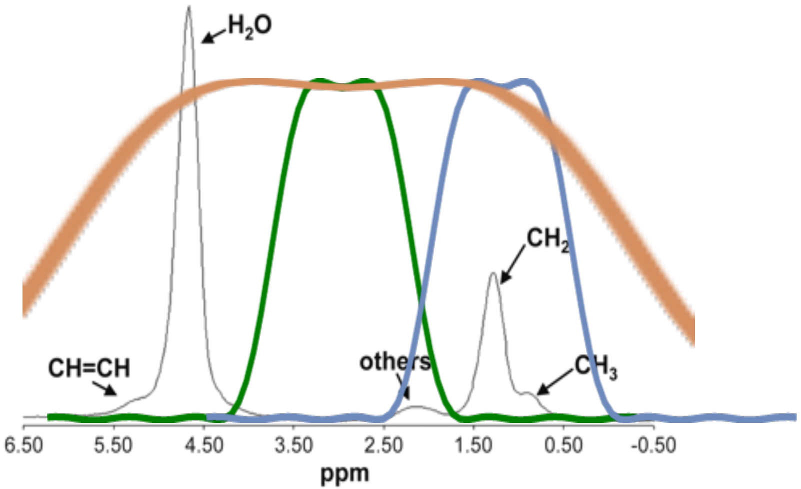
TBW = 10

TBW = 10

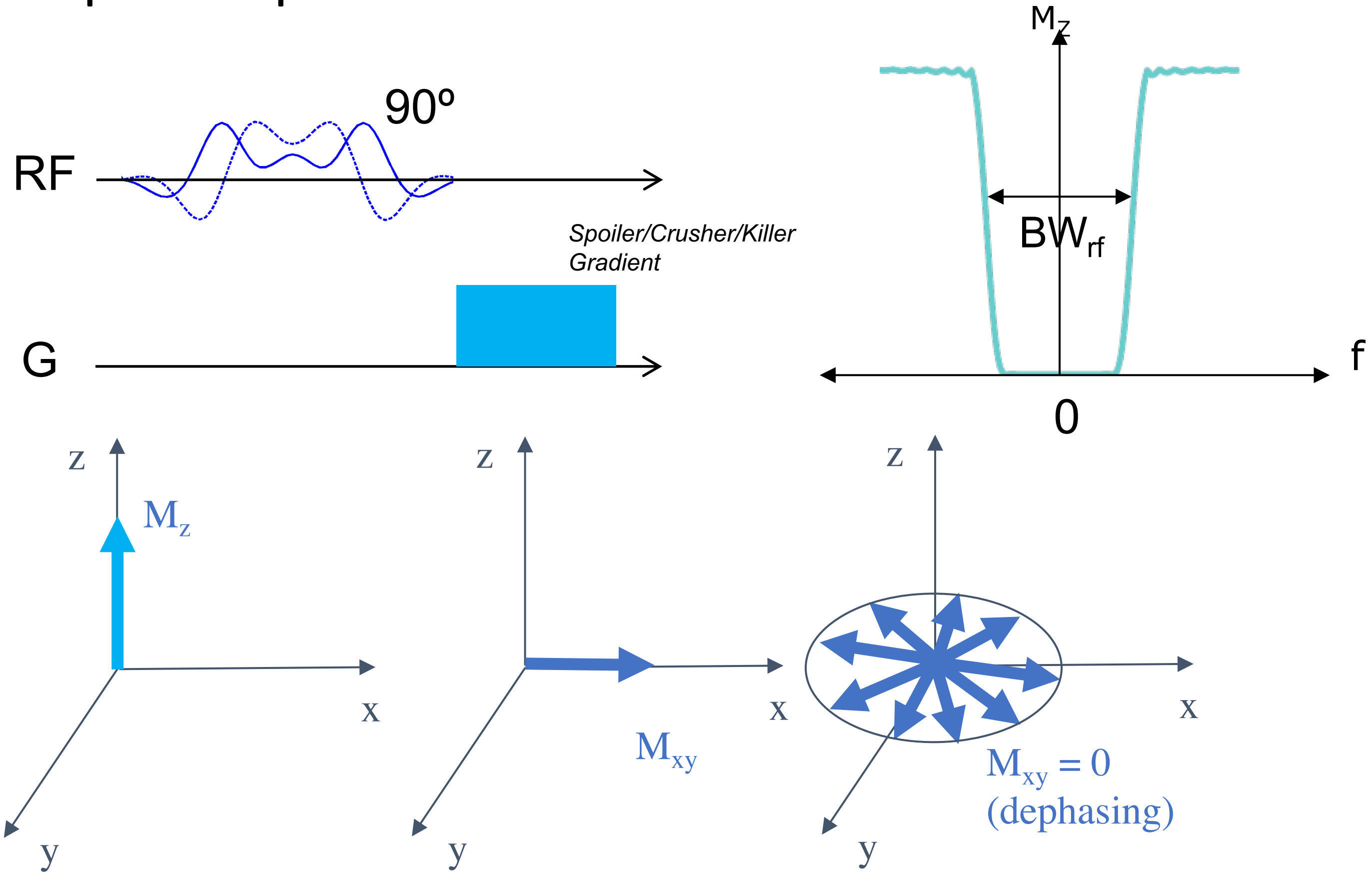


Example: Spectral Excitation

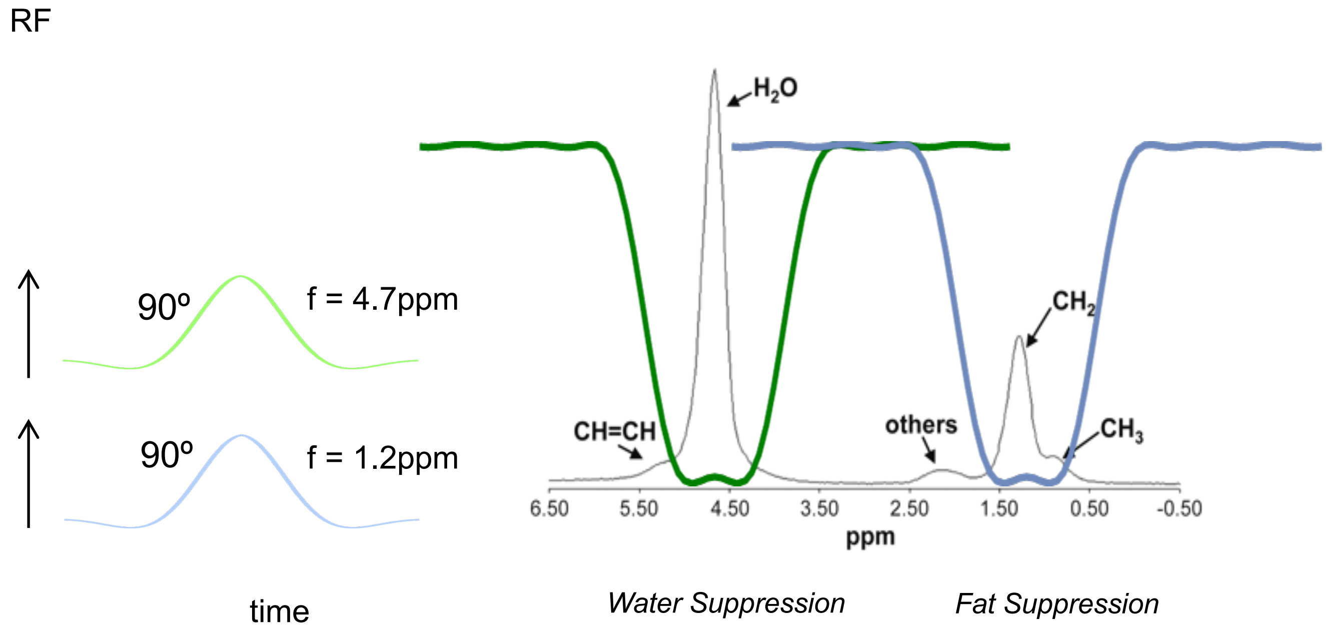




Example: Spectral Saturation



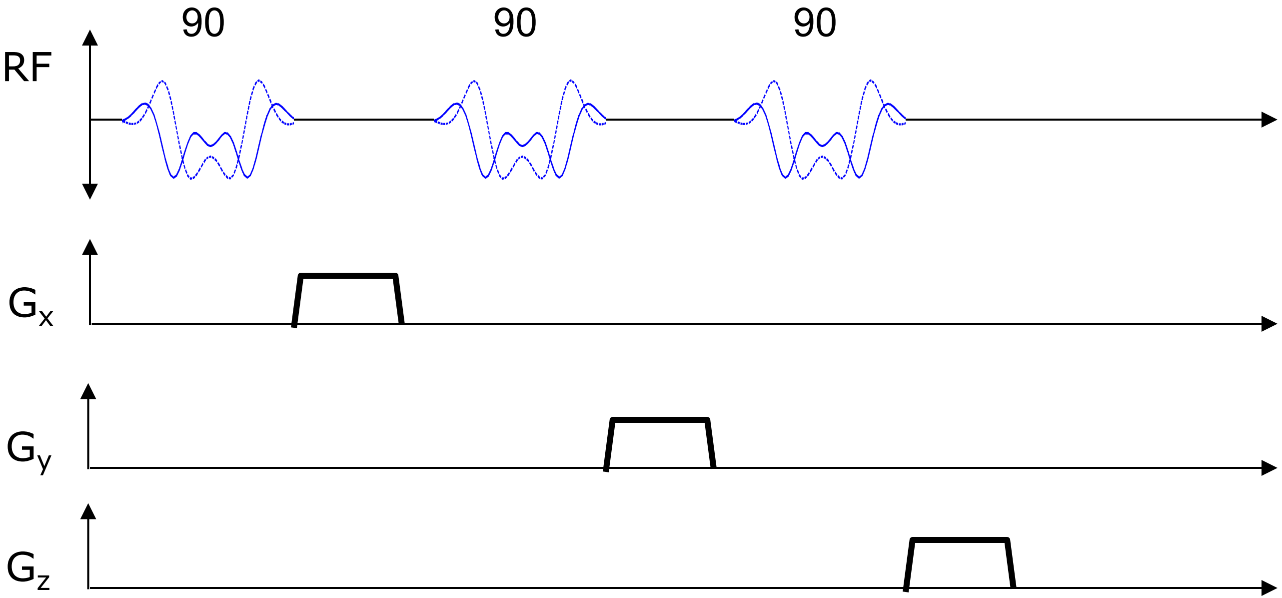
Example: Spectral Suppression



Chemical shift selective imaging sequence: CHESS

- Spectrally-selective RF saturation (90º) pulse applied at fat or water frequency
- Followed by crusher
- Repeated RF pulses for improved suppression with flip angle errors

CHESS

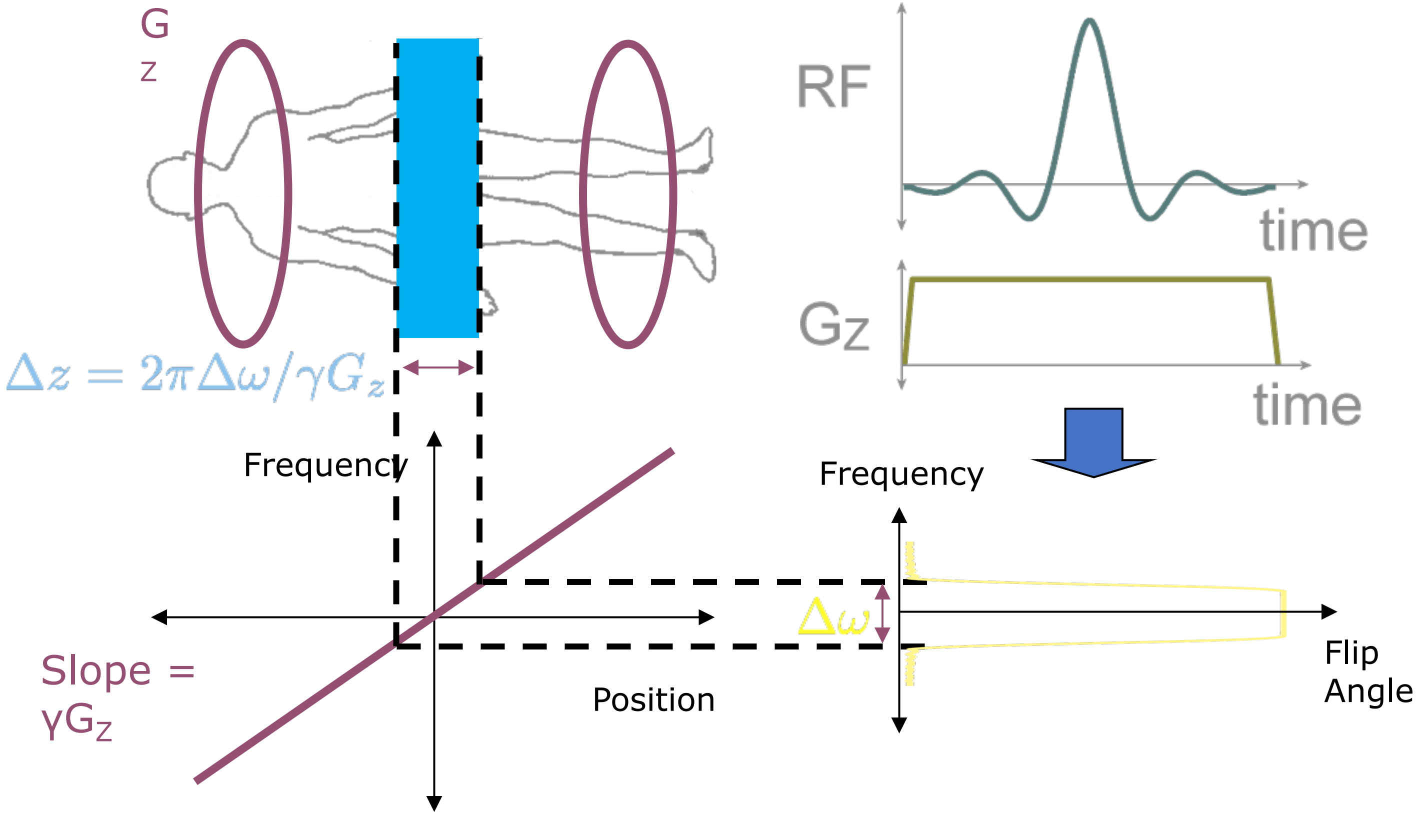


Pulses can be "non-linear" phase so are not sinc-shaped, which allows for higher TBW
Crusher gradients on different axes to prevent refocusing

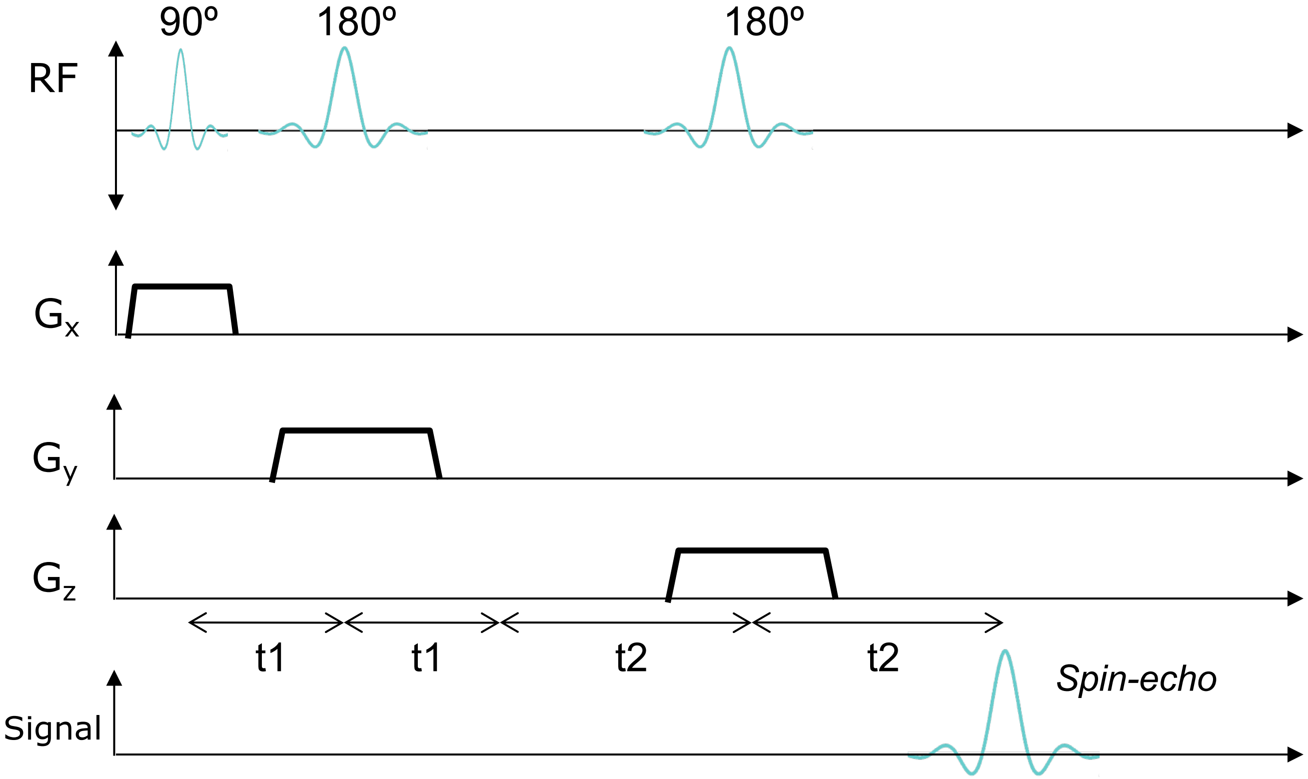
Spatial localization

- Goals
  - Reduce scan time by reducing FOV
  - Reduce contamination by fat
- Methods
  - Three pulse localization
  - Spatial saturation

