
Pulse Sequences: RARE and Simulations

M229 Advanced Topics in MRI

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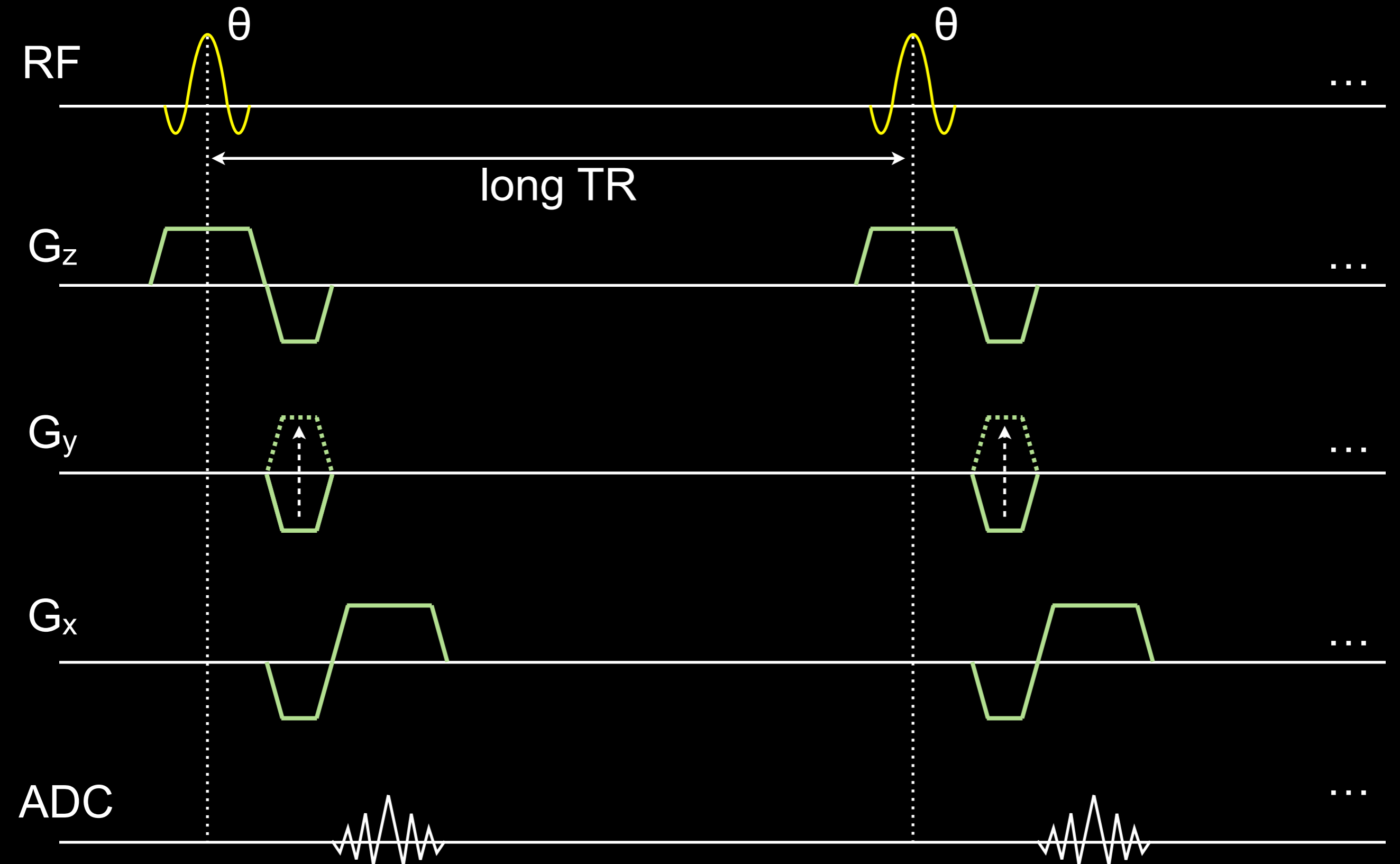
Class Business

- Office hours
 - Holden: by appointment
 - Wenqi: Fri 1-3 pm
- Homework 1 due on 4/19 Fri
- Final project
 - Start thinking
 - Discuss over email or during office hours
 - Discussion in class on 5/2 Thu