Spatial Selectivity

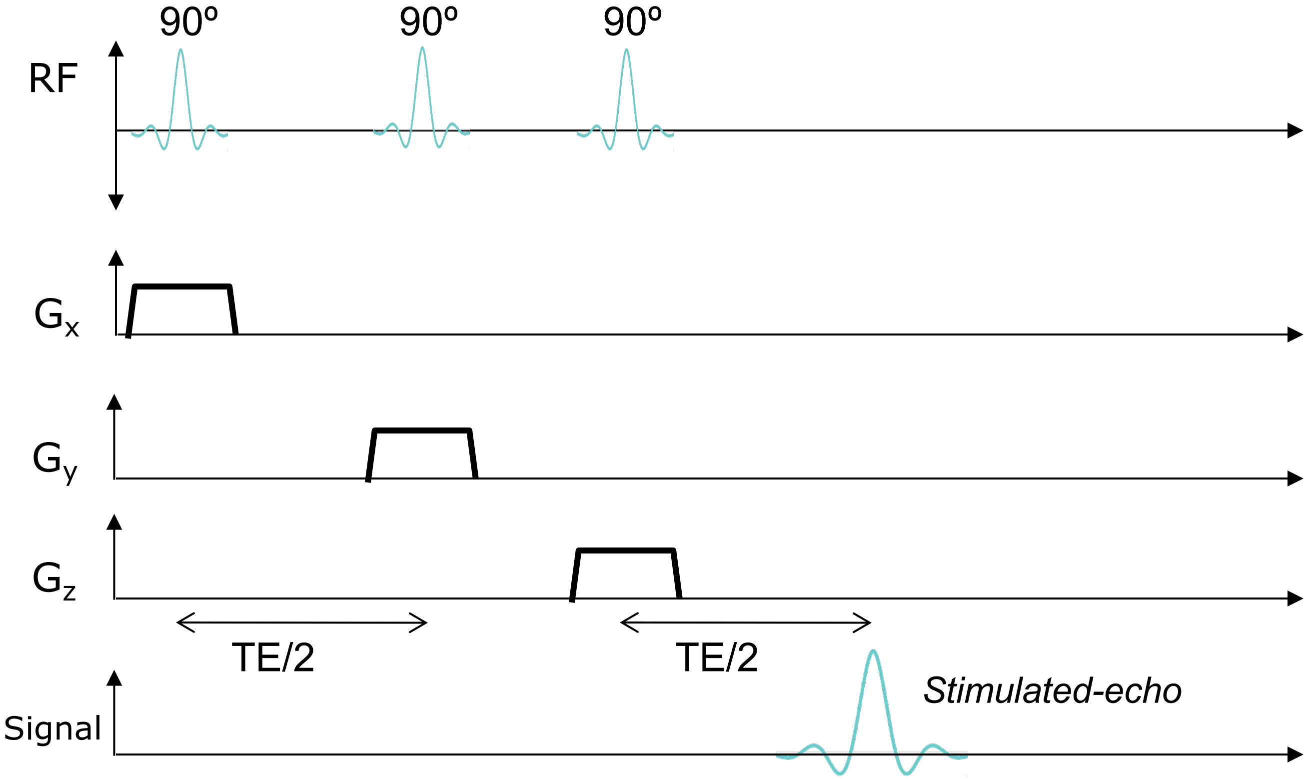


Localization Methods - PRESS



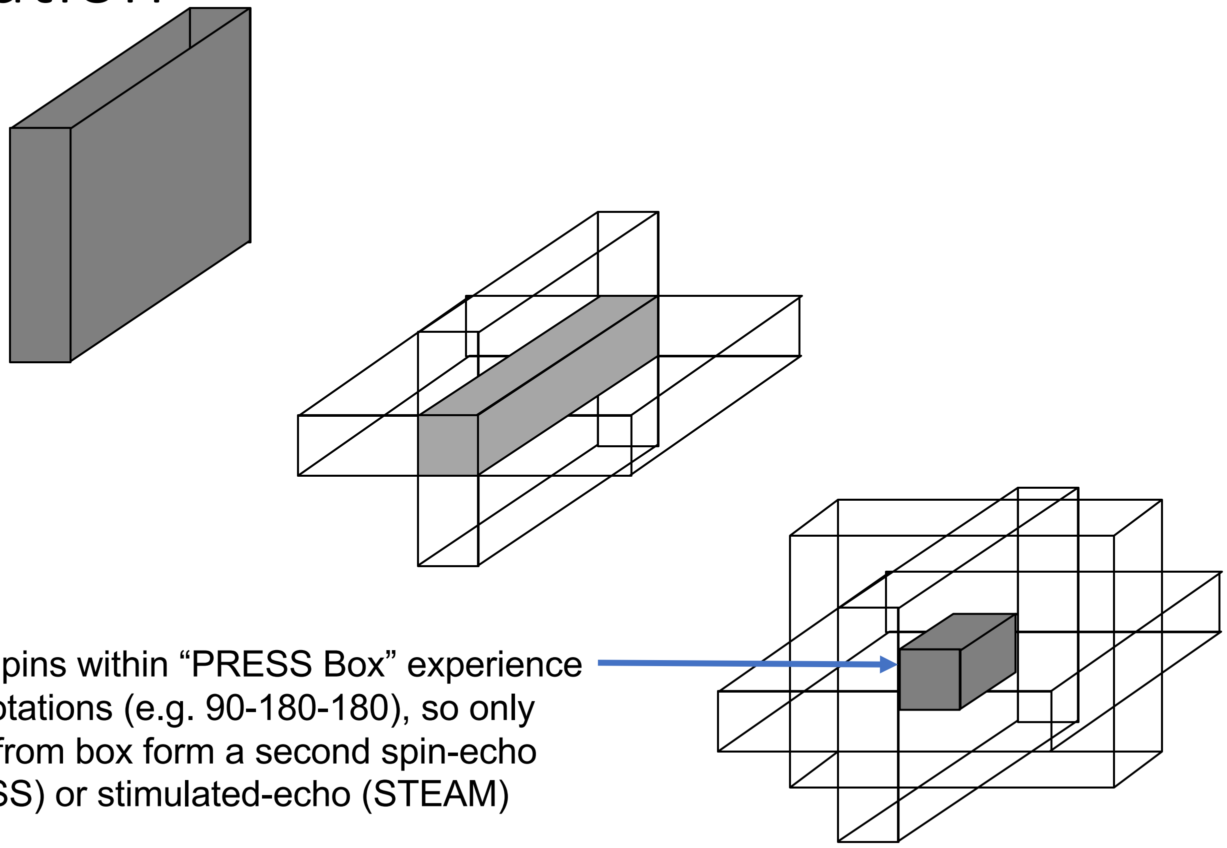
Crushers and refocusing gradients not shown, but they are important!

Localization Methods - STEAM



Crushers and refocusing gradients not shown, but they are important!

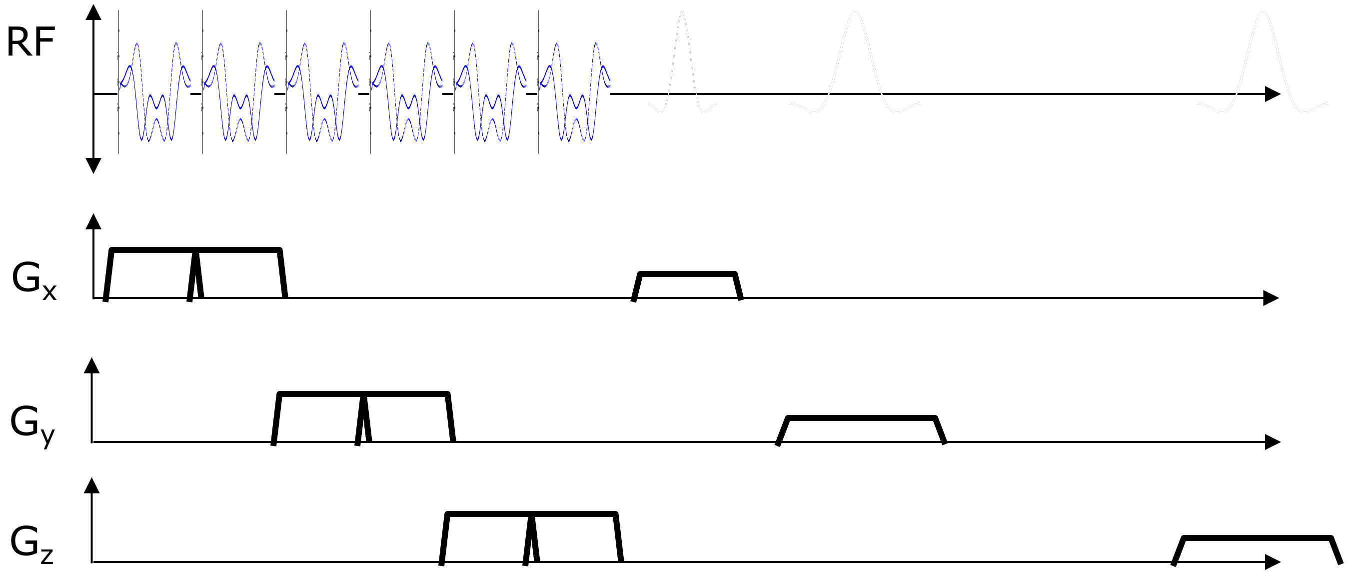
Localization



Only spins within "PRESS Box" experience all 3 rotations (e.g. 90-180-180), so only spins from box form a second spin-echo (PRESS) or stimulated-echo (STEAM)

Saturation Pre-pulses

- Prior to PRESS/STEAM localization, play very-selective saturation (VSS) pulses



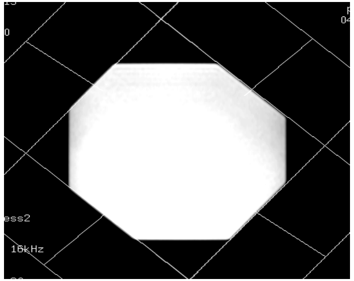
Why use additional Spatial Saturation?

- 90/180 bandwidths can be increased, but at expense of long TEs
- Saturation pulses can have *non-linear phase* for increased pulse bandwidth

✓Sharper profile

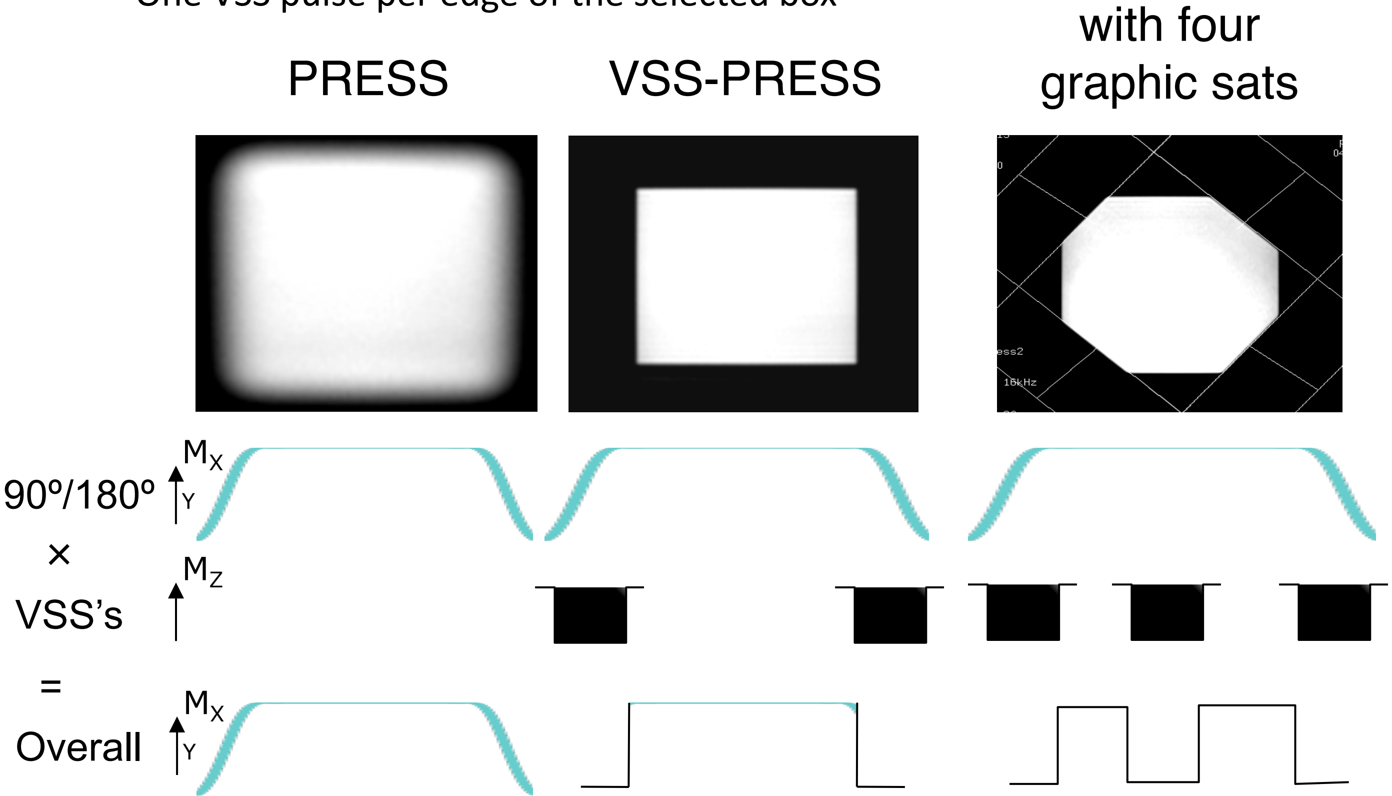
✓Arbitrary placement for non-rectangular selections

✓Less chemical shift misregistration



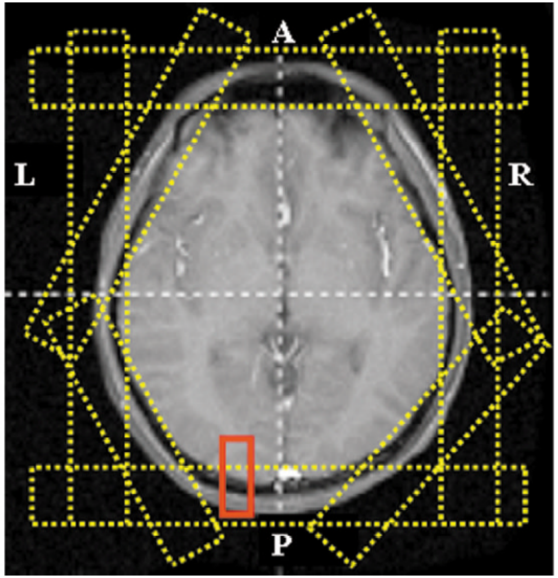
Spatial Saturation Selectivity

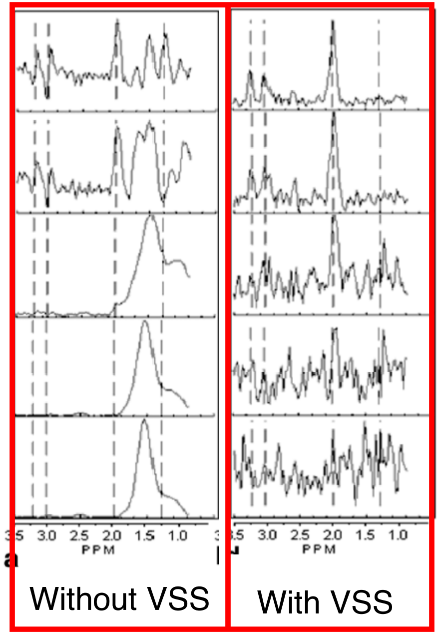
- Localization is much more selective
- One VSS pulse per edge of the selected box



Spatial Lipid Suppression

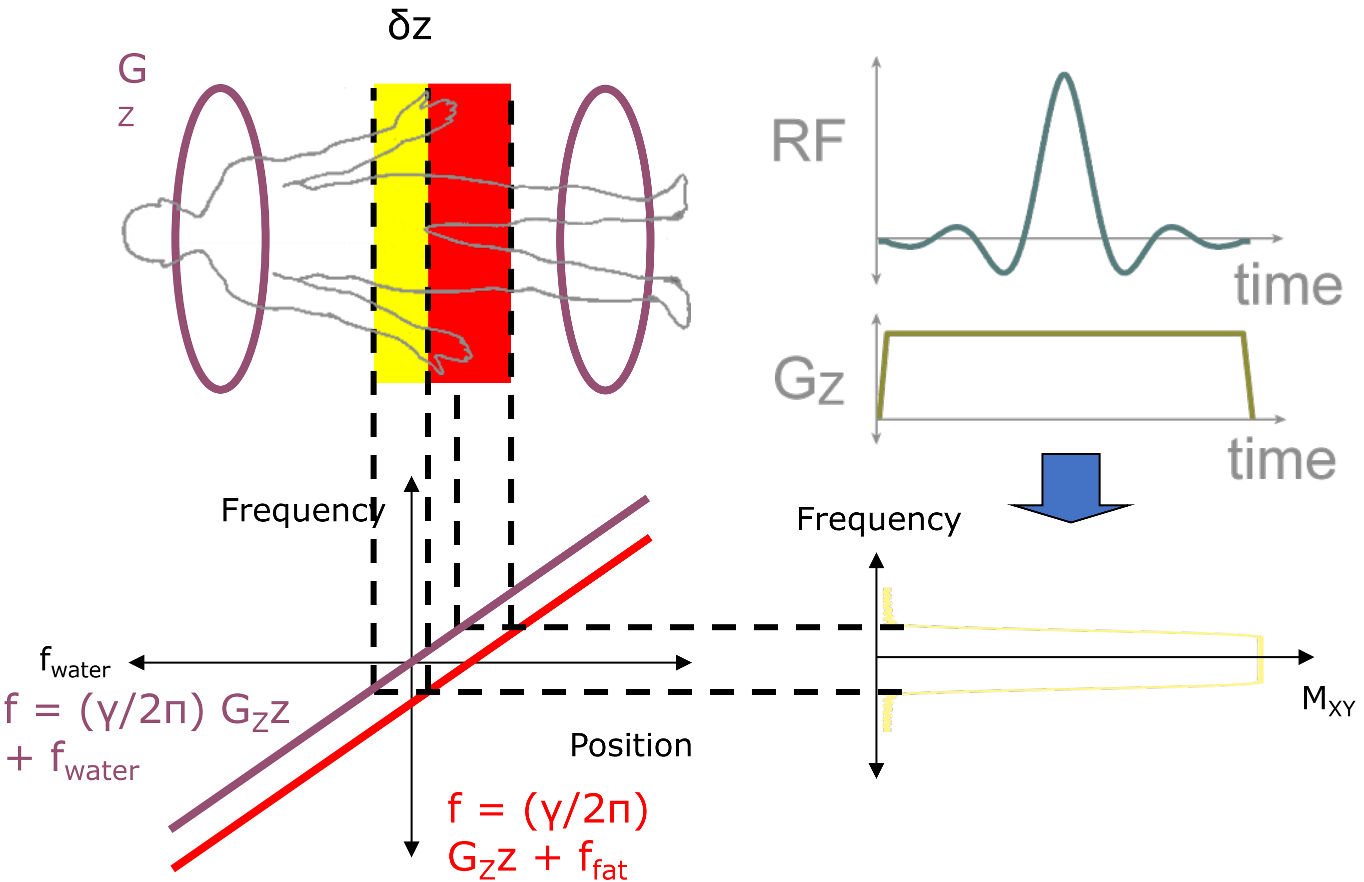
a



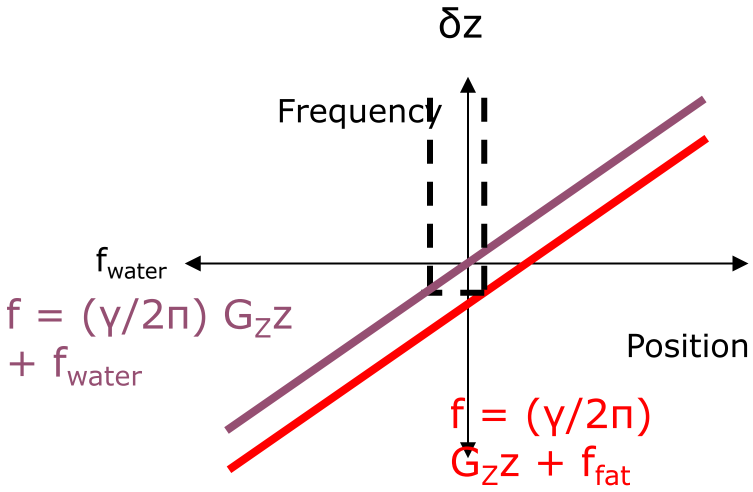


- High lipid signals make metabolite signal hard to detect
- Gibb’s ringing from high fat signal into the FOV
- Excite a spatial region with VSS (yellow) and dephase (using spoilers)

Chemical Shift Slice Misregistration



Chemical Shift Slice Misregistration



$$\delta z = (f_{fat} - f_{water}) / ((\gamma/2\pi)\, G_Z)$$

$$= (f_{fat} - f_{water})\, \Delta z / BW_{rf}$$

Larger pulse bandwidth (larger gradient) reduces chemical shift misregisration

Fat-Water Slice Shift

$$\delta z = (f_{fat} - f_{water}) / ((\gamma/2\pi) G_Z)$$

- What is the slice shift at 3T between fat and water ($f_{fat} - f_{water} \cong 440$ Hz) for a 2 ms, TBW = 4 pulse with $G_Z = 4$ G/cm?

$\delta z =$

(440 Hz) / (4.257 kHz/G x 4 G/cm)

= 0.26 mm

Relative Fat-Water Slice Shift

$$\delta z = (f_{fat} - f_{water})\ \Delta z\ /\ BW_{rf}$$

- What is the *relative* slice shift at 3T between fat and water ($f_{fat} - f_{water} \cong 440$ Hz) for a 2 ms, TBW = 4 pulse?

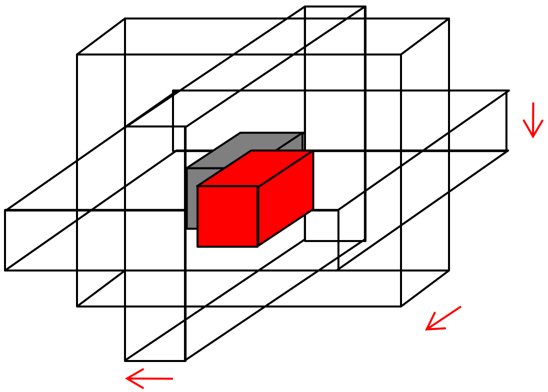
$BW_{rf} = 4\ /\ 2ms = 2$ kHZ

$\delta z =$

$(440 \text{ Hz}/2 \text{ kHz})\ \Delta z = 0.22\ \Delta z$

(Approximately a quarter slice shift)

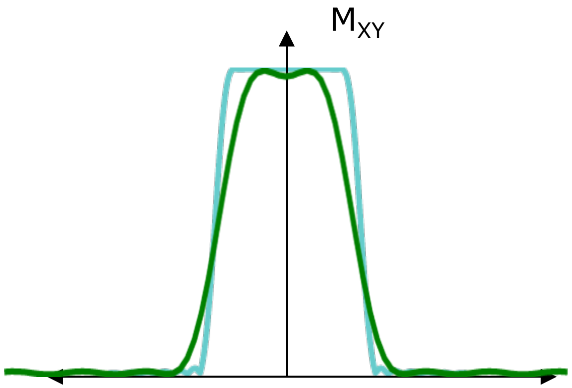
PRESS Chemical-shift Misregistration

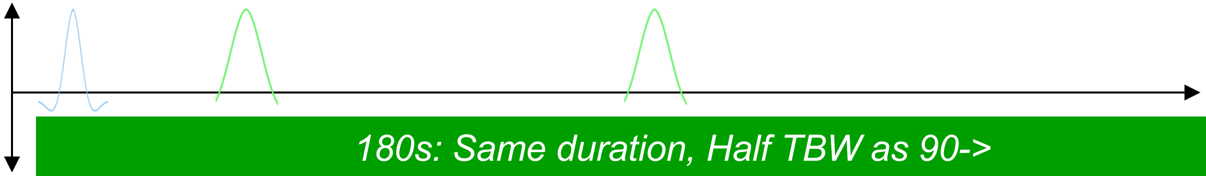


- Shift in all three dimensions
- Direction of shift depends on gradient polarity
- Size of shift depends on pulse bandwidth

Localization Selectivity

- 90,180 pulses generally have TBW ≈ 3-6
- In PRESS, Spin-echo (180) pulses will generally be less selective because they run into peak power limitations
    - Longer duration, same TBW -> Lower BW
    - OR
    - Same duration, lower TBW -> Lower BW
    - ➢ *More chemical-shift misregistration*



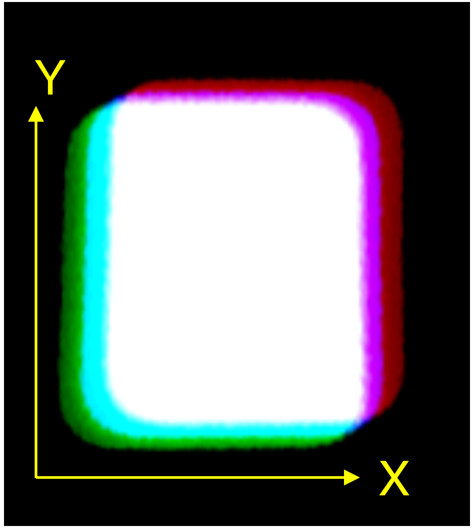


180s: Same duration, Half TBW as 90->
Reduced selectivity & ½ bandwidth == 2X the chemical shift misregistration!

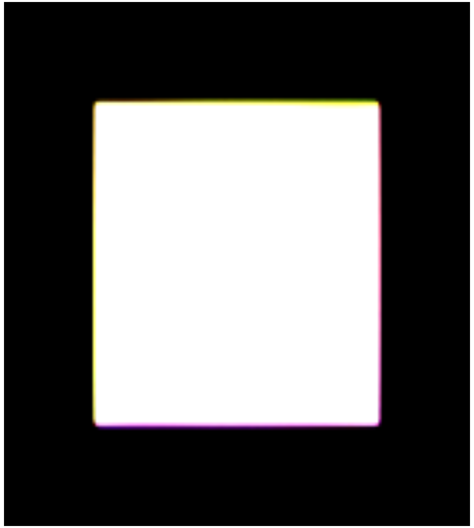
Chemical Shift Misregistration Images

3 Overlaid Phantom PRESS Box Images acquired
with Δf = -100 0 +100

Conventional PRESS
X: 180 SLR (1.1 kHz)
Y: 90 SLR (2.5 kHz)

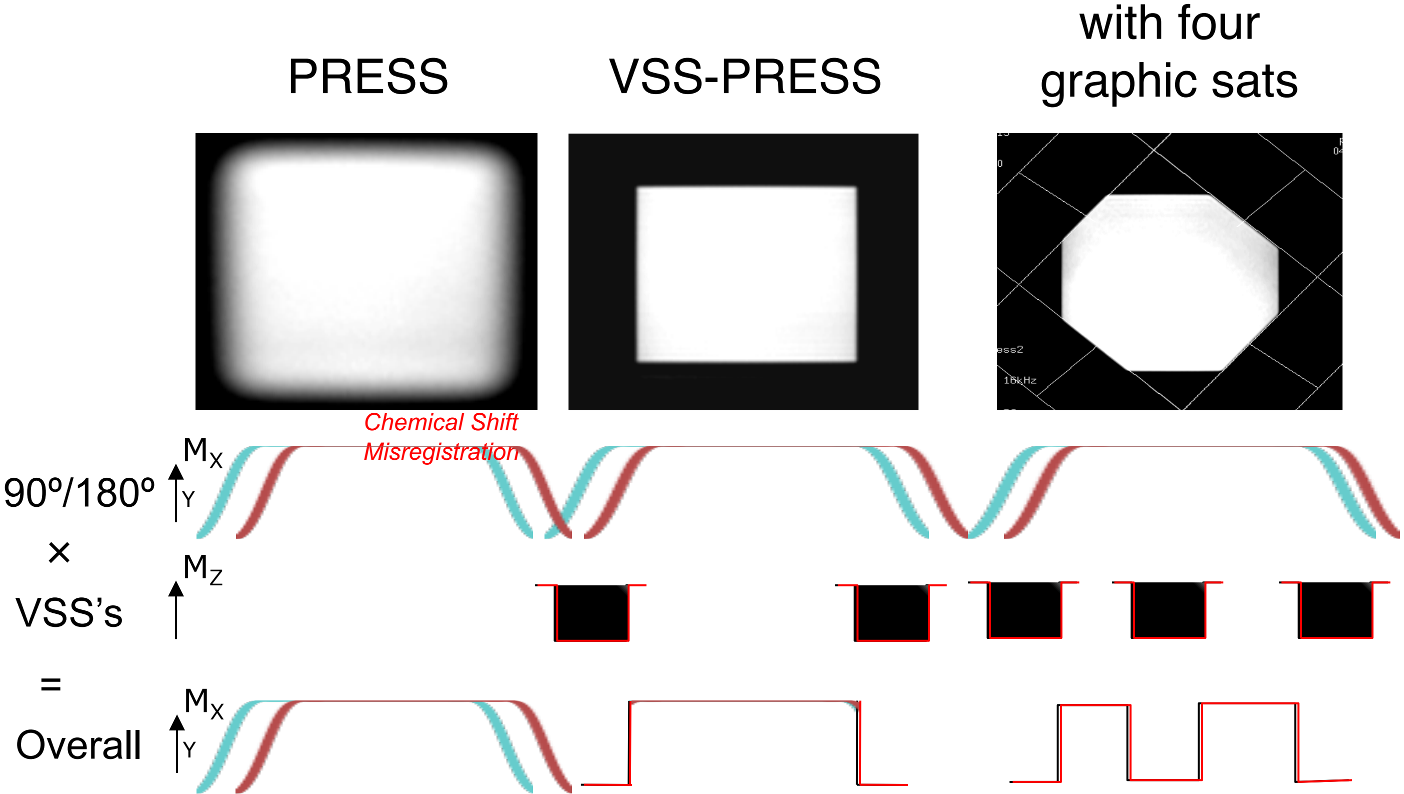


Overprescribed
PRESS Box with VSS



Spatial Saturation with Chemical Shift

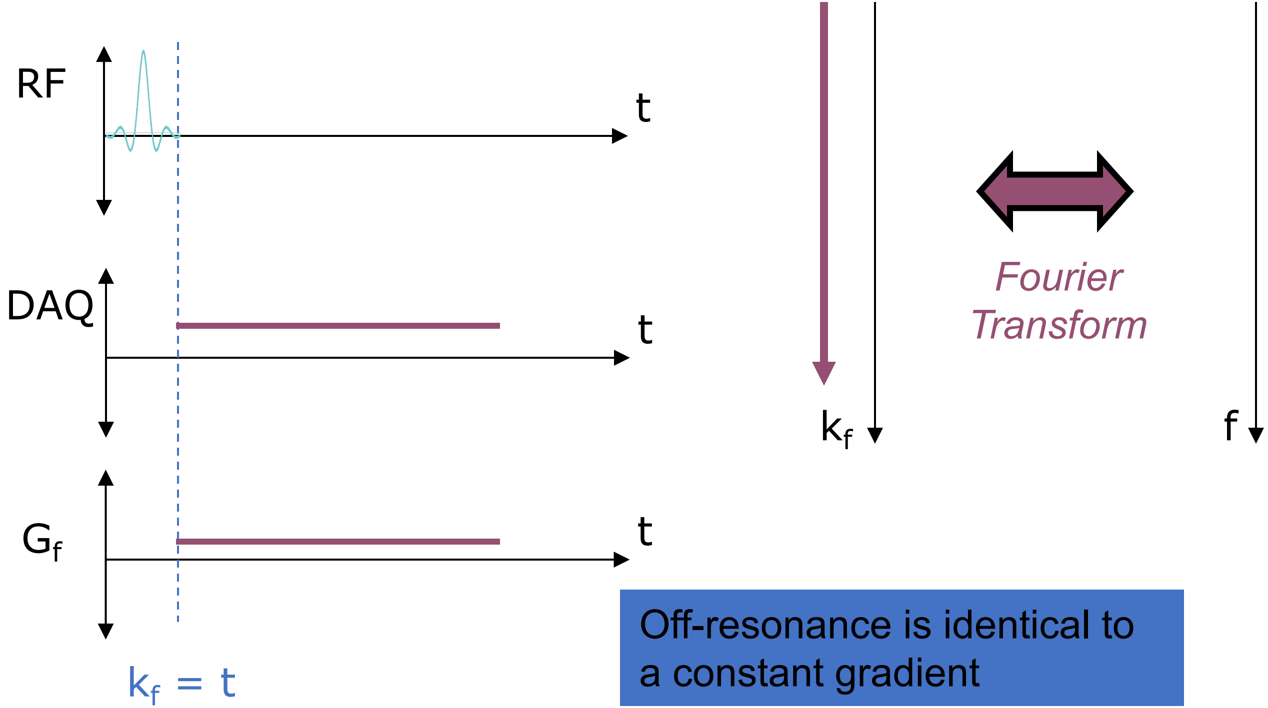
- Localization with spatial saturation is much more selective & less chemical shift misregistration



Fast Spectroscopic Imaging

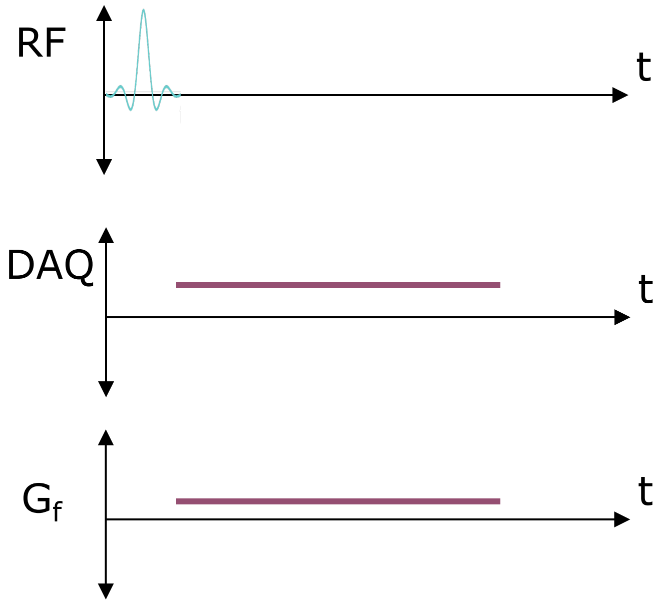
- Simultaneous acquisition of spectral and spatial k-space data
- Methods
  - Echo-planar spectroscopic imaging (EPSI)
  - Spirals, concentric rings
- Considerations
  - Spatial FOV, resolution
  - Spectral BW, resolution
  - Speed
  - Robustness to imperfections (e.g. gradient fidelity)

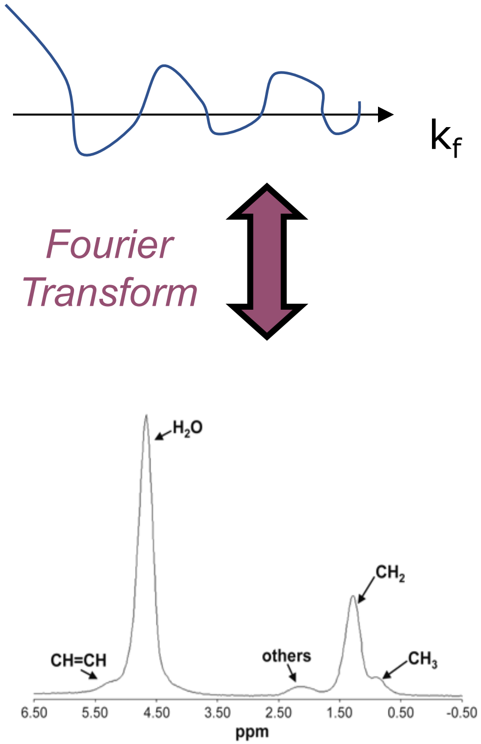
MRS (FID) Acquisition K-space



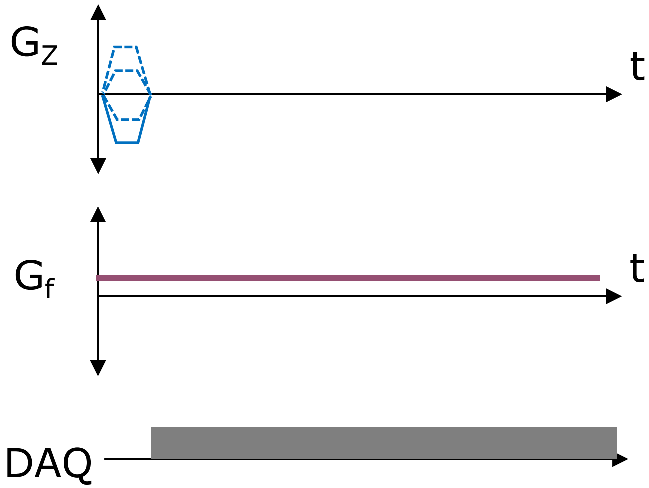
Off-resonance is identical to a constant gradient