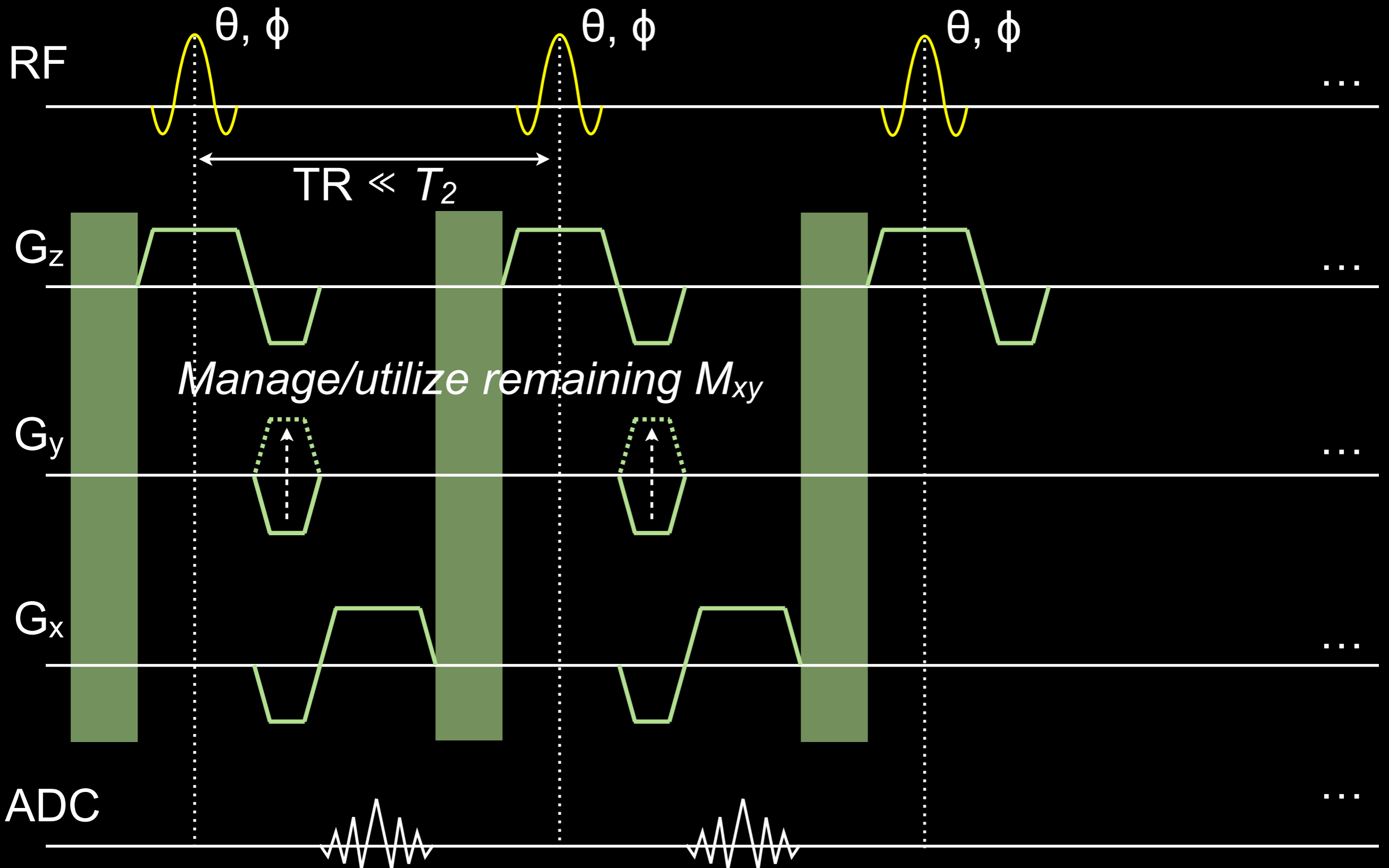
Outline

- Rapid GRE
 - Review
- RARE (aka FSE, TSE)
- Pulse sequence simulations
 - MATLAB Bloch simulations
 - Homework 2