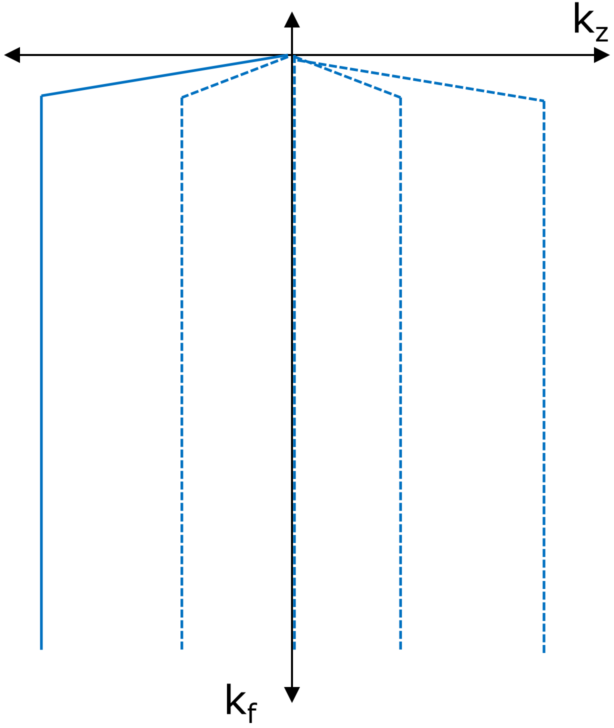
MRS (FID) Acquisition K-space





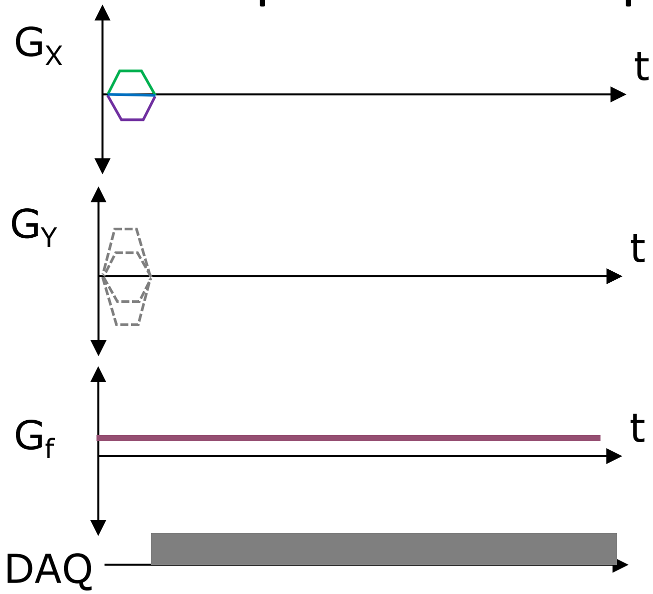
Spectral-Spatial Sampling

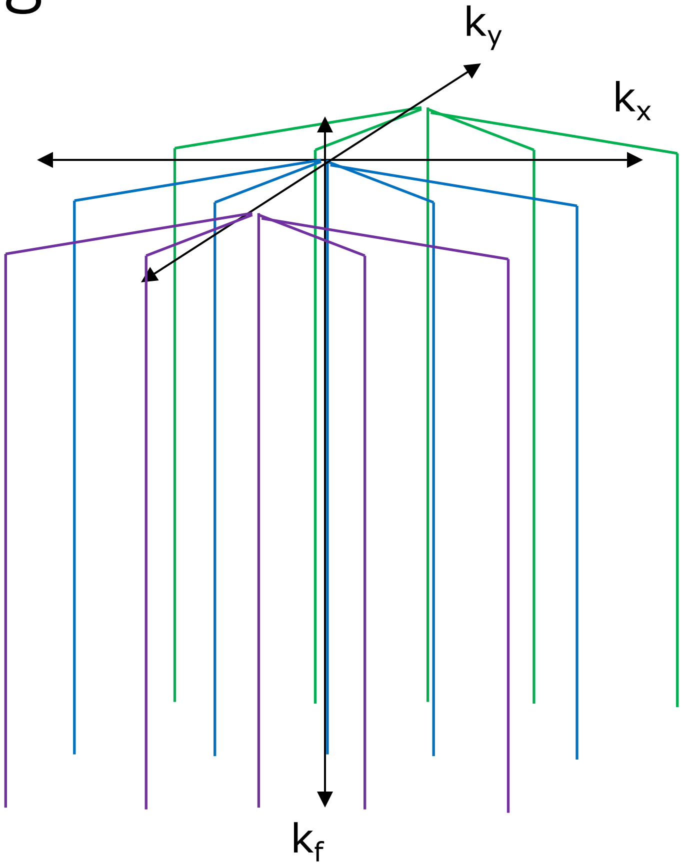




- Data sampled in k_f (spectroscopy) + $k_{x,y,z}$ (imaging)
- Fourier Transform reconstruction from $k_{x,y,z}$ -k_f space to x-y-z-f space

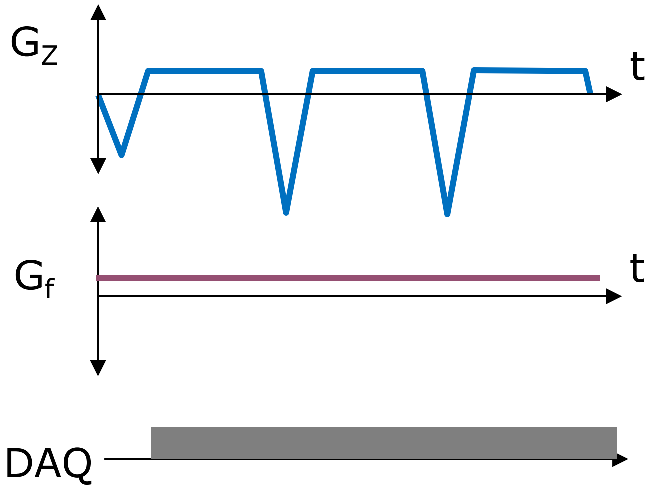
Spectral-Spatial Sampling

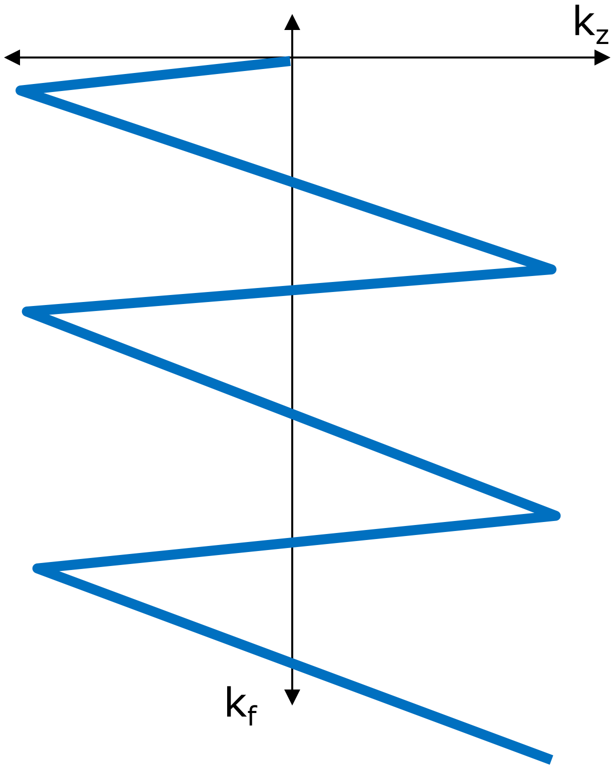




- Data sampled in k_f (spectroscopy) + $k_{x,y,z}$ (imaging)
- Fourier Transform reconstruction from $k_{x,y,z}$ -k_f space to x-y-z-f space

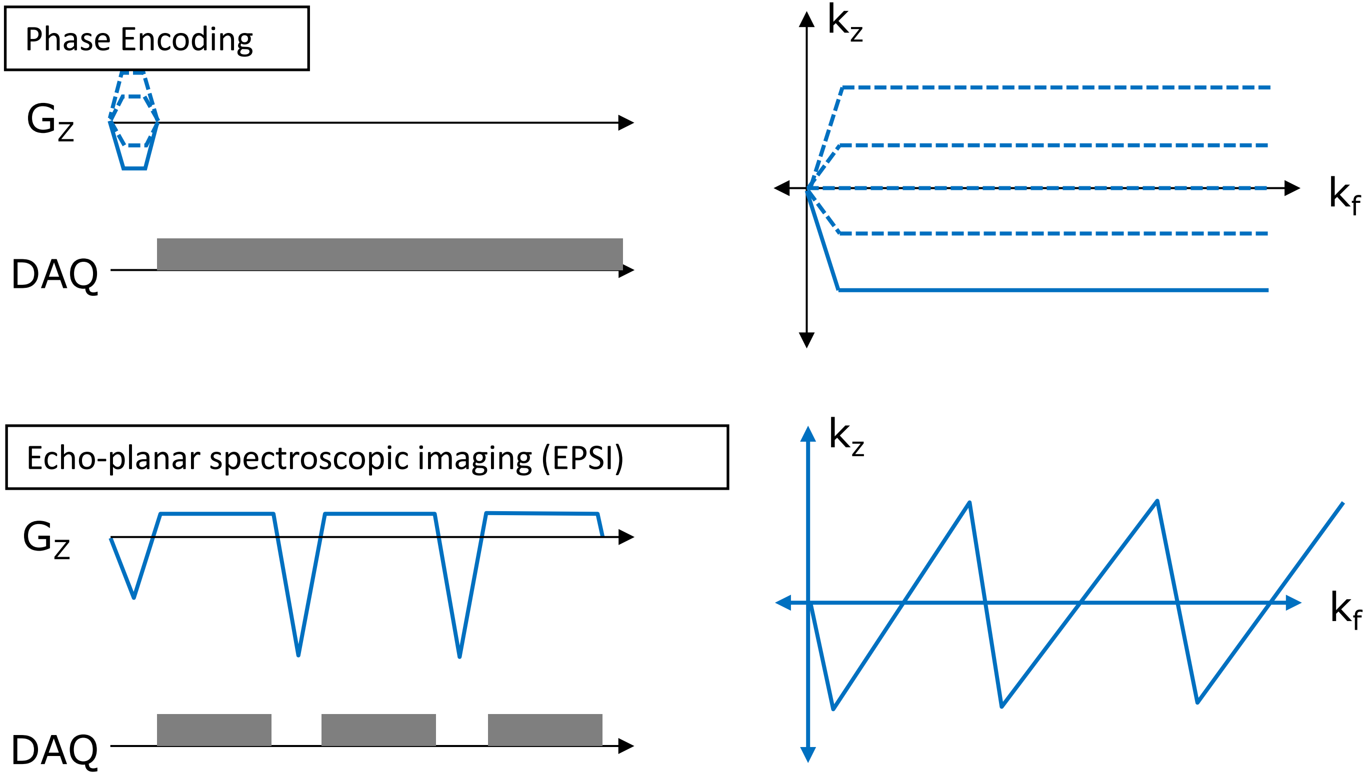
Fast Spectral-Spatial Sampling



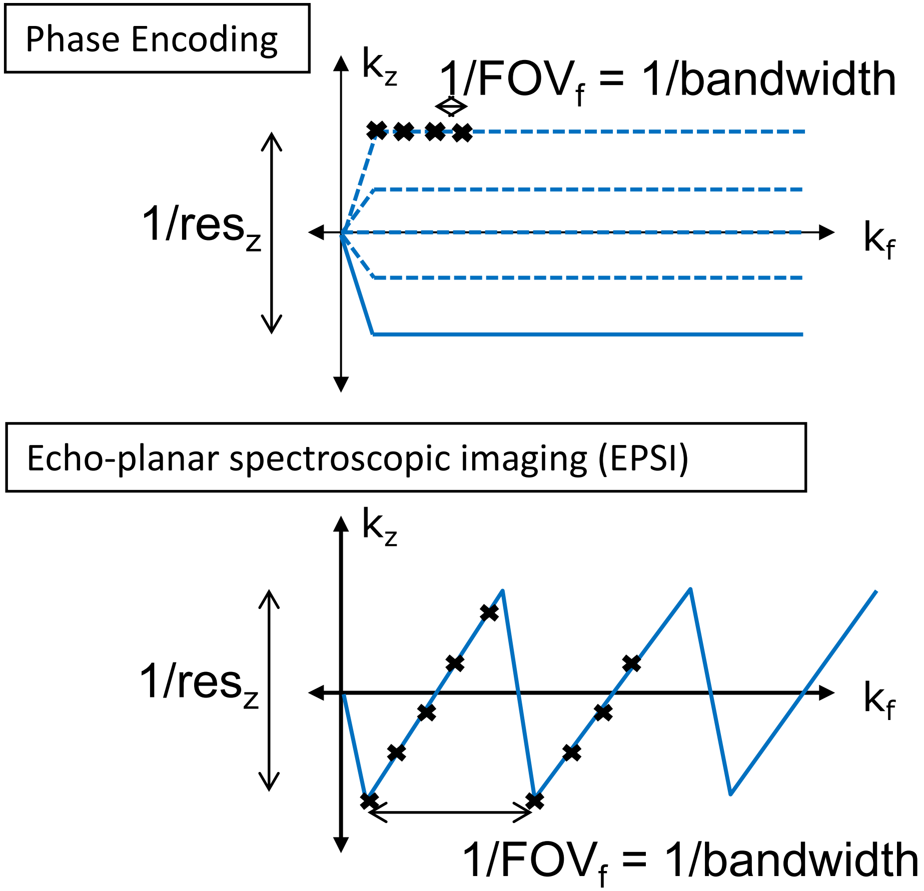


- Vary gradients during data acquisition
- Example: Echo-planar spectroscopic imaging (EPSI)

MRSI Readout

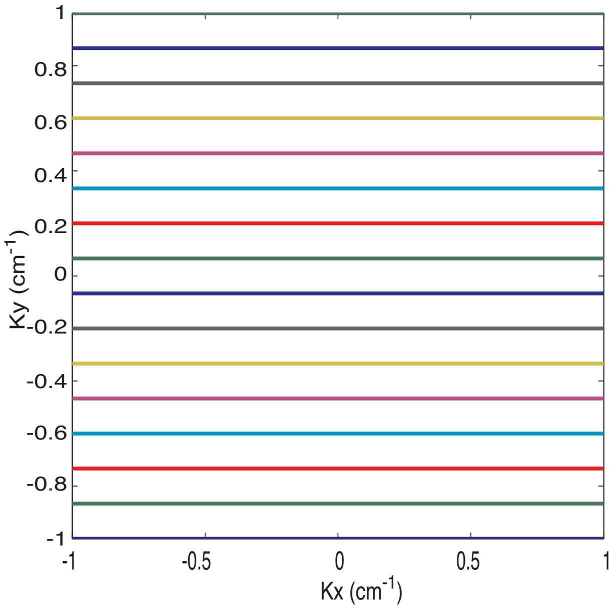


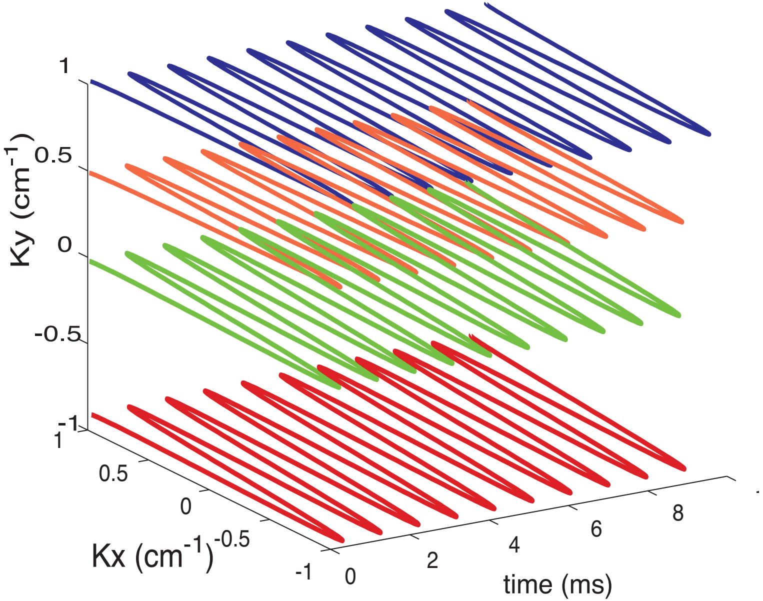
MRSI Readout – Sampling Requirements



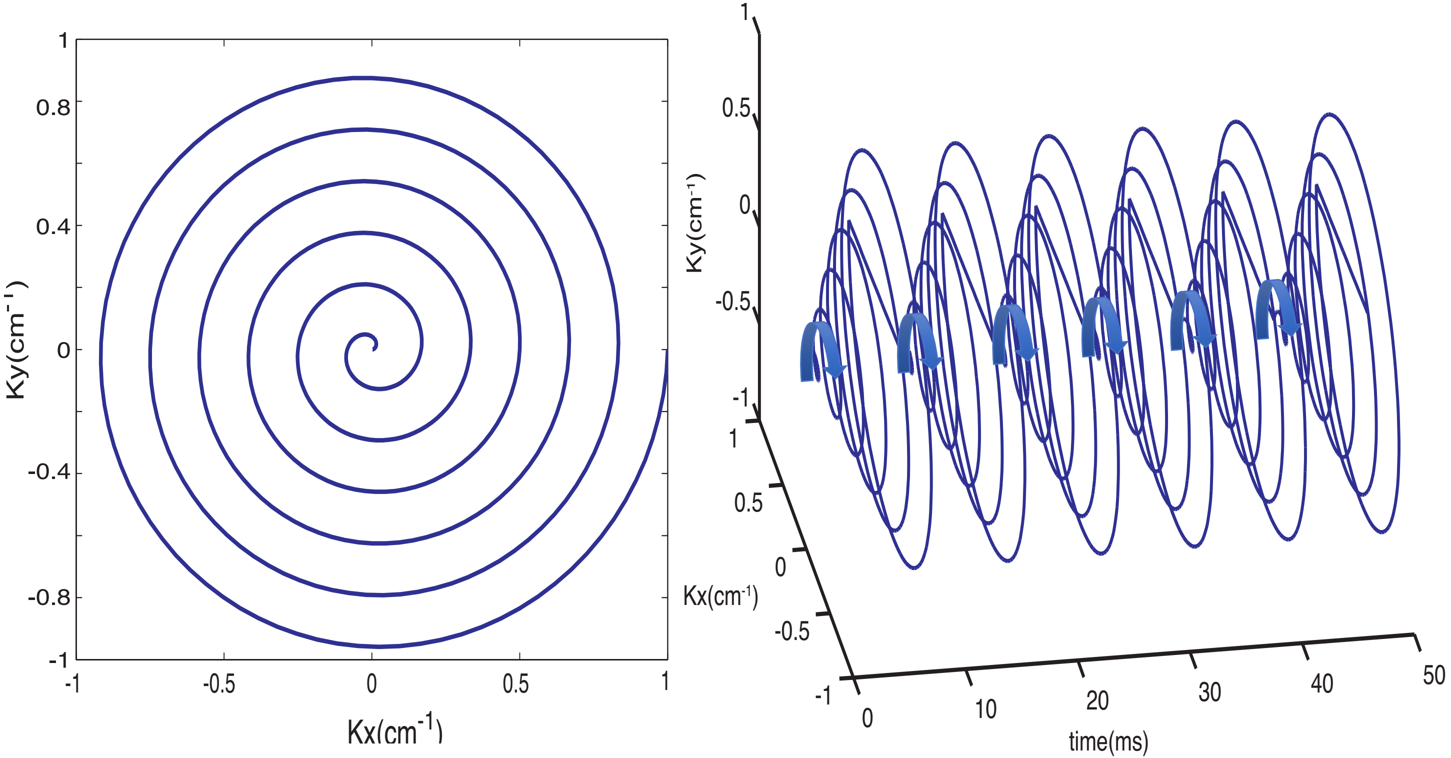
- Fast Acquisition
- Reduced SNR efficiency
- Tradeoff between spatial resolution and bandwidth

EPSI (Echo Planar Spectroscopic Imaging)