Gradient Echo



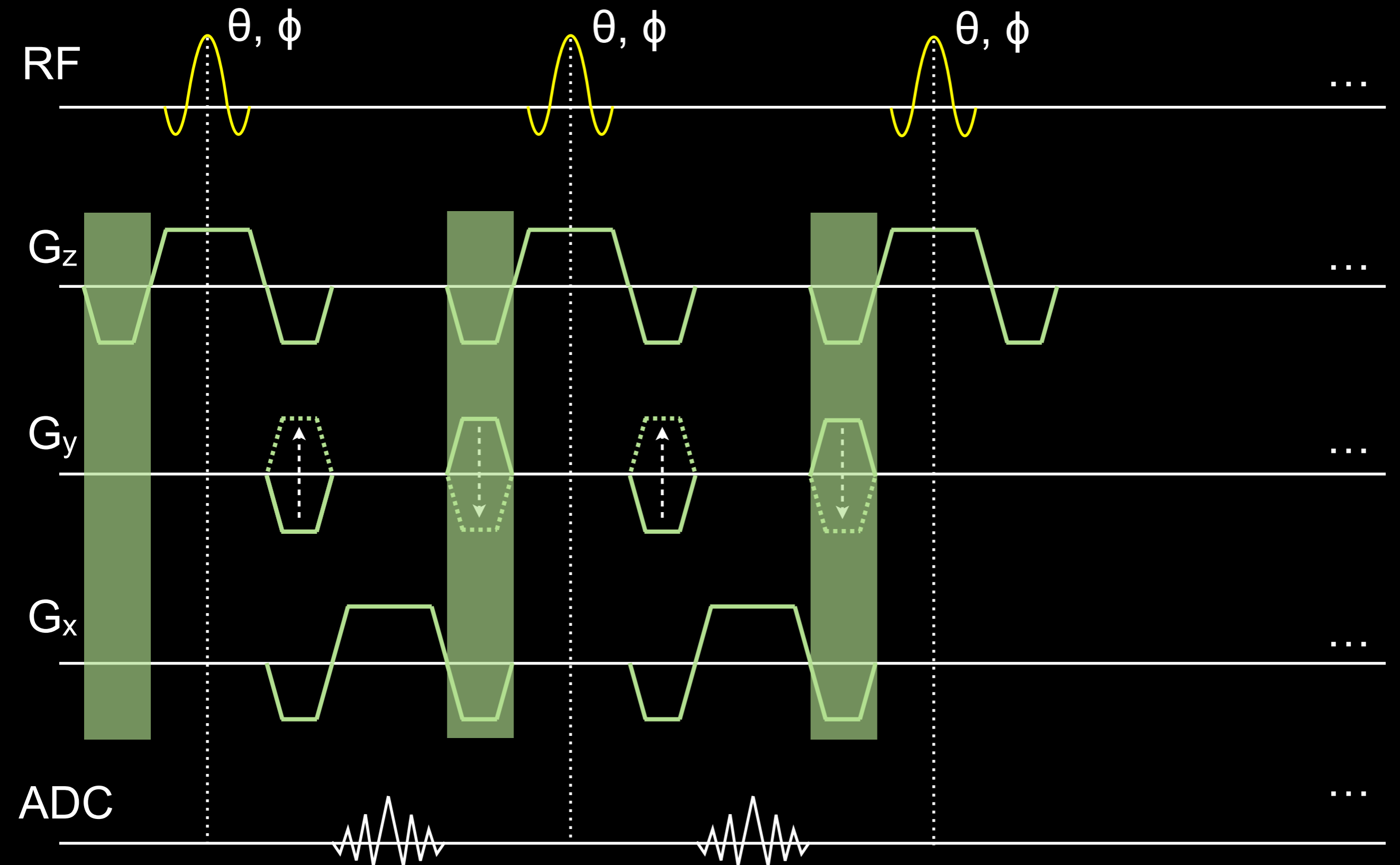
Rapid Gradient Echo



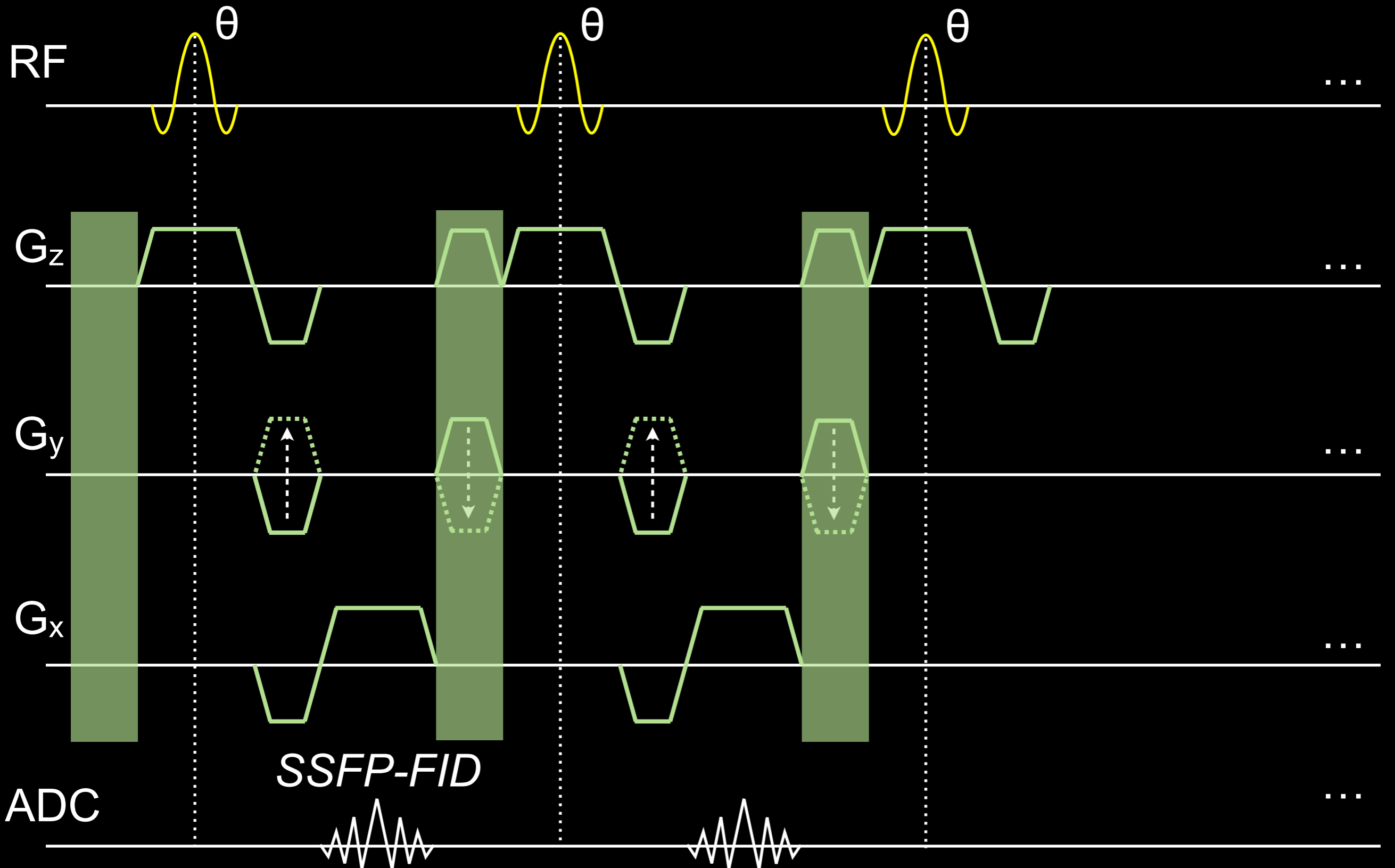
Rapid Gradient Echo

- Rapid imaging with $TR \ll T_2 < T_1$
- Steady state
 - Involves a mixture of M_z and M_{xy}
 - Necessary and sufficient conditions:
 1. Constant RF flip angle θ
 2. Constant TR
 3. Constant dephasing β between RF pulses
 4. RF phase $\phi_n = a + bn + cn^2$