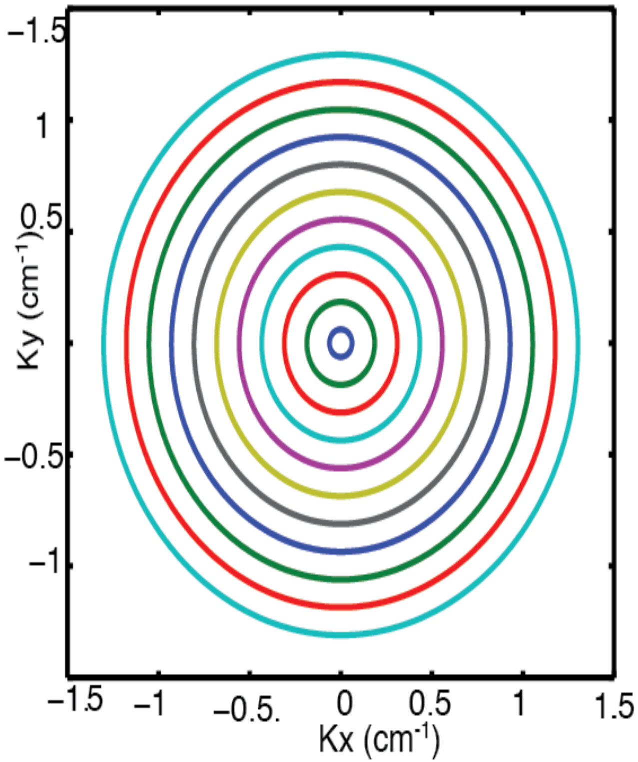


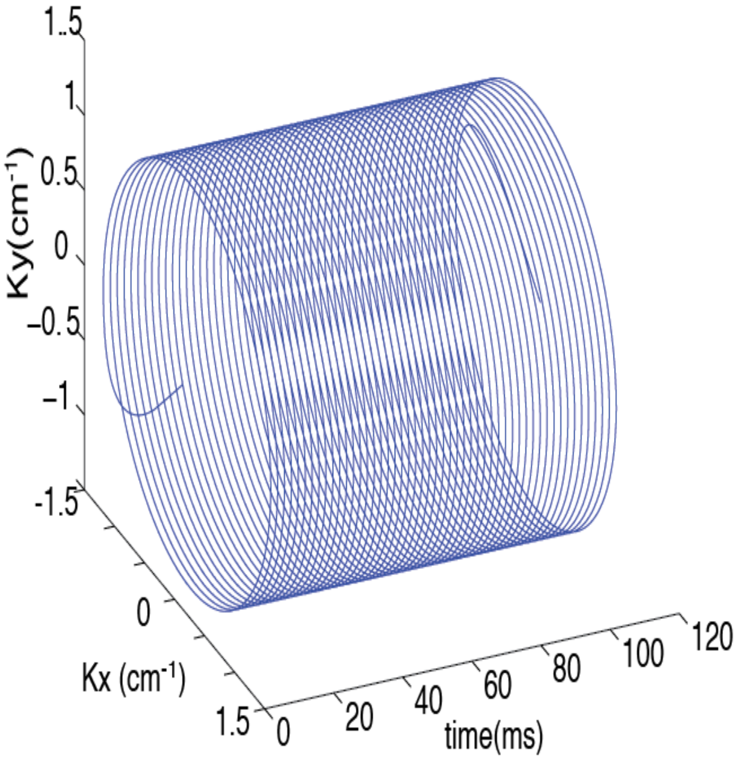


Spiral Spectroscopic Imaging



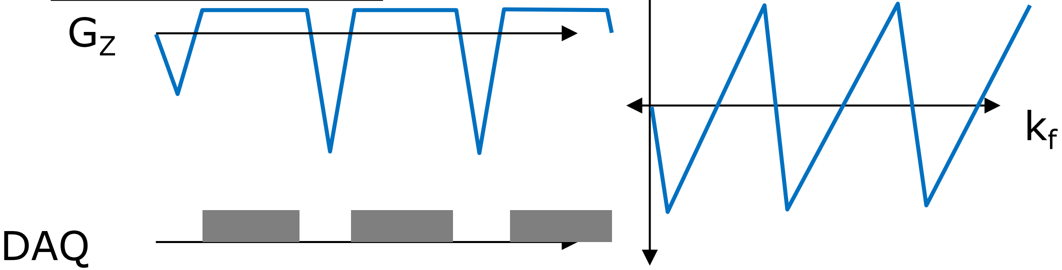
Concentric Rings Trajectory





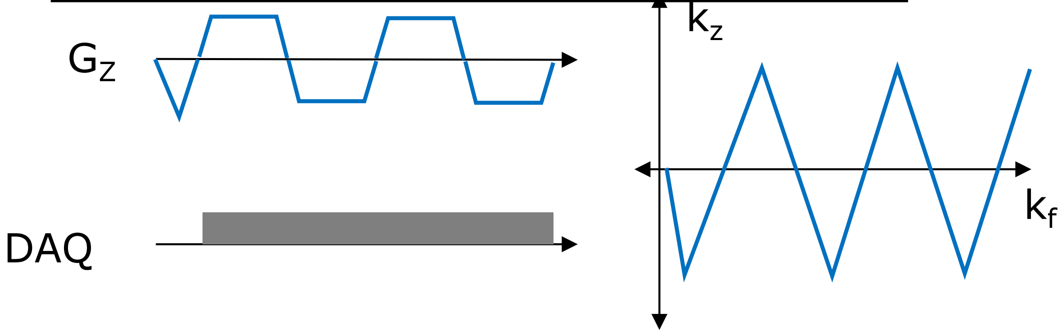
Flyback and Symmetric EPSI

Flyback EPSI



- Robust to system imperfections
- Simple reconstruction

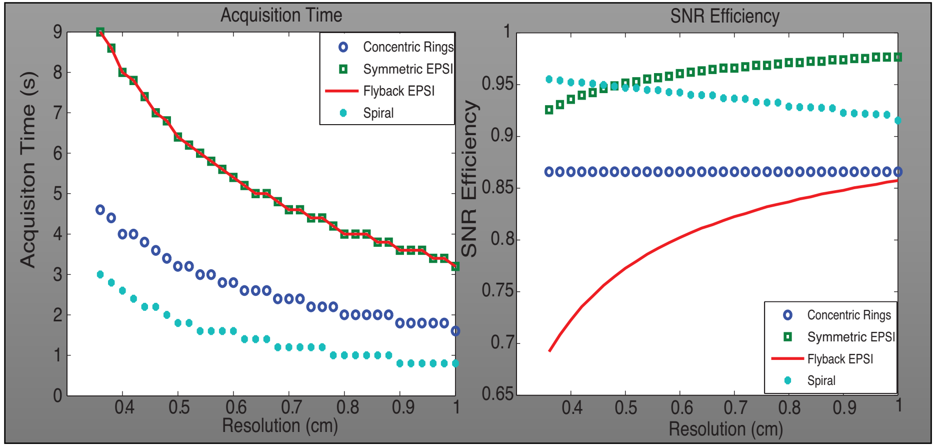
Symmetric EPSI (with ramp sampling)



- Improved SNR efficiency
- Better resolution/bandwidth tradeoff
- Complex reconstruction
- Sensitive to delays and eddy currents

Comparison of Accelerated MRSI Strategies

Tradeoffs
- Speed
- SNR efficiency
- Robustness to hardware imperfections
- Bandwidth
- Resolution



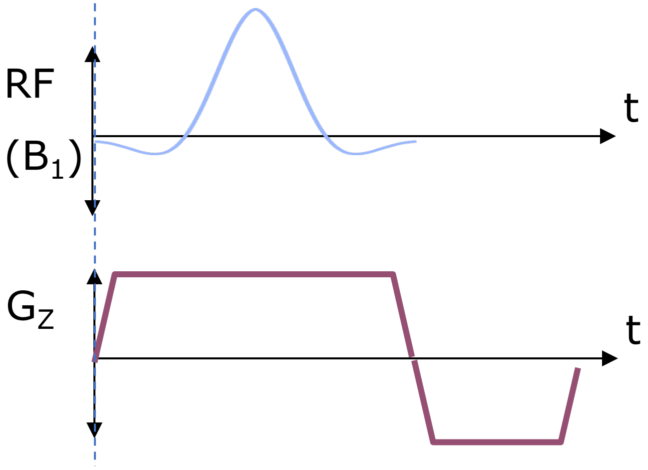
	Flyback EPSI	Symmetric EPSI	Concentric Rings	Spiral
Speed	-	-	+	++
SNR	-	++	+	++
Robustness	++	-	++	--

Jiang W, et al, MRM 2014.

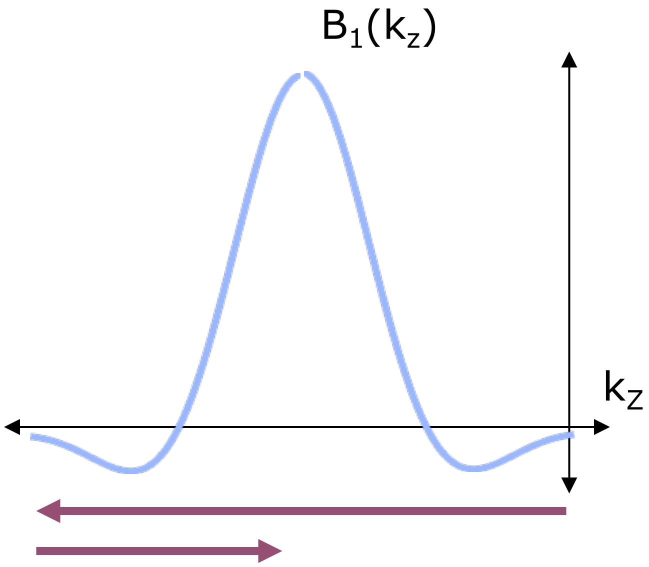
Spectral-Spatial RF Pulses

- Goals
  - Combine spectral and spatial selectivity into a single RF Pulse
- Methods
  - Excitation k-space
  - Joint Spectral and spatial k-space design

Excitation K-space



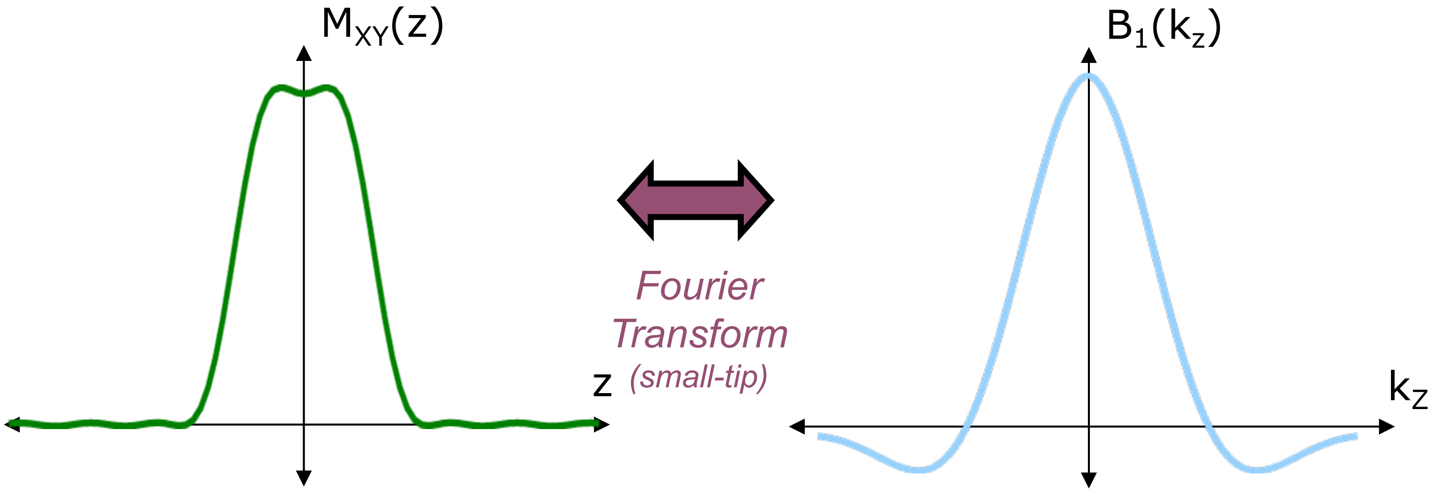
$k_Z = 0$



$$\vec{k}_{ex}(t) = \frac{\gamma}{2\pi} \int_t^T \vec{G}(\tau) d\tau$$

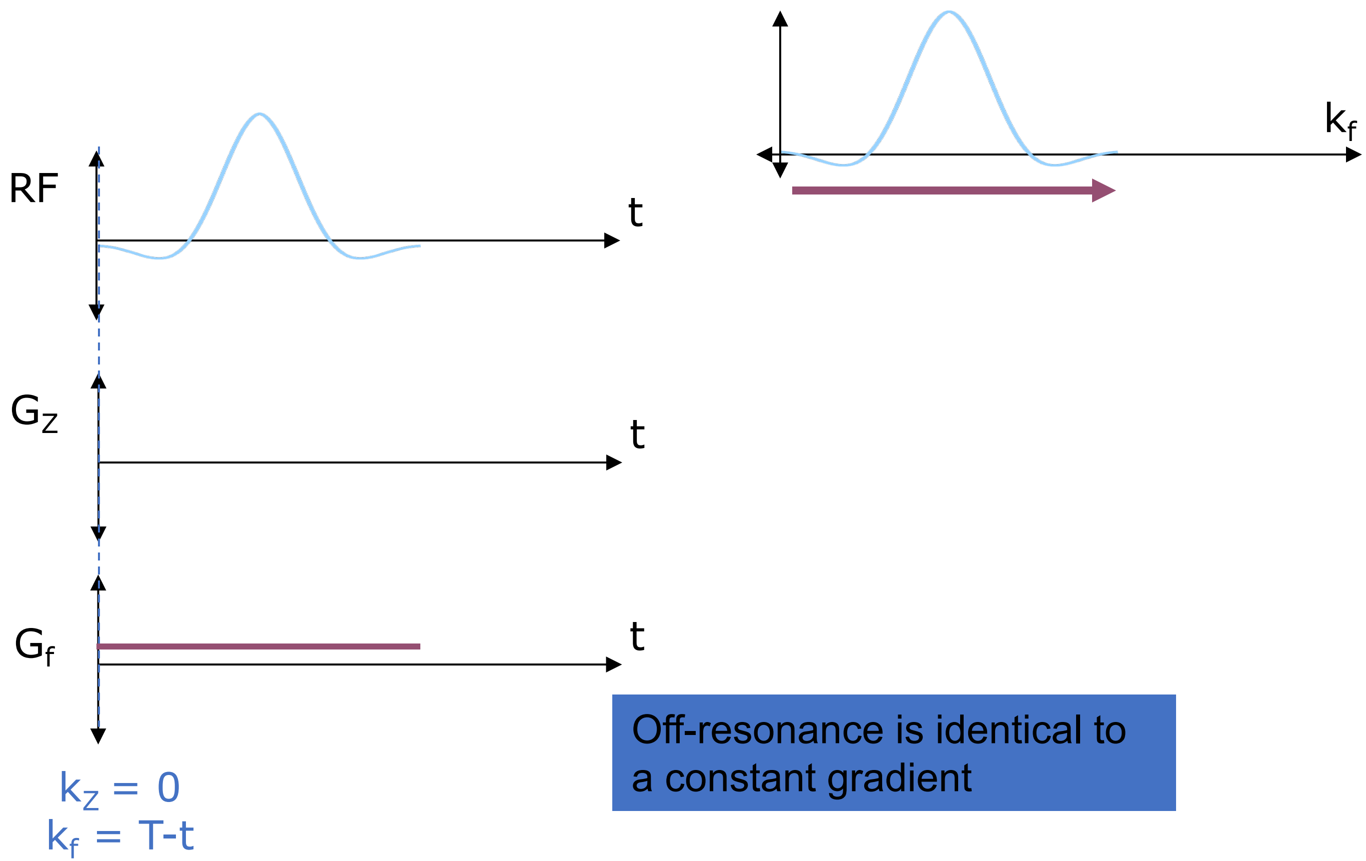
Always ends at center of excitation k-space: $\vec{k}_{ex}(T) = 0$

Excitation K-space



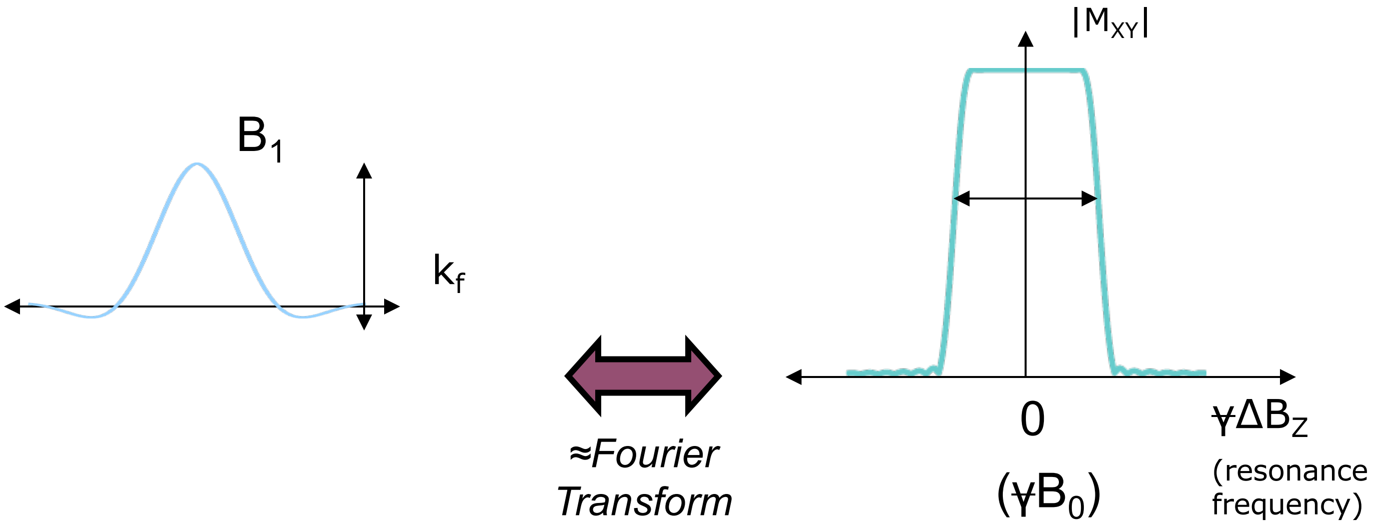
- RF pulse applied during gradient (kz) leads to magnetization profile in space (z)
- Analogous principle to (acquisition) k-space, where data acquired during gradient (kz) leads to image of the magnetization in space (z)

Excitation Spectral k-space



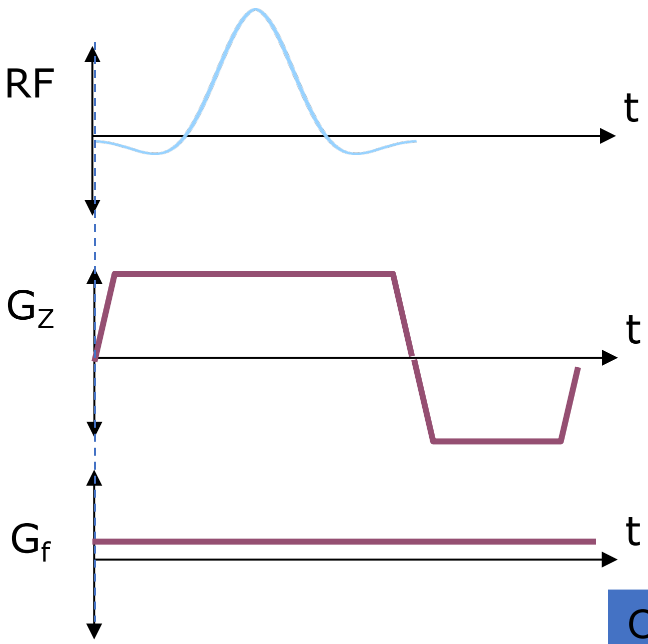
Off-resonance is identical to a constant gradient