Balanced SSFP

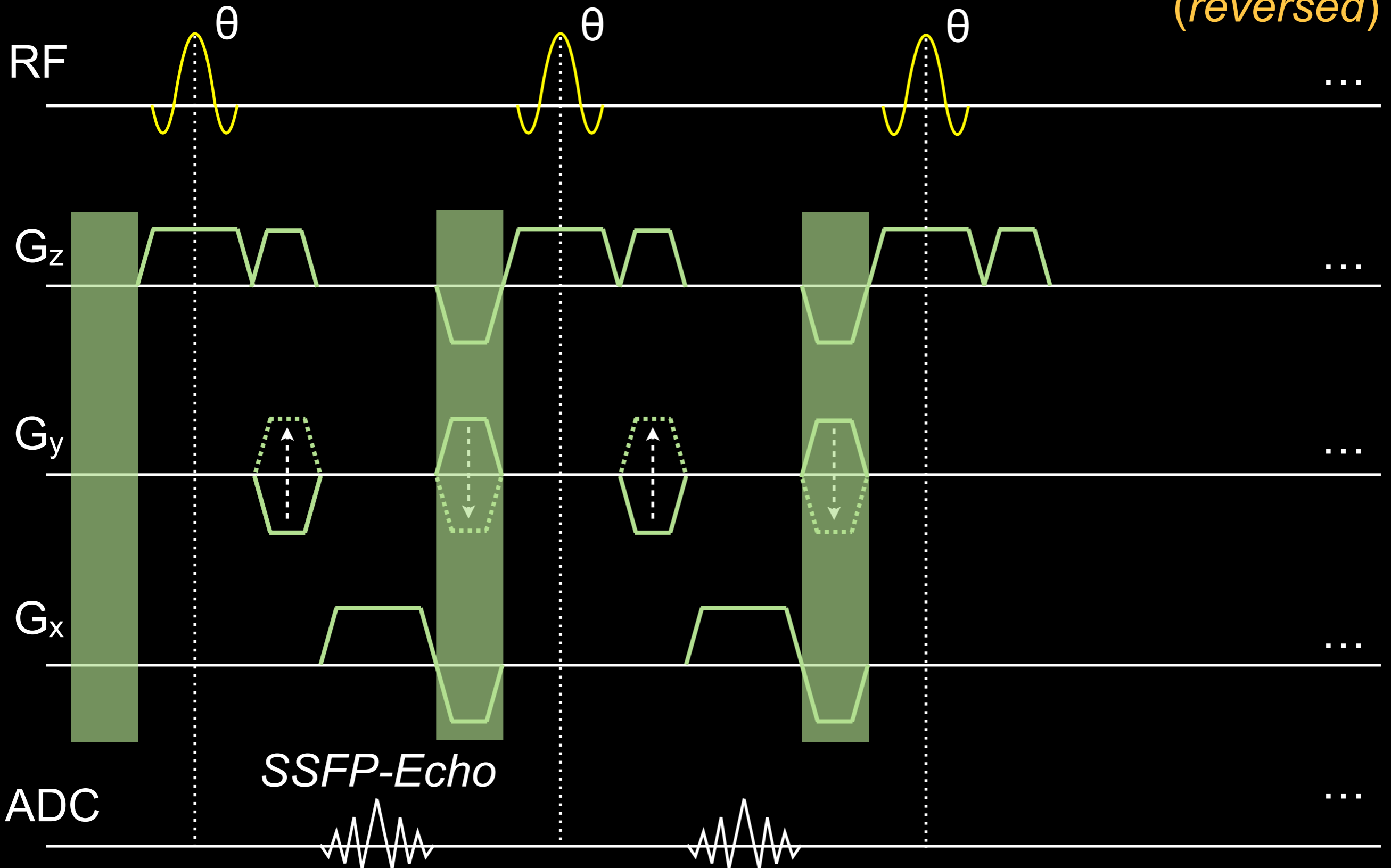


Gradient-spoiled GRE

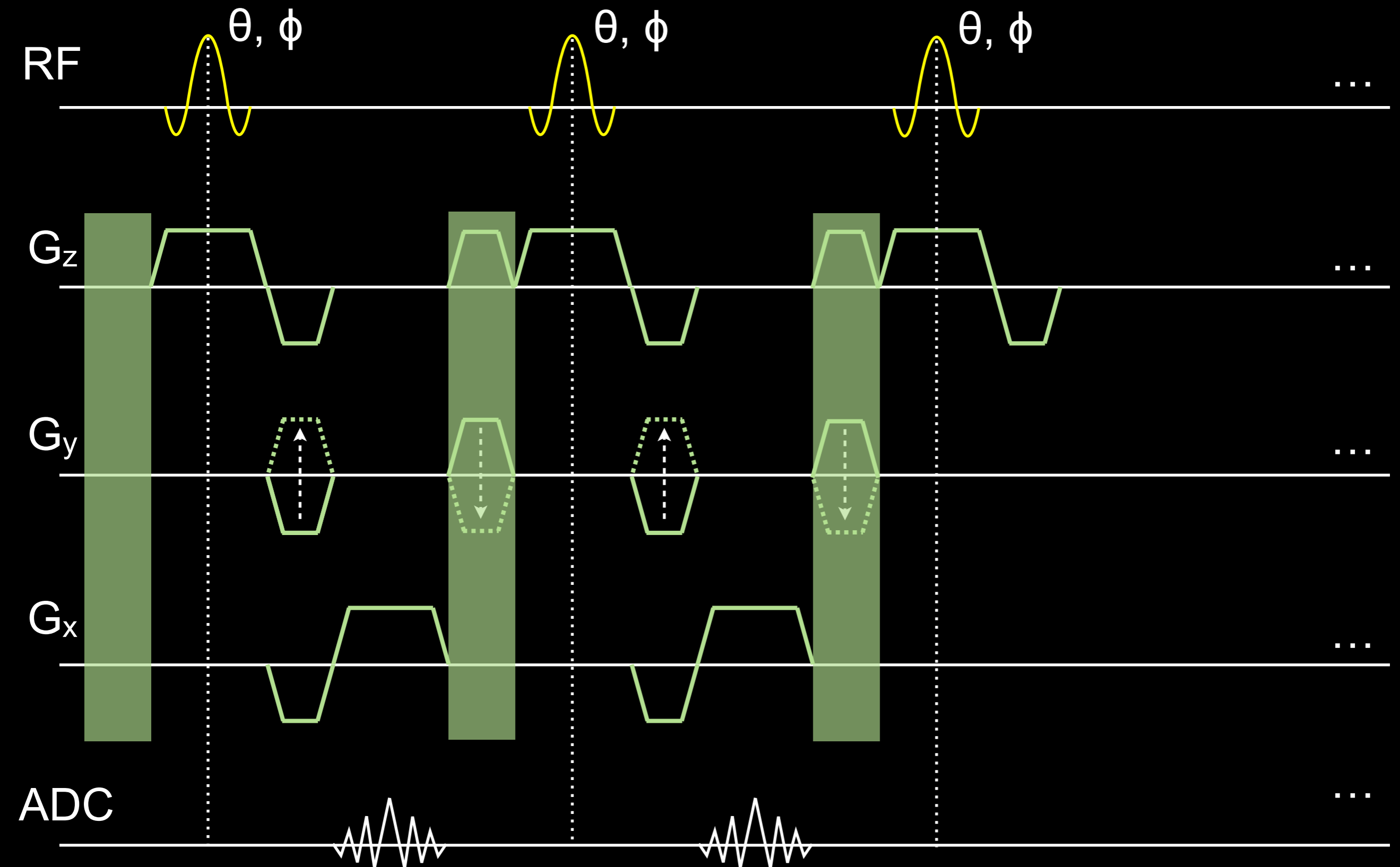


Gradient-spoiled GRE

(reversed)



Gradient & RF-spoiled GRE

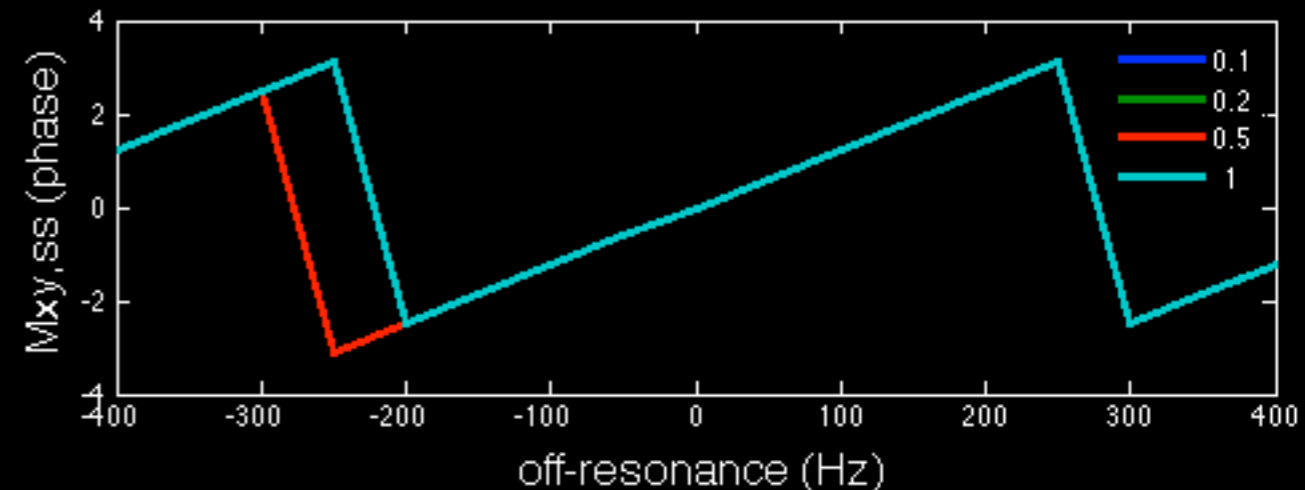
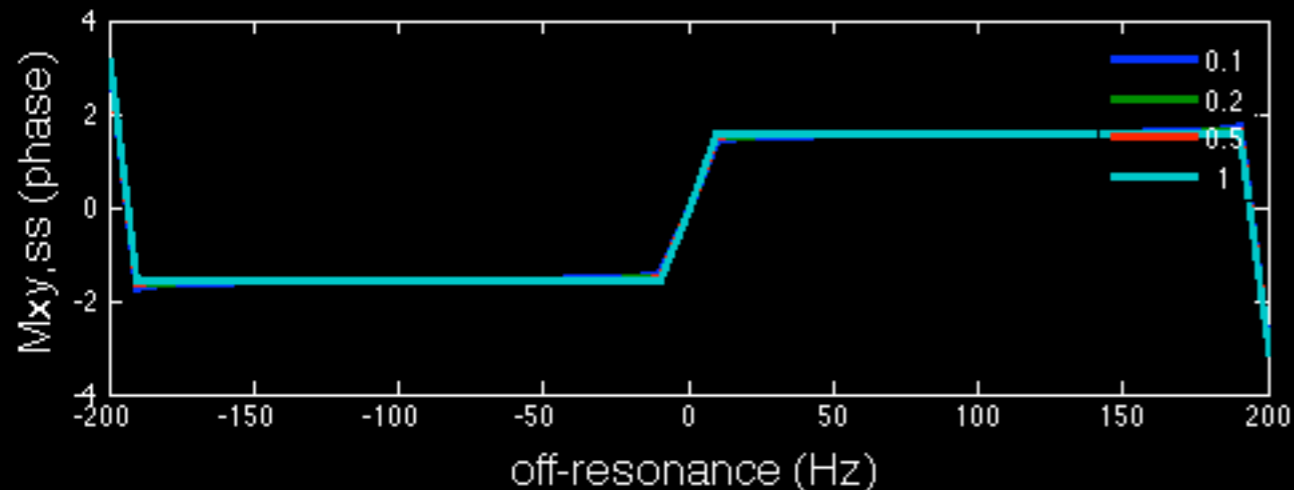
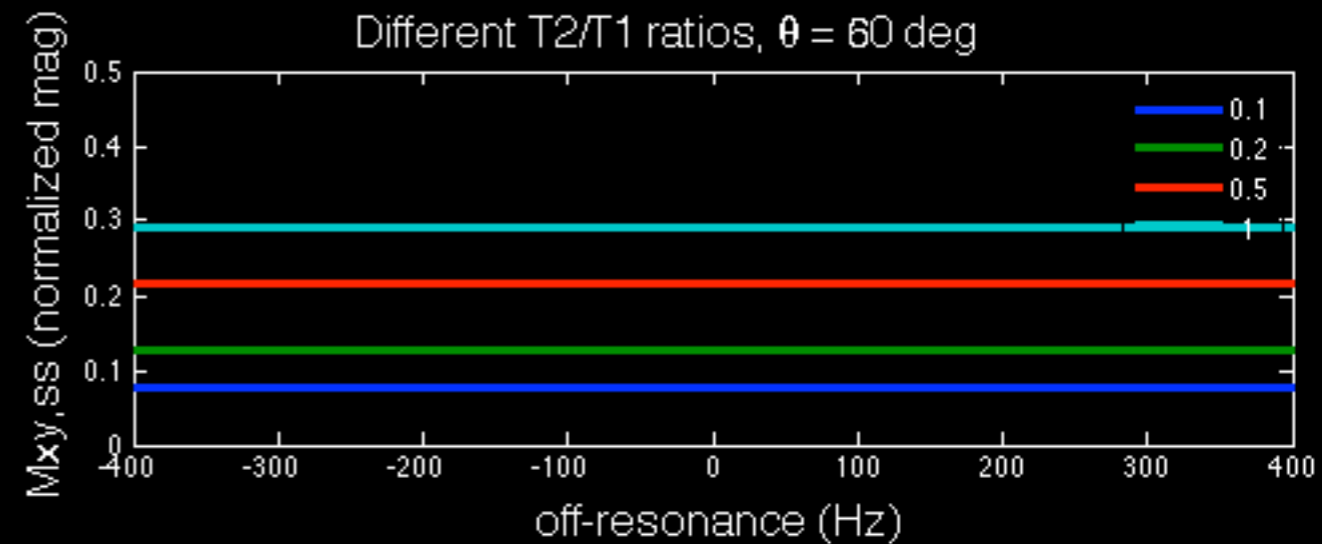
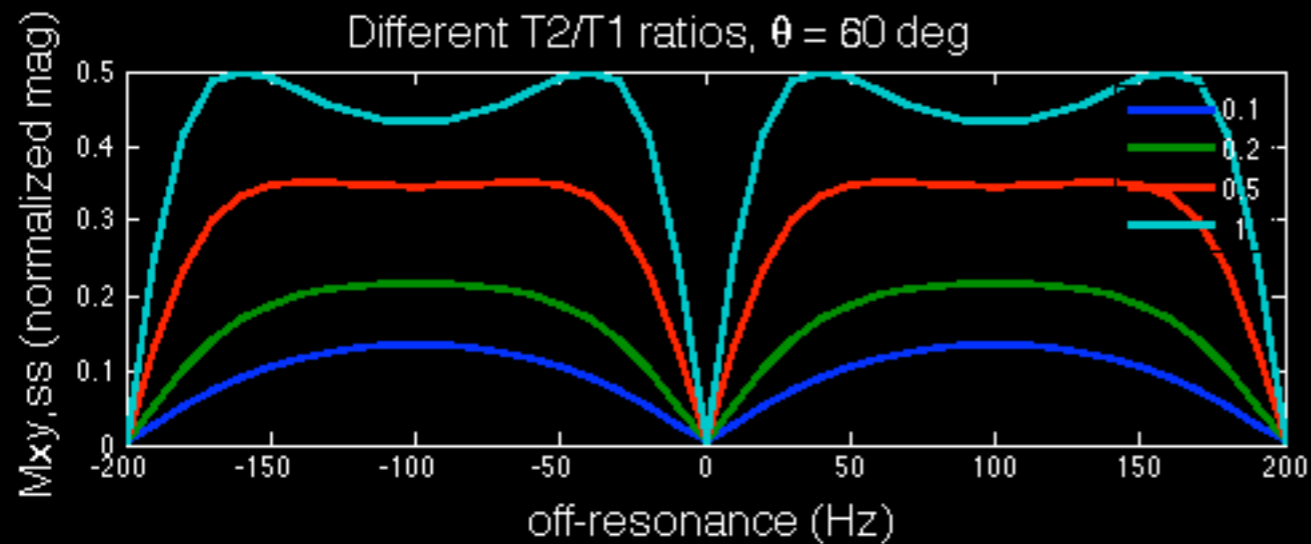