Excitation K-space

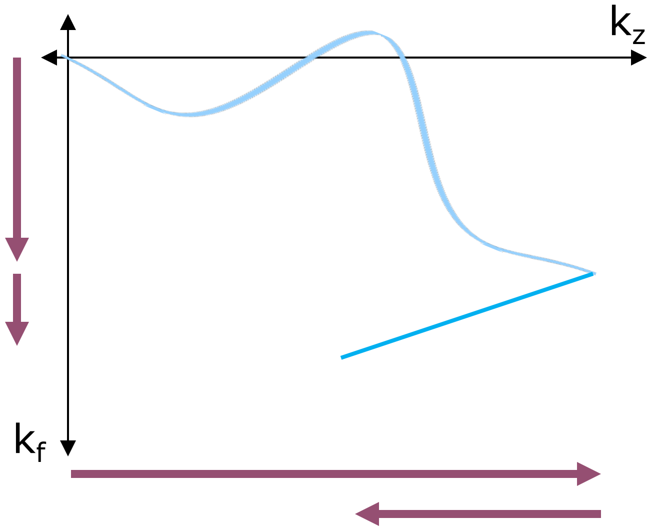


- RF pulse applied over time (kf) leads to magnetization profile in frequency (f)
- Analogous principle to (acquisition) k-space, where data acquired over time (kf) leads to spectrum of magnetization in frequency (f)

Excitation Spectral-spatial k-space



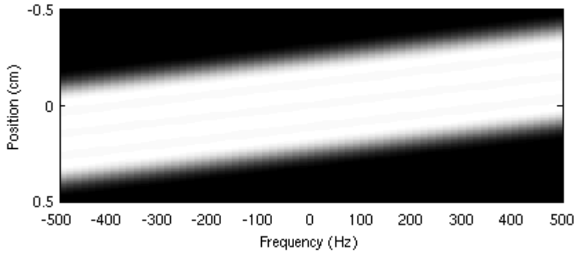
$k_Z = 0$
$k_f = t$



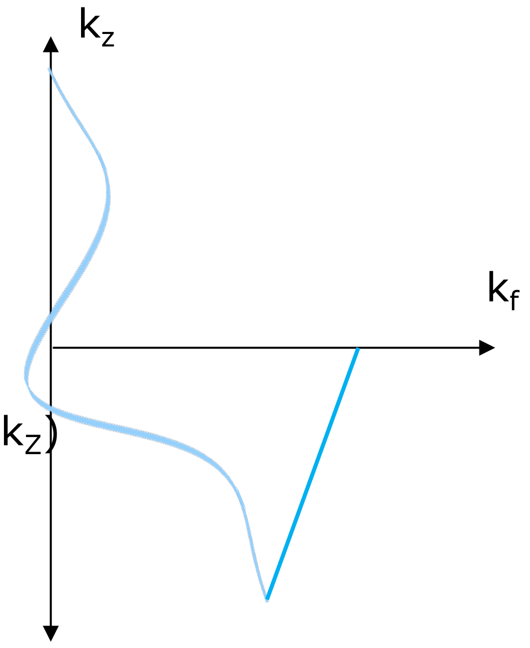
Off-resonance is identical to a constant gradient

Spectral-spatial Profile

$M_{XY}(f,z)$



≈Fourier Transform

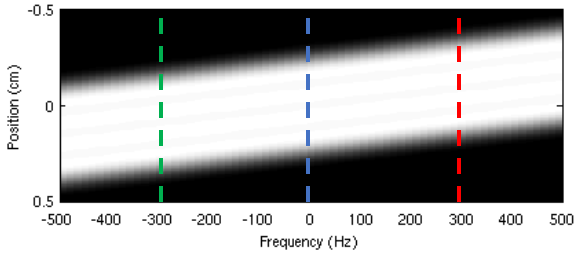


$b(k_f, k_Z)$

- RF pulse applied over time (kf) with gradient (kz) leads to magnetization profile in frequency and space (f,z)
- Analogous principle to (acquisition) k-space, where data acquired over time (kf) with gradient (kz) leads to spectroscopic image of magnetization in frequency and space (f,z)

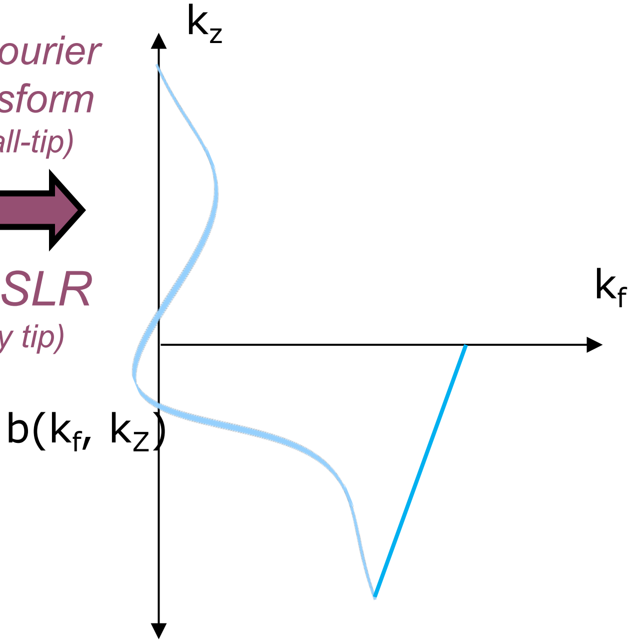
Spectral-spatial Profile

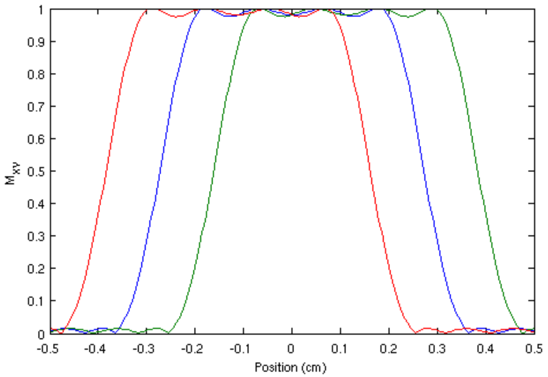
$M_{XY}(f,z)$



2D Fourier Transform
(small-tip)

2D SLR
(any tip)

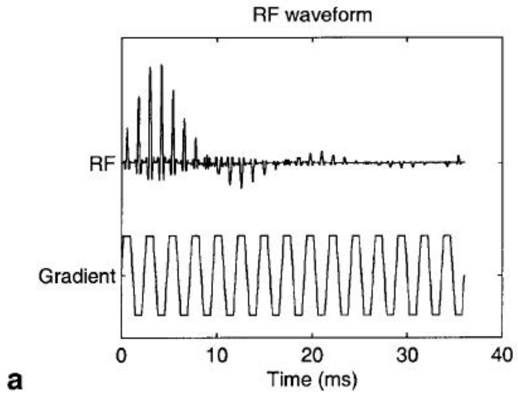


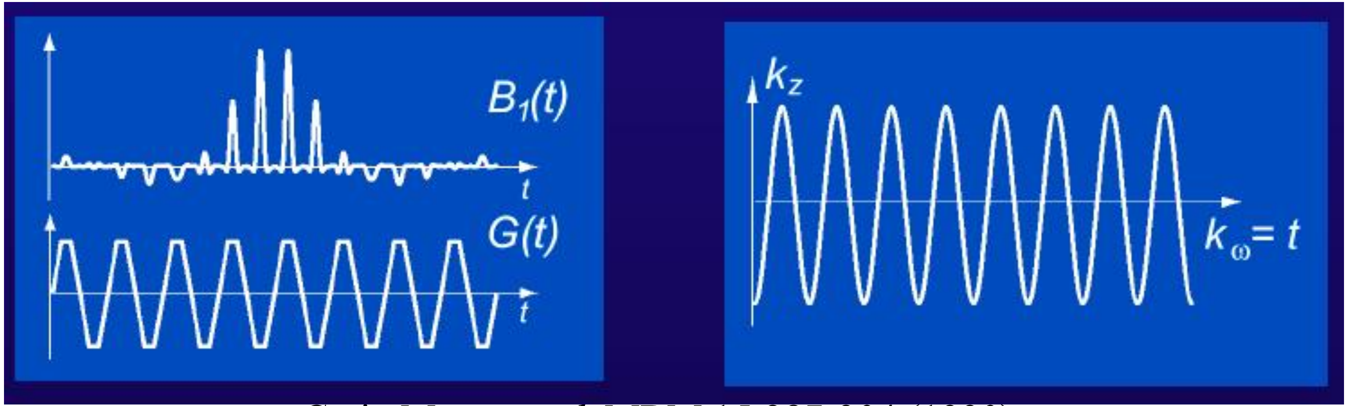


Chemical Shift slice misregistration

Spectral-spatial pulses

- Designed with spectral-spatial k-space ($k_{x,y,z}$ & $k_f = t$) in mind
- Spectrally and spatially selective

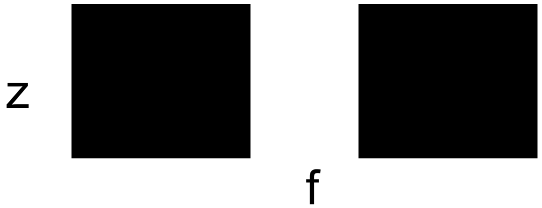




Craig Meyer *et al*. MRM 15:287-304 (1990)

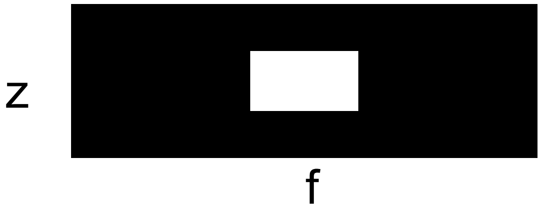
Spectral-Spatial Design

1. Design spectral pulse

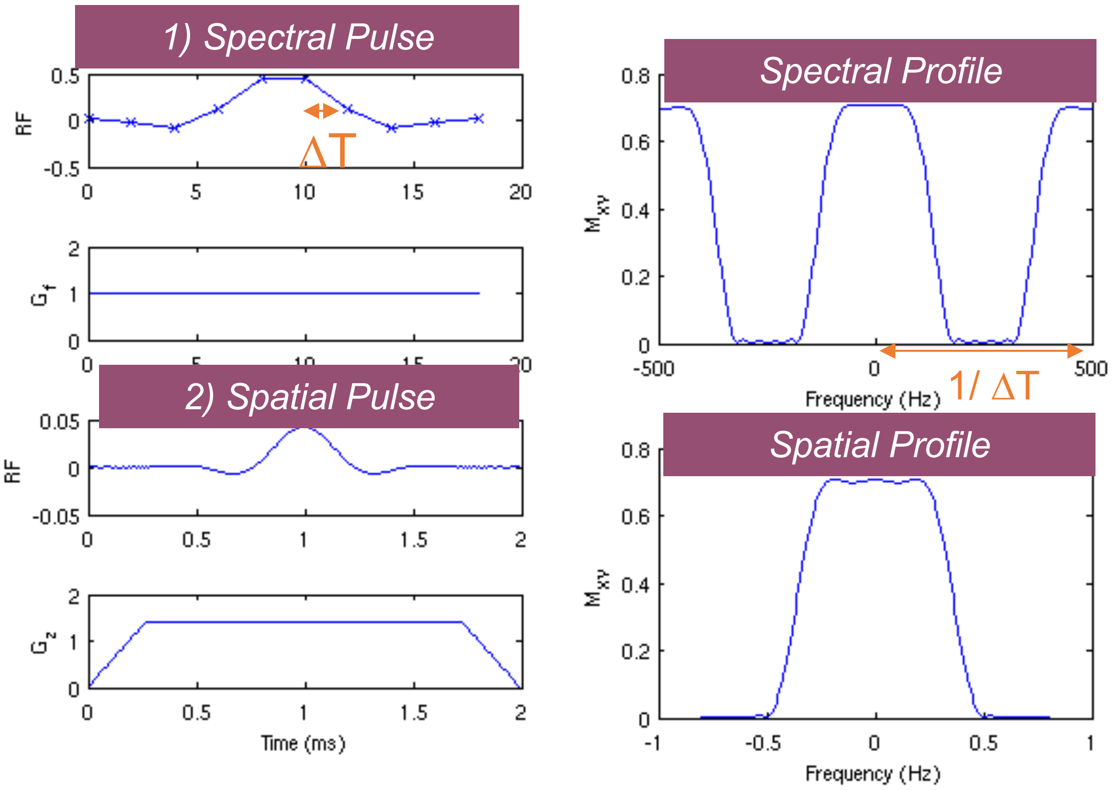


2. Design spatial pulse and slice select gradient

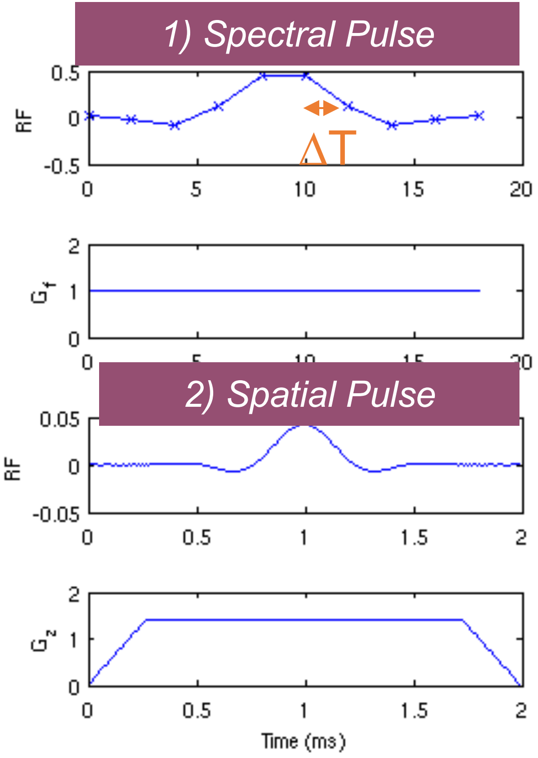
3. Use multiple spatial pulses and gradients
    - Weight spatial pulses with spectral pulse envelope
    - Alternate sign of gradient (EP) or add rewinder (flyback)

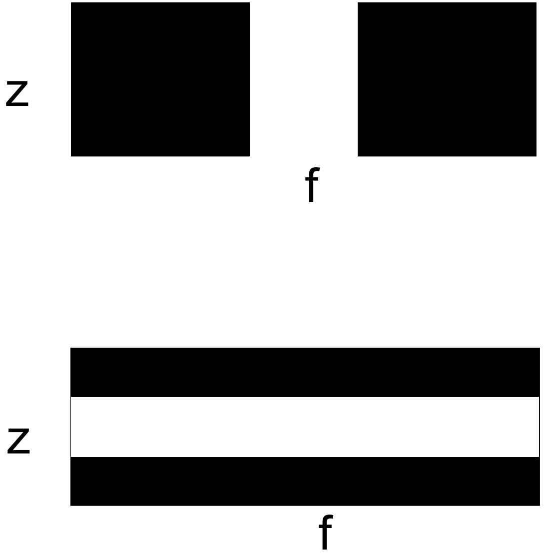


Spectral-Spatial Design

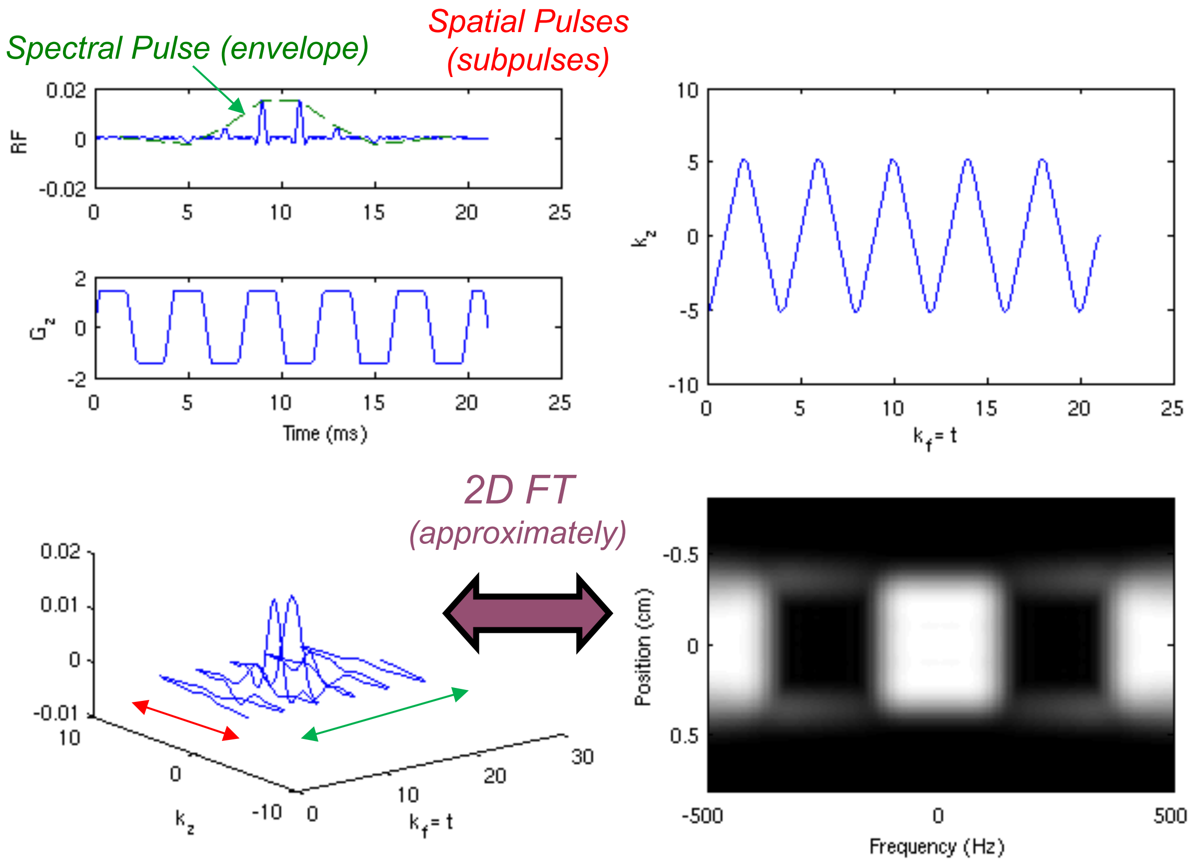


Spectral-Spatial Design

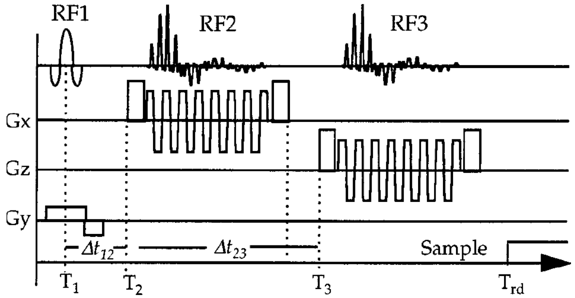




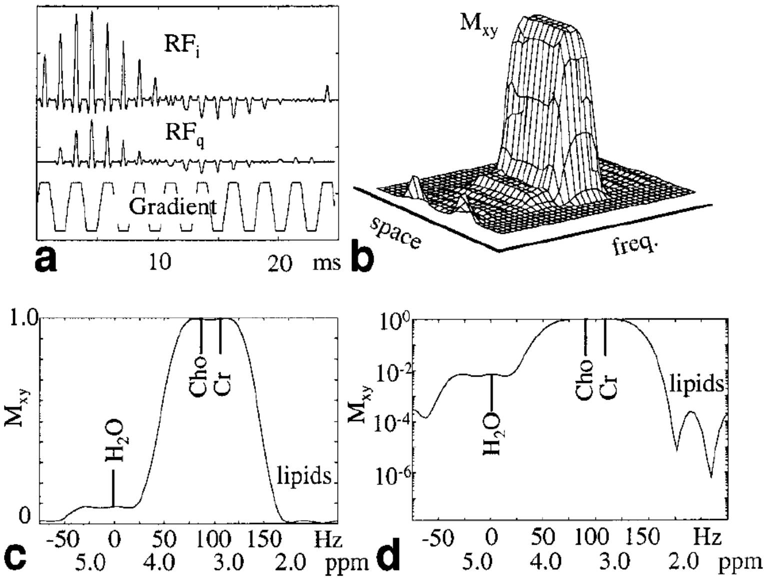
Spectral-Spatial Design



Spectral-Spatial Prostate MRSI Example



- Replace spin echo 180 pulses with spectral spatial pulses in PRESS
- Design such that NAA/Cr/Cho only within passband and water/fat are in stopband
- No need for CHESS (Spectrally-selective water suppression pulses)



A. Schricker et al. MRM 46:1079-1087 2001

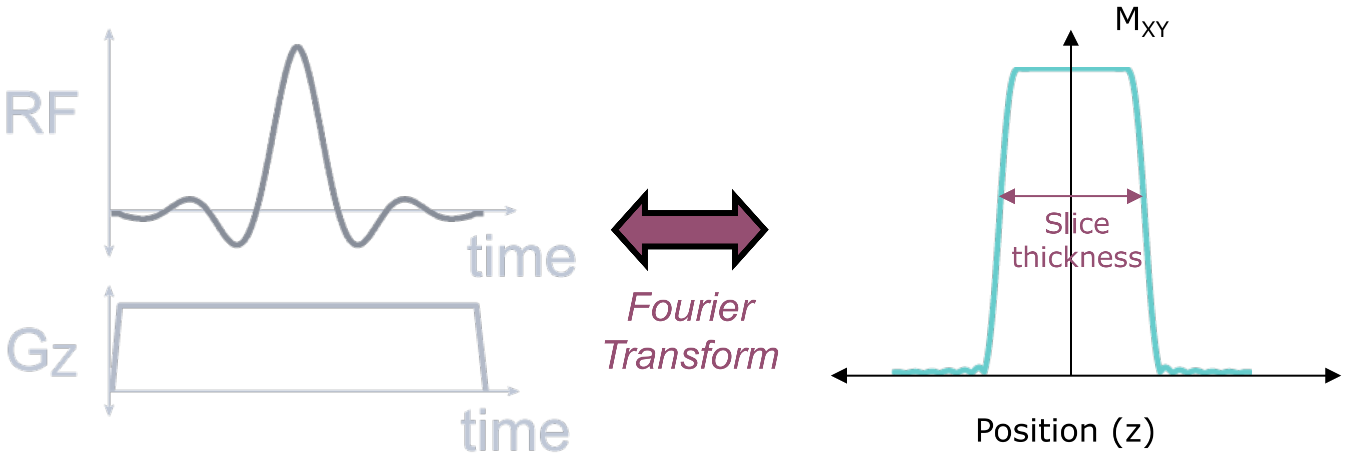
Designing a spectral-spatial RF Pulse?

- https://github.com/LarsonLab/Spectral-Spatial-RF-Pulse-Design
- Example pulse designs included

Other Materials for Reference

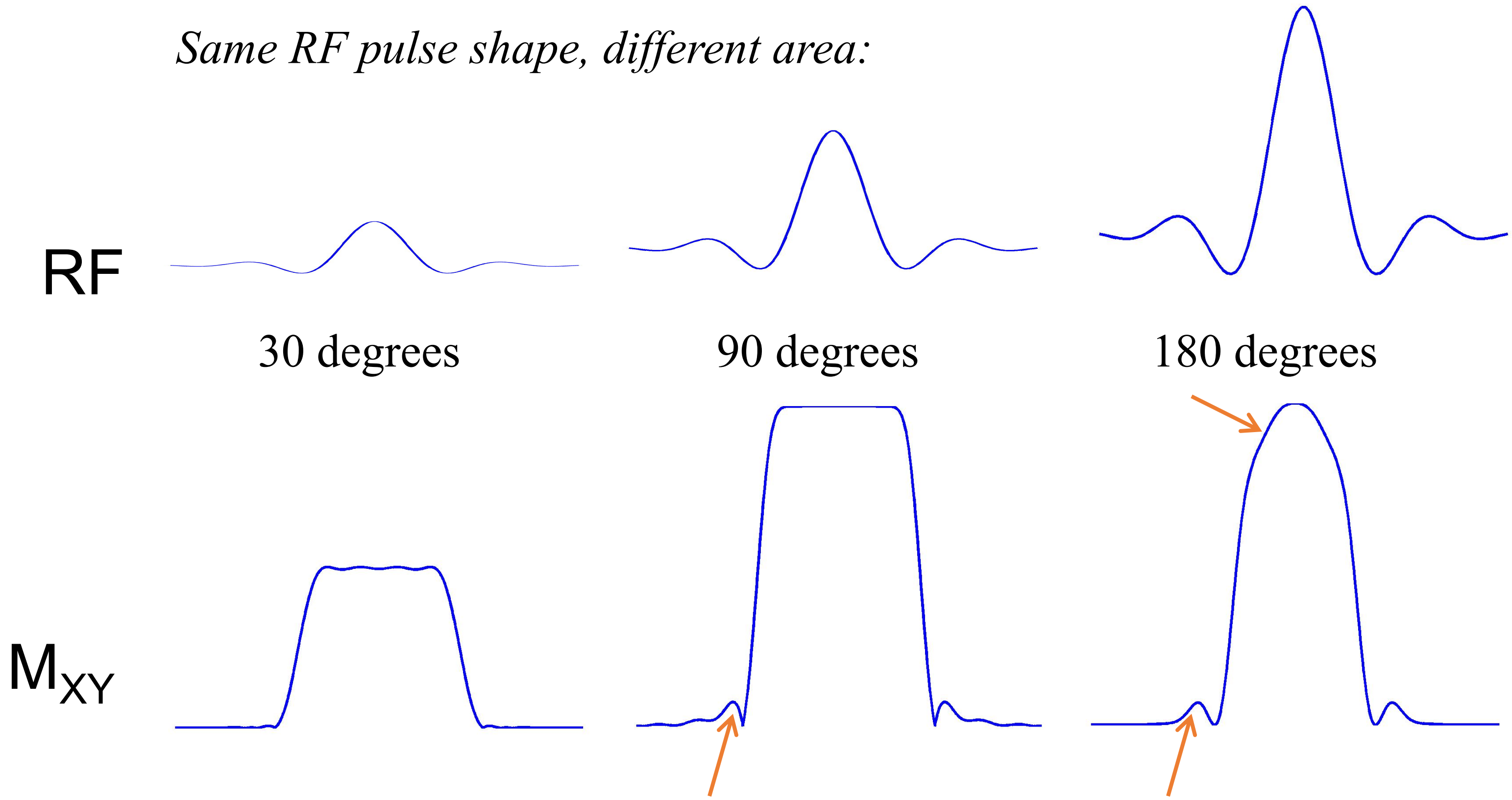
- Small vs Large Tip RF Pulse Design
- Adiabatic Pulses
- Non-linear Phase Pulses

Spatial Profile (Small-Tip)



Breakdown of the small-tip/Fourier approximation

Same RF pulse shape, different area:

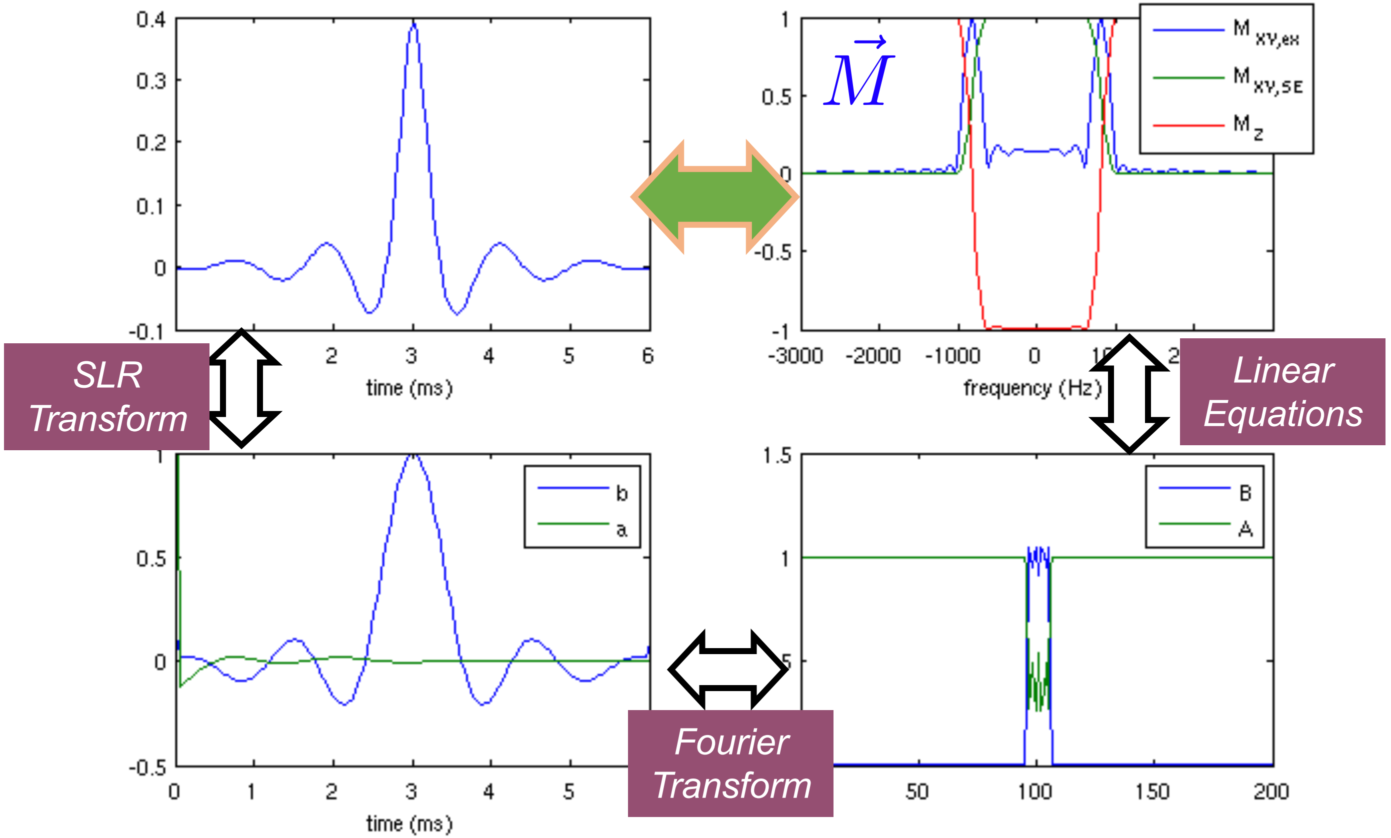


Shinnar-Le Roux (SLR) Transform

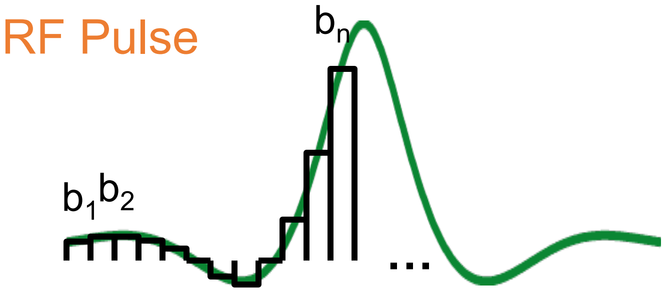
- Accounts for non-linearity in Bloch Equation (unlike Fourier Transform)
- Precisely match desired profile – critical for large tip angles (90°, 180°s)
- Can design for
  - Excitation (M_Z ➔ M_{XY})
  - Saturation (M_Z ➔ M_Z)
  - Spin-echo (M_{XY} ➔ M_{XY})
  - Inversion (M_Z ➔ M_Z)
- Phase control
- Time-bandwidth (TBW) - primary design parameter

Pauly JM et al. IEEE-TMI 10:53-65 (1991).

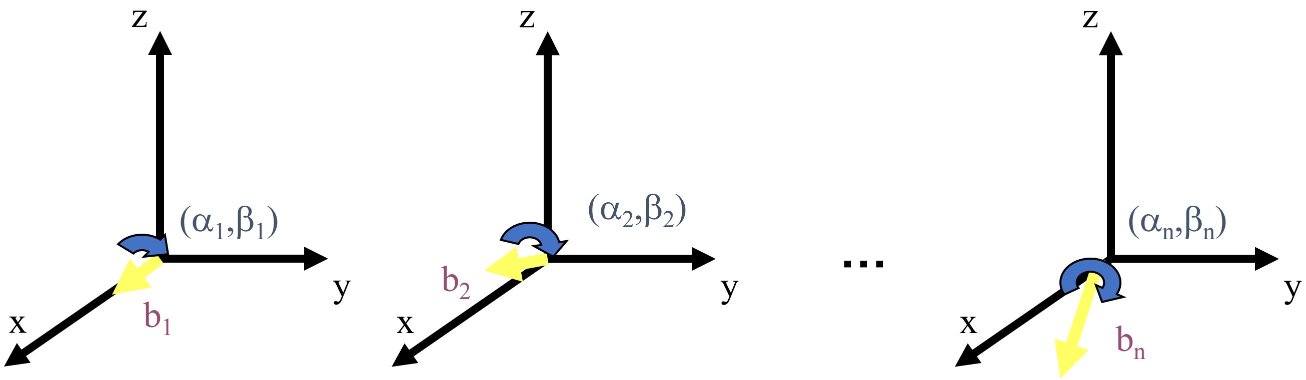
SLR Transform



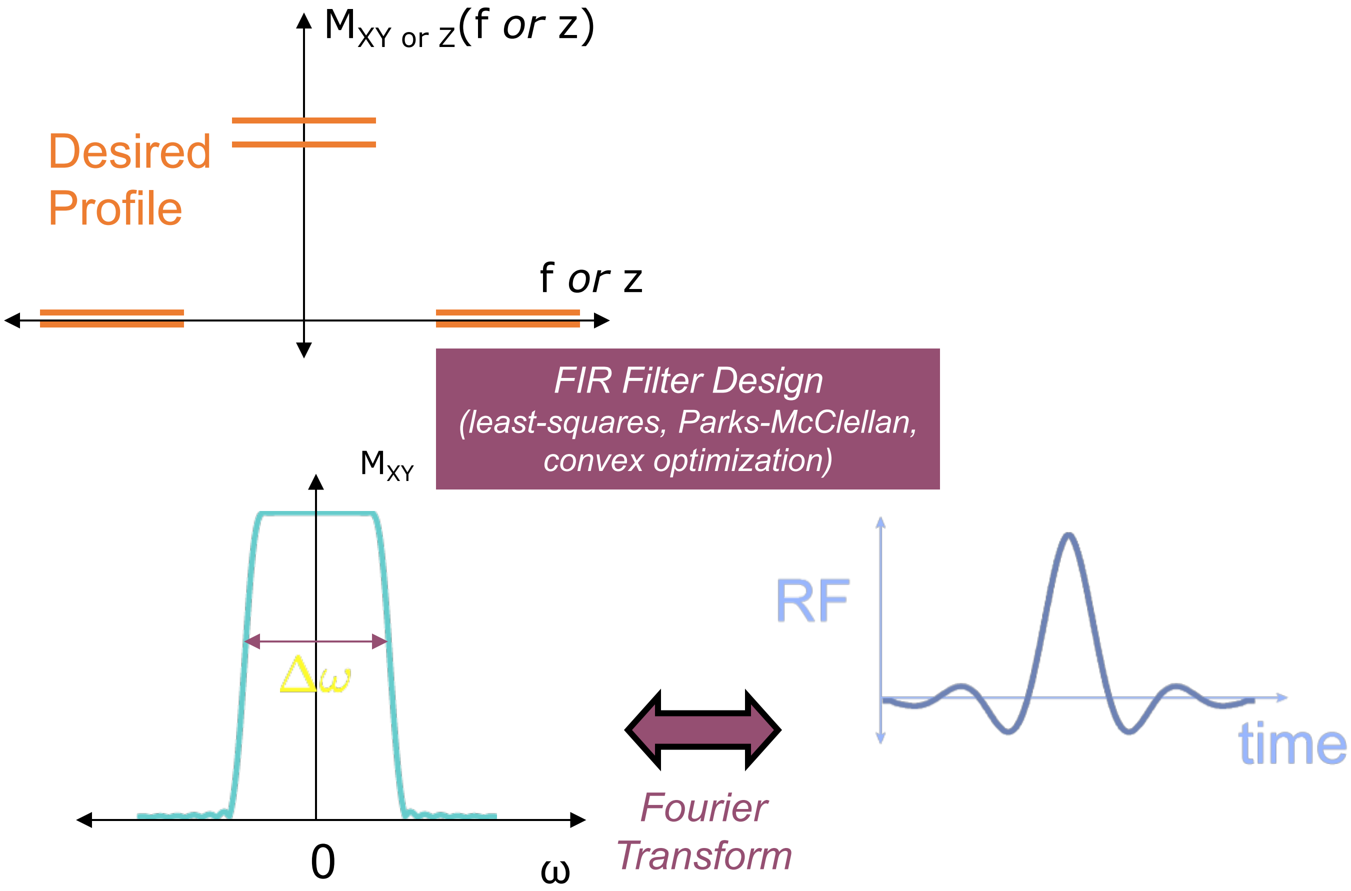
SLR uses Hard Pulse Approximation



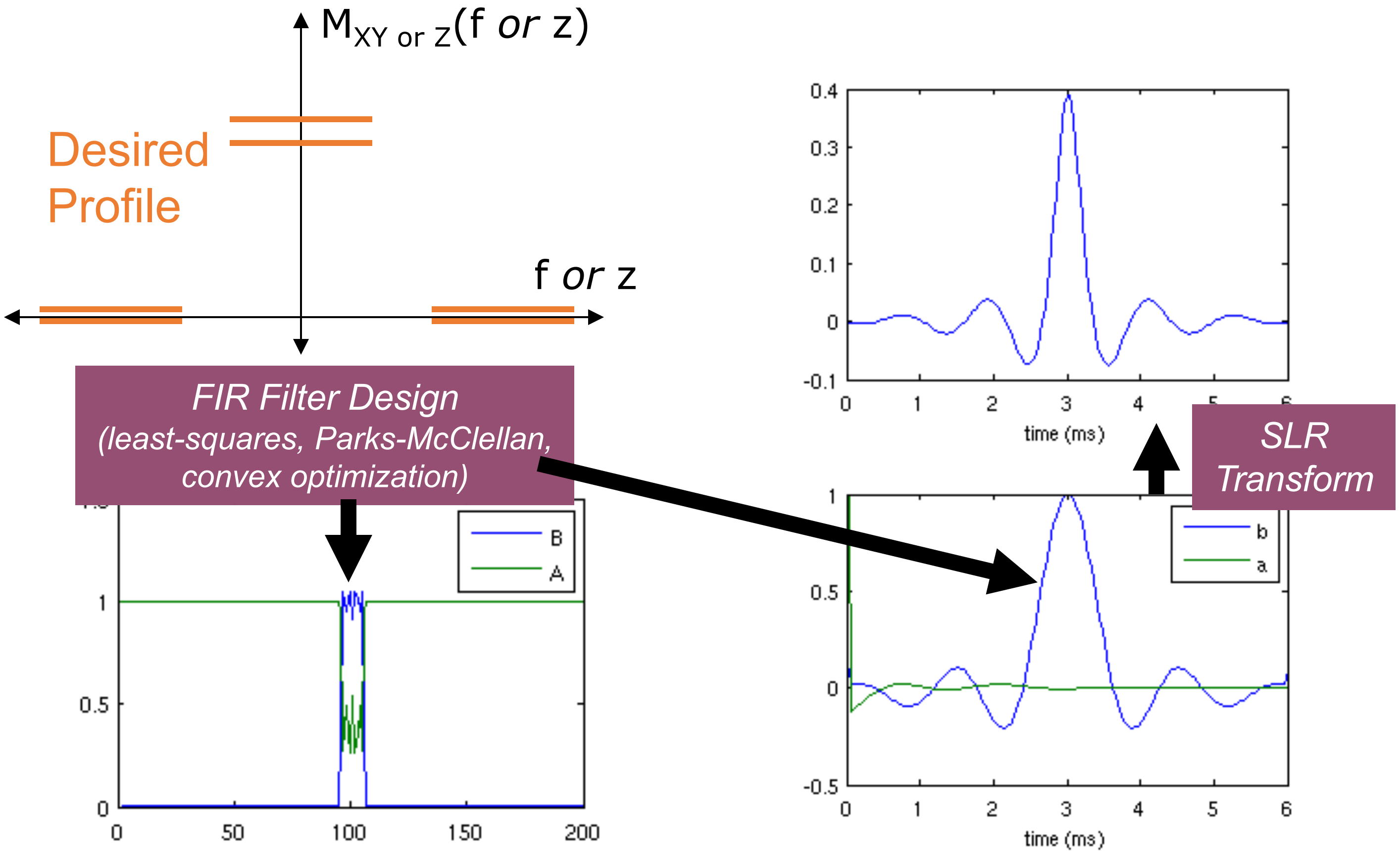
- Can describe rotation for each RF sample by (α_1,β_1)
  - Done at off-resonance frequencies too
- These determine a(n), b(n) and the magnetization profiles