Gradient-spoiled GRE

SS signal as a function of off-resonance:

bSSFP

GRE (SSFP-FID)



$T_1 = 1000$ ms, $T_2 = 100, 200, 500, 1000$ ms

Gradient and RF-spoiled GRE

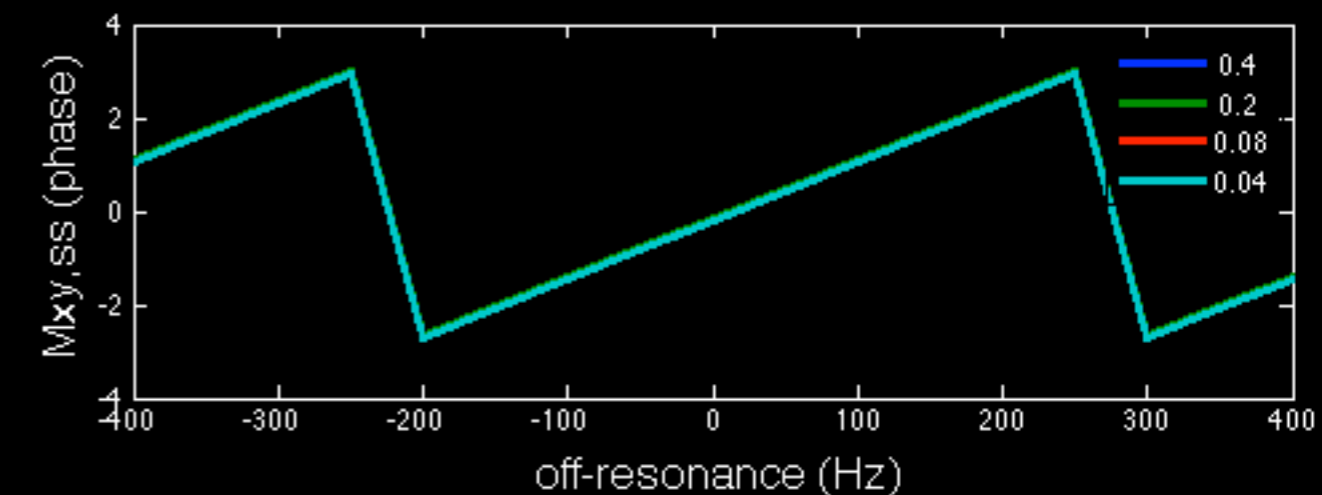
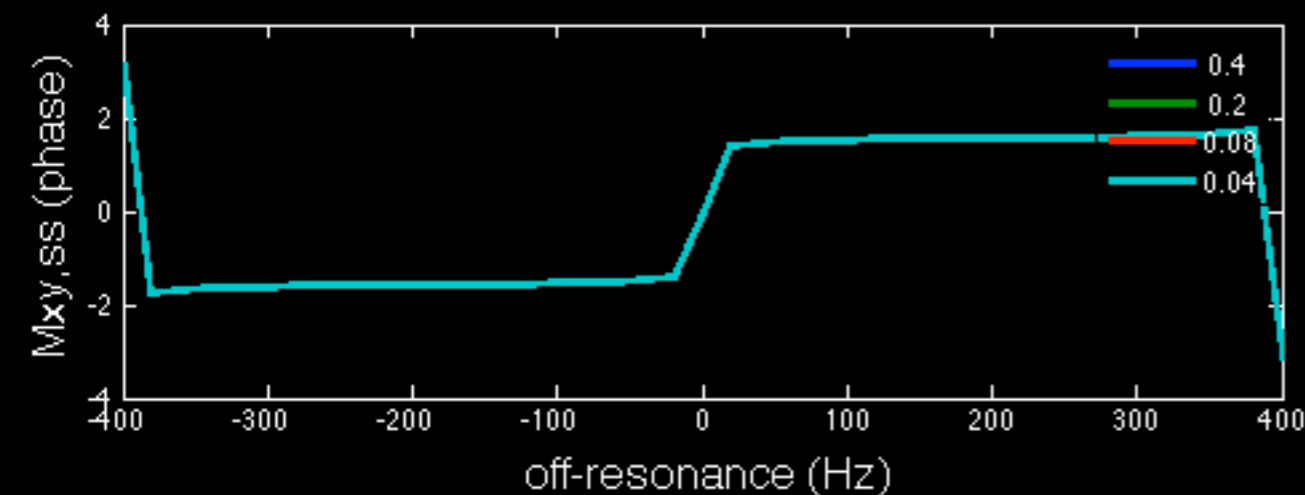
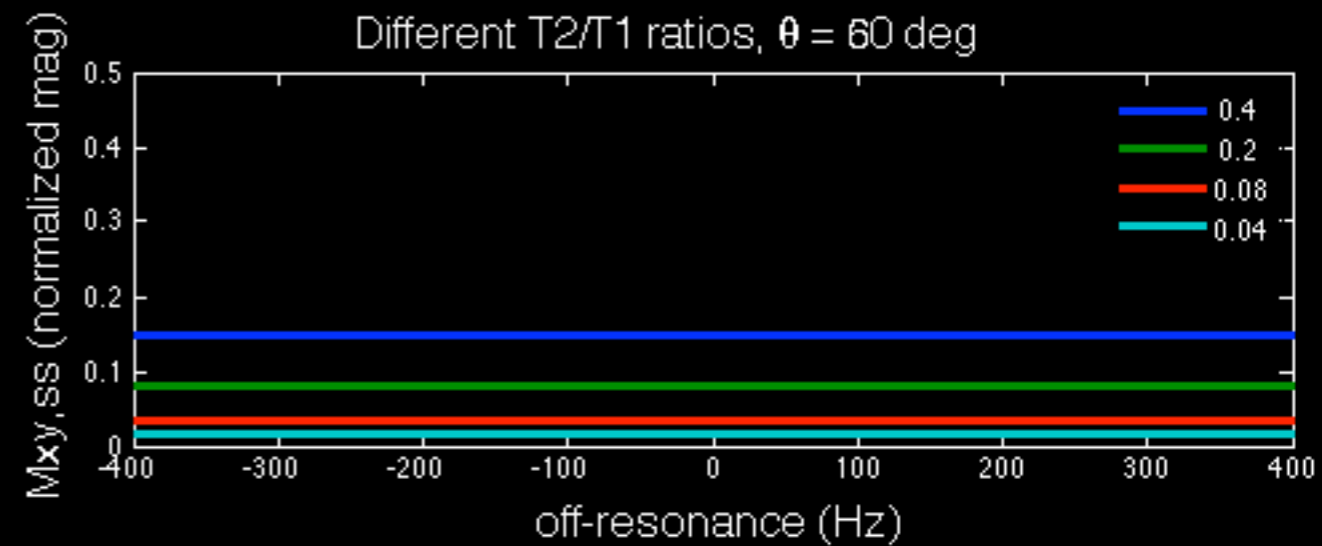
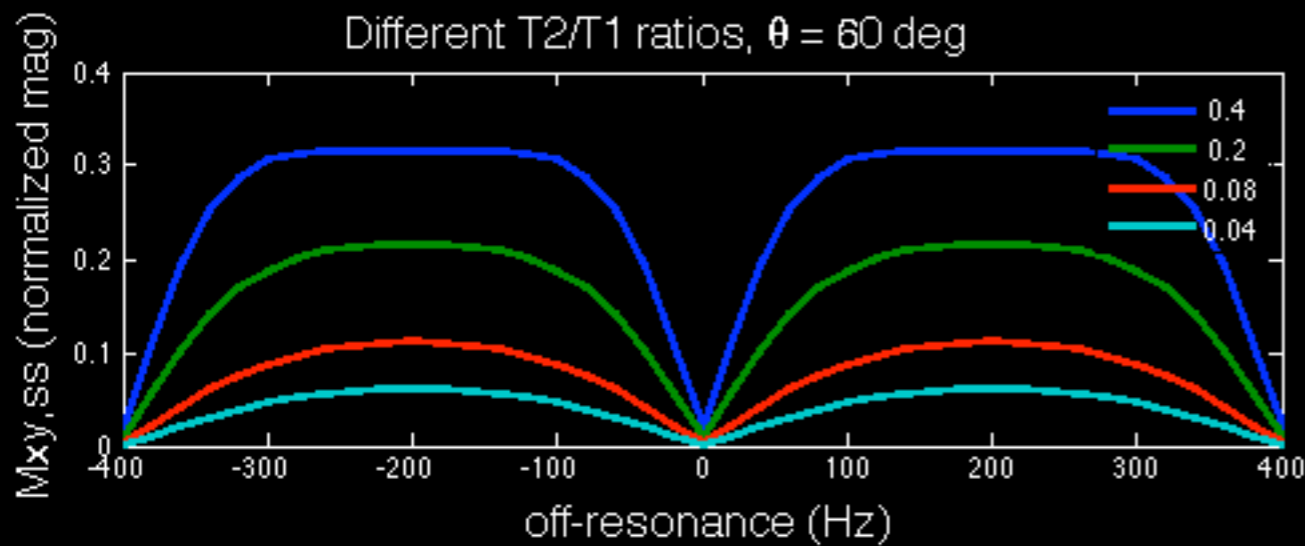
- RF spoiling (quadratic)
 - $\phi_n = \phi_{n-1} + n\phi_0 = (1/2)\phi_0(n^2 + n + 2)$
 - typically $\phi_0 = 50^\circ$ or 117°
 - ADC phase each TR also needs to match ϕ_n
- T_1 -weighted contrast
 - approaches contrast of ideally spoiled GRE
 - at expense of reduced SNR
(removes T2w contributions)