RF Pulse Design: Small-tip



RF Pulse Design: SLR Transform



SLR Summary

- Design large-tip (90°, 180°) pulses
- Based on hard-pulse approximation
- Can utilize tools from FIR Filter Design from electrical engineering
  - Well-established
  - Precise control over magnitude and phase response

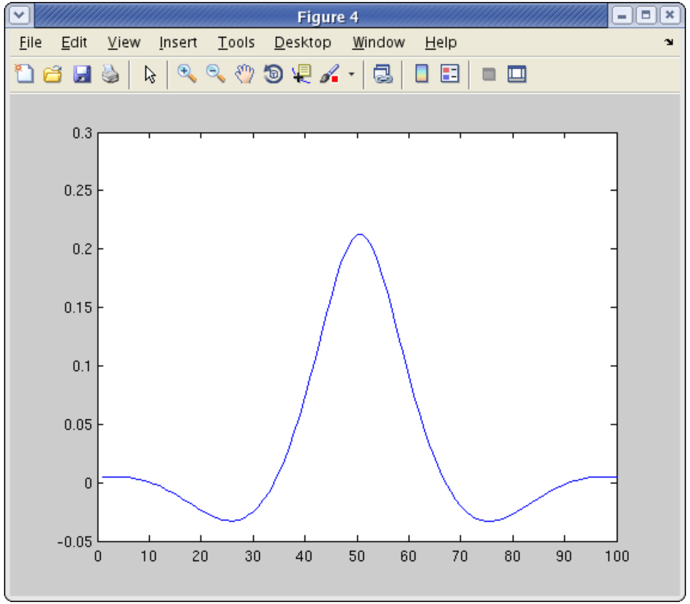
MATLAB RF Pulse Design

Designing an RF pulse using rf_tools package (available at http://rsl.stanford.edu/research/software.html)

- Includes SLR transforms for pulse design and pulse simulation
- rf = dzrf(Npoints, TBW, pulse_type, filter_type, passband_ripple, stopband_ripple);
  - TBW: time-bandwidth product
  - pulse_type: small-tip, excitation, spinecho, inversion, saturation
  - filter_type: Equi-ripple, least-squares, min/max phase
  - ripple: allowed variations in pass and stop bands

dzrf

rf = dzrf(100, 4, ‘se’);

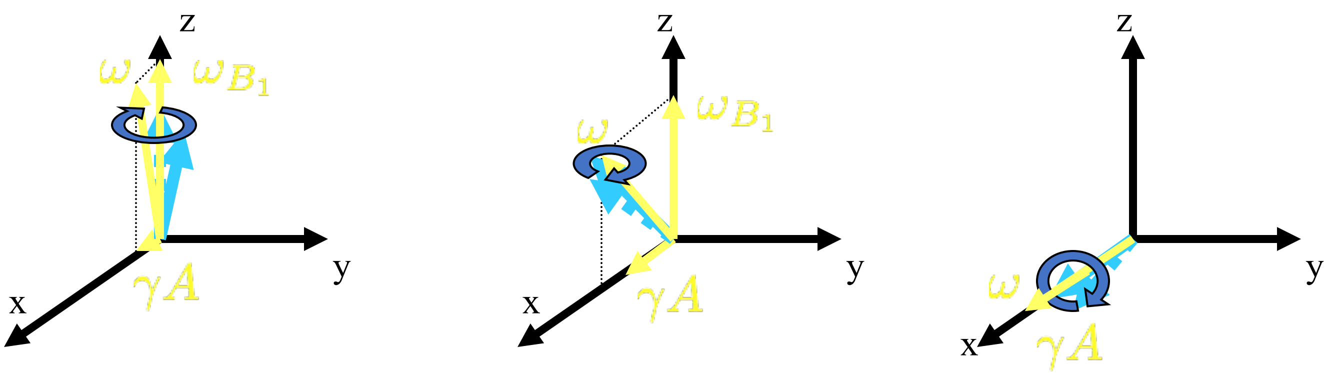


Adiabatic Pulses

- Utilize Spin-locking
  - Different from non-adiabatic pulses
  - Different design methods
- Advantages
  - Pulses are insensitive to fluctuations in B1
  - Best for 180º pulses
- Disadvantages
  - Less flexible design
  - arbitrary flip pulses (BIR-4) require very long durations (~ 4X SLR pulses)
- Applications:
  - Inversion
  - B1-insensitive spin-echo

Spin-locking

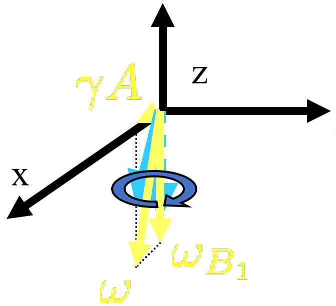
$$d\vec{M} = \vec{\omega} \times \vec{M}$$



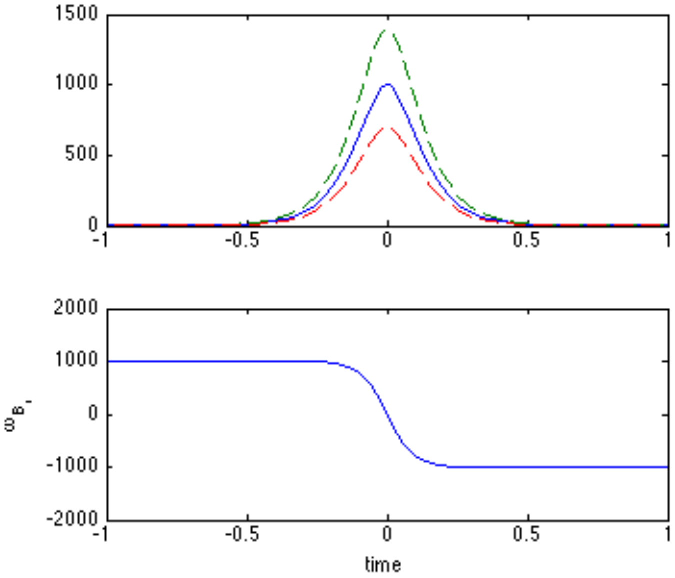
Apply the RF pulse at off-resonant frequency (time-varying)

Frequency modulated RF pulse:

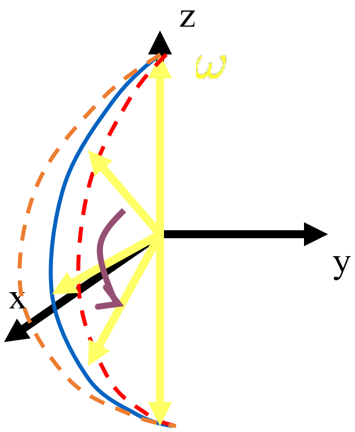
$$B_1(t) = A(t)e^{\omega_{B_1}(t)t}$$



Adiabatic Inversion Pulse (Sech)



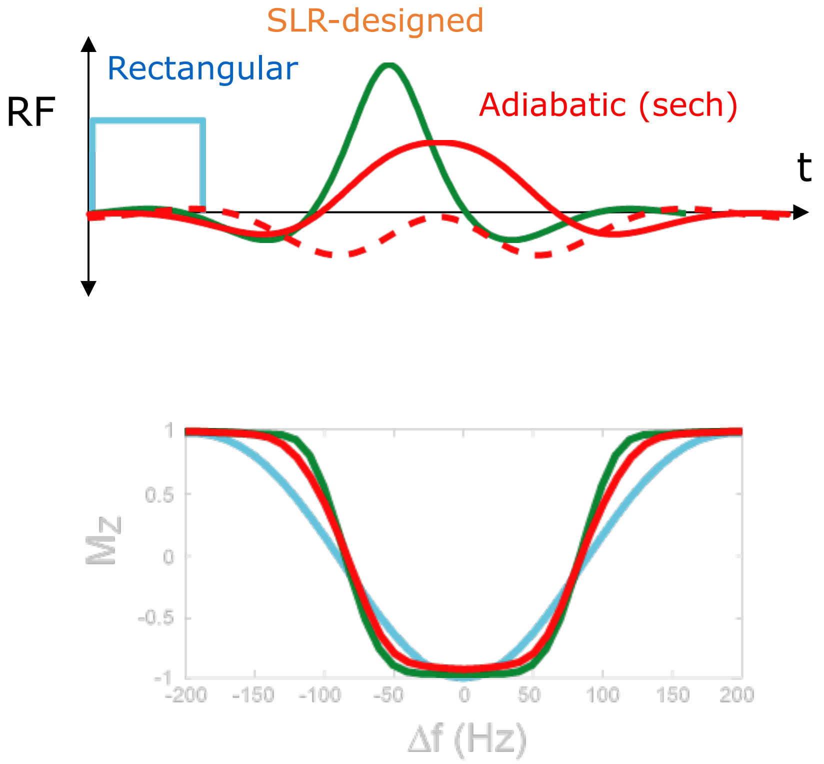
$$\omega_1(t) = \omega_1^{max} \mathrm{sech}(\beta t) e^{i\mu\beta \tanh(\beta t) t}$$



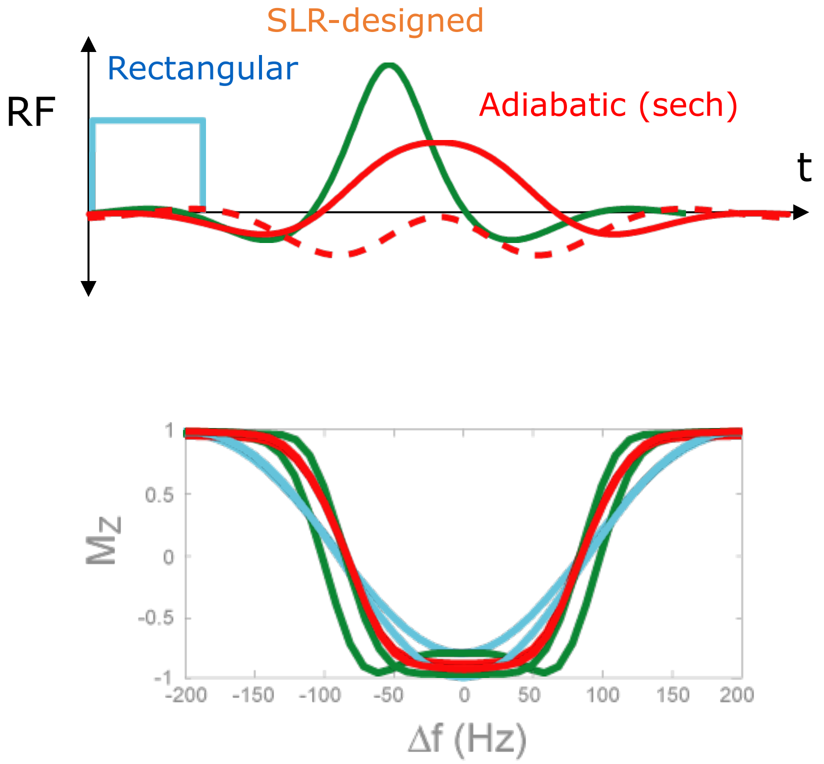
"Frequency Sweep"

Tolerant of B1 amplitude variations

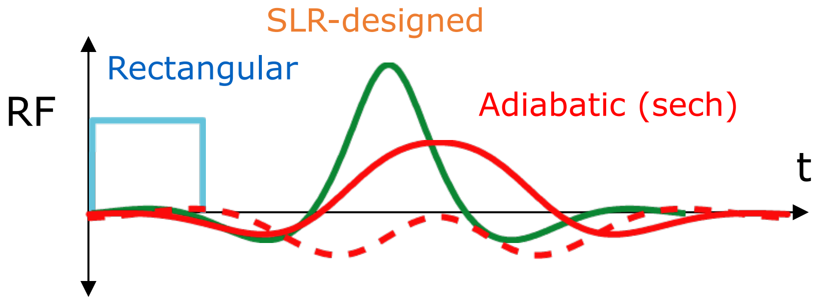
Inversion Pulses

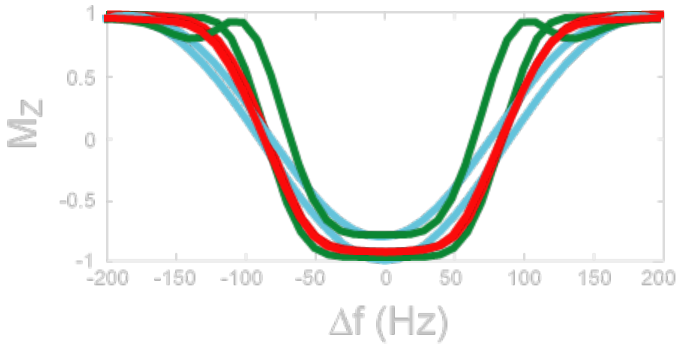


Inversion Pulses



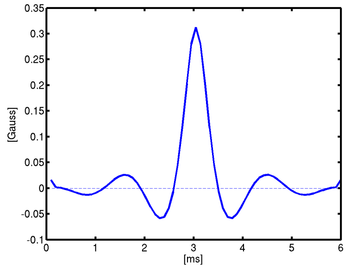
Inversion Pulses





Linear Phase RF pulses

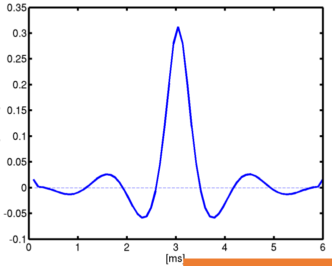
- Most common RF pulse type
- Sinc and sinc-like SLR are linear phase
- Conjugate symmetric in time
- Linear phase required for 2D slice imaging
- Linear phase can be refocused by gradient and/or spin-echo



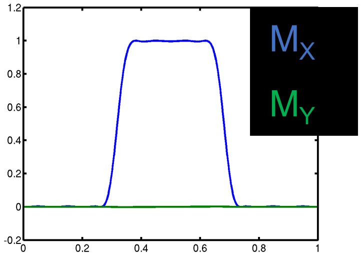
Non-linear Phase Pulses

Linear Phase

RF pulse



Refocused Profile



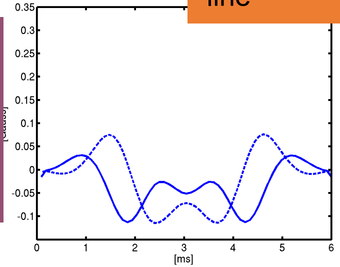
- ***|Profile| is the same***
- Peak B1 reduced
- Good for saturation, since phase is not important

real(RF) - solid line

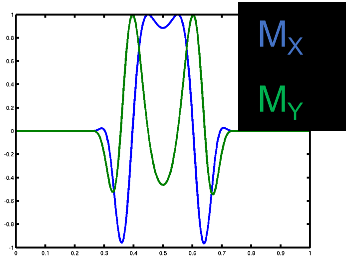
imag(RF) - dashed line

Quadratic Phase

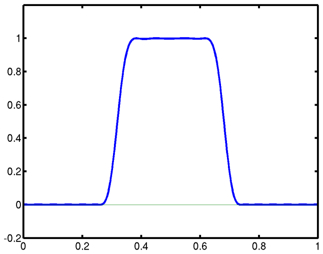
RF pulse



Refocused Profile

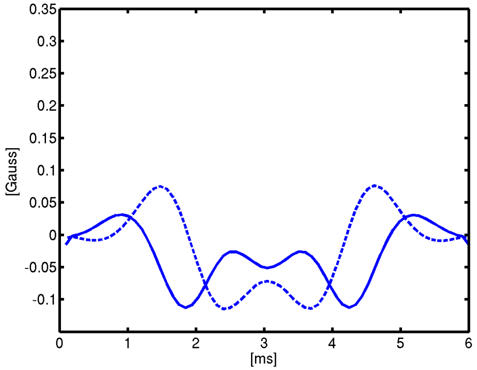


|Profile|



Non-linear Phase RF pulses

- Non-linear phase advantages
  - Reduced peak B1 amplitude
  - Sharper slice profiles
- Applications
  - Saturation (VSS)
  - Slab excitation
- Maximum-phase saturation pulse:
  - rf = dzrf(100, 4, ‘sat’, ‘max’);



RF Pulse Design Resources

- rf_tools software package (Matlab) by John Pauly
  http://rsl.stanford.edu/research/software.html
  - Lots of simple design functions
  - Includes SLR transform
  - Simulates profiles
  - Inversion, excitation, non-linear phase
  - dzrf.m is primary function
- John Pauly's RF Pulse Design Class at Stanford
  http://ee469b.stanford.edu
  - Includes notes, assignments, code examples
  - Can take it for UCSF credit