Gradient and RF-spoiled GRE

SS signal as a function of off-resonance:

bSSFP

Spoiled GRE



$T_1 = 100, 200, 500, 1000$ ms, $T_2 = 40$ ms

Rapid GRE - Comparison

Pulse Sequence		Mxy	Contrast	SNR	Artifacts
Balanced SSFP	bSSFP	retained	T_2/T_1	high	banding
Gradient-spoiled GRE	SSFP-FID	averaged	T_2/T_1	mid	motion
	SSFP-Echo	averaged	T_2+T_2/T_1	mid	motion
Gradient and RF-spoiled GRE	Spoiled GRE	cancelled	$T_1; T_2^*$	low	minimal

SS transition

Why RARE (TSE)?

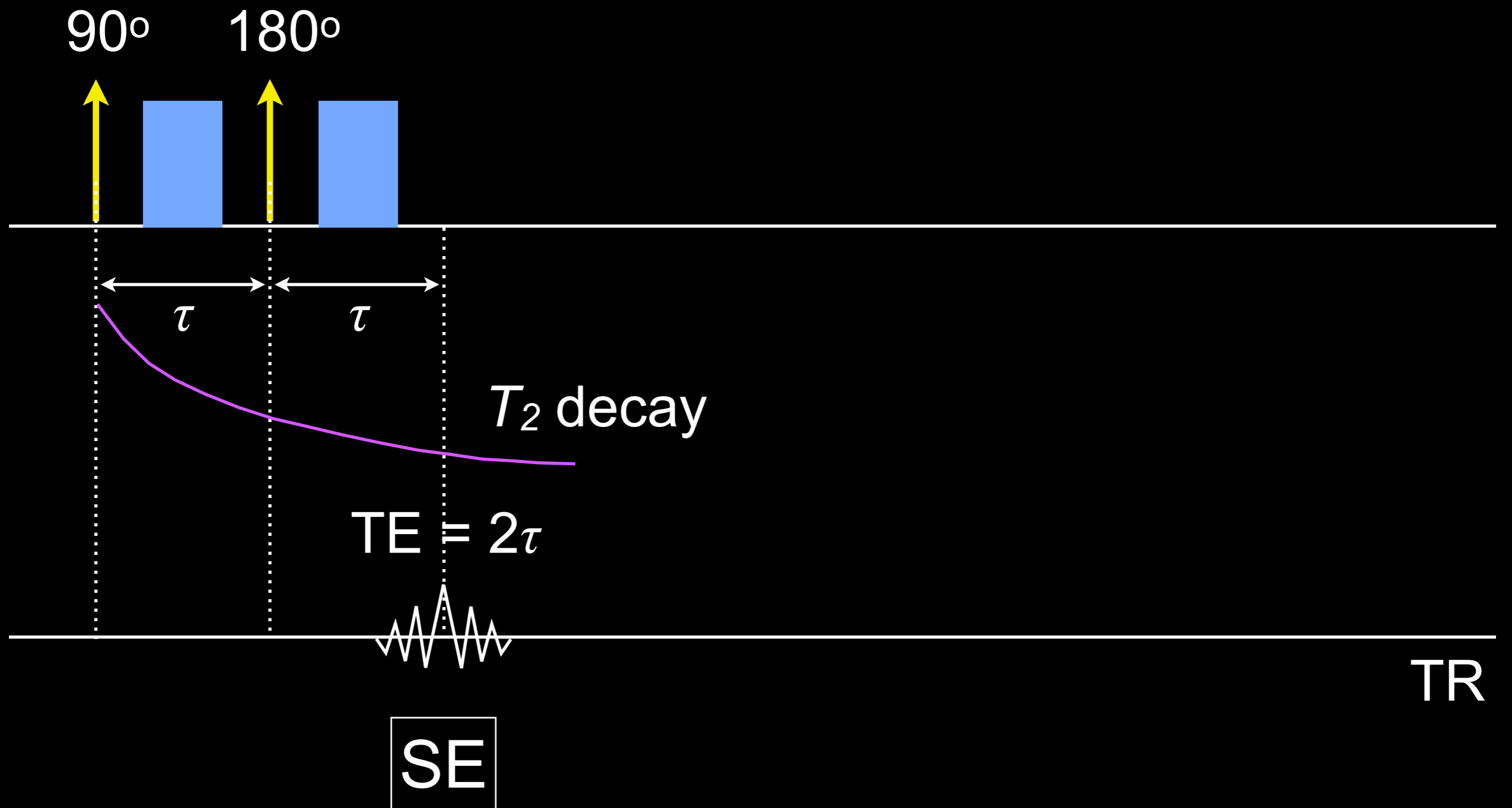
- Basic spin echo (SE) MRI is slow
 - TR on the order of 500 - 5000 ms
 - Data acquisition of one k-space line per TR, readout duration of 10 ms or less
 - Could acquire more lines before complete T_2 decay of M_{xy}

RARE (TSE) MRI

- Rapid Acquisition with Relaxation Enhancement (RARE)¹, aka Fast Spin-Echo (FSE) or Turbo Spin-Echo (TSE)
- Has virtually replaced SE for multiple clinical applications, esp. T2w imaging
- Challenging at high field (≥ 3 T)

¹Hennig J et al., *MRM* 1986

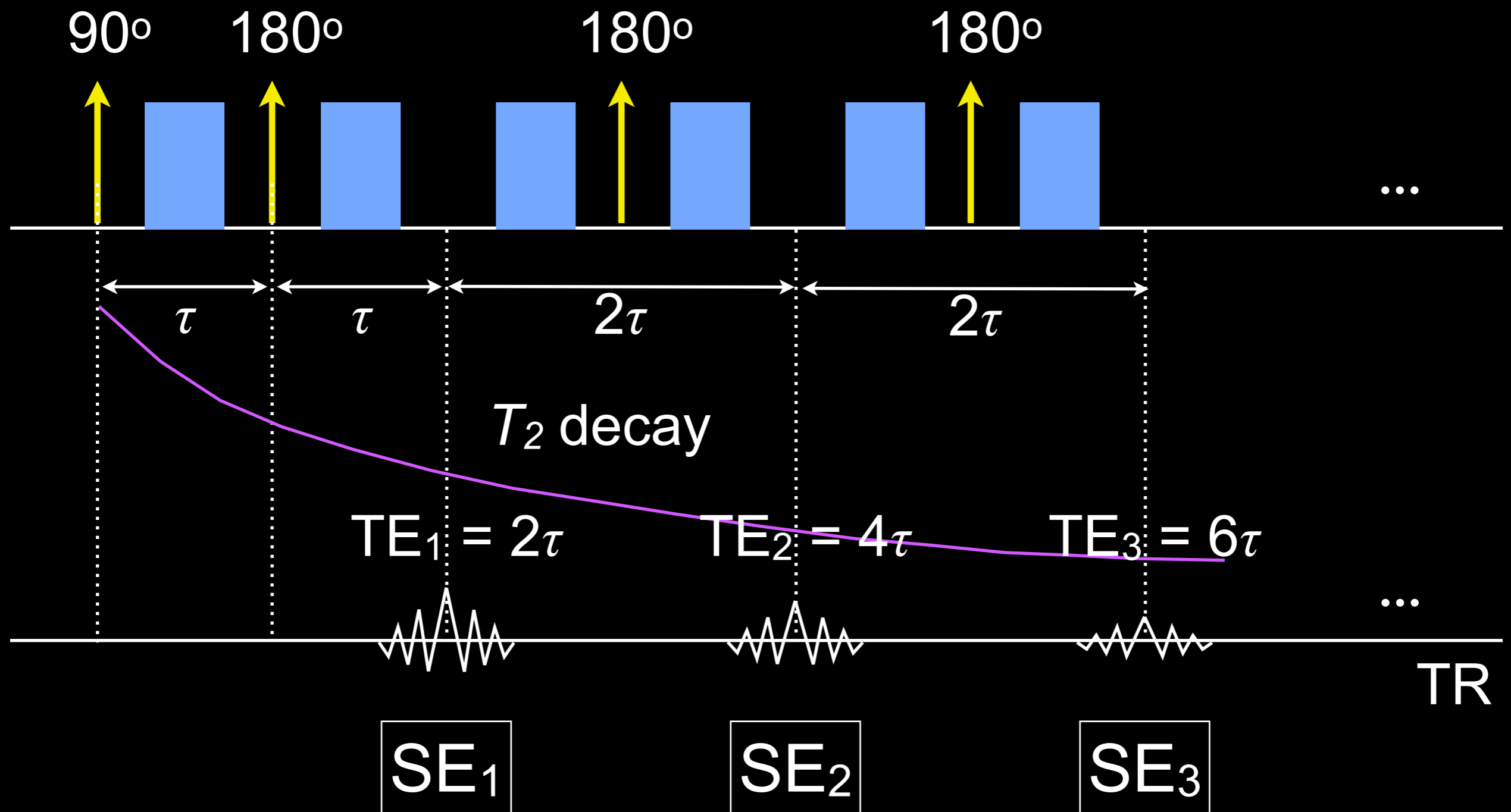
Spin Echo



Spin Echo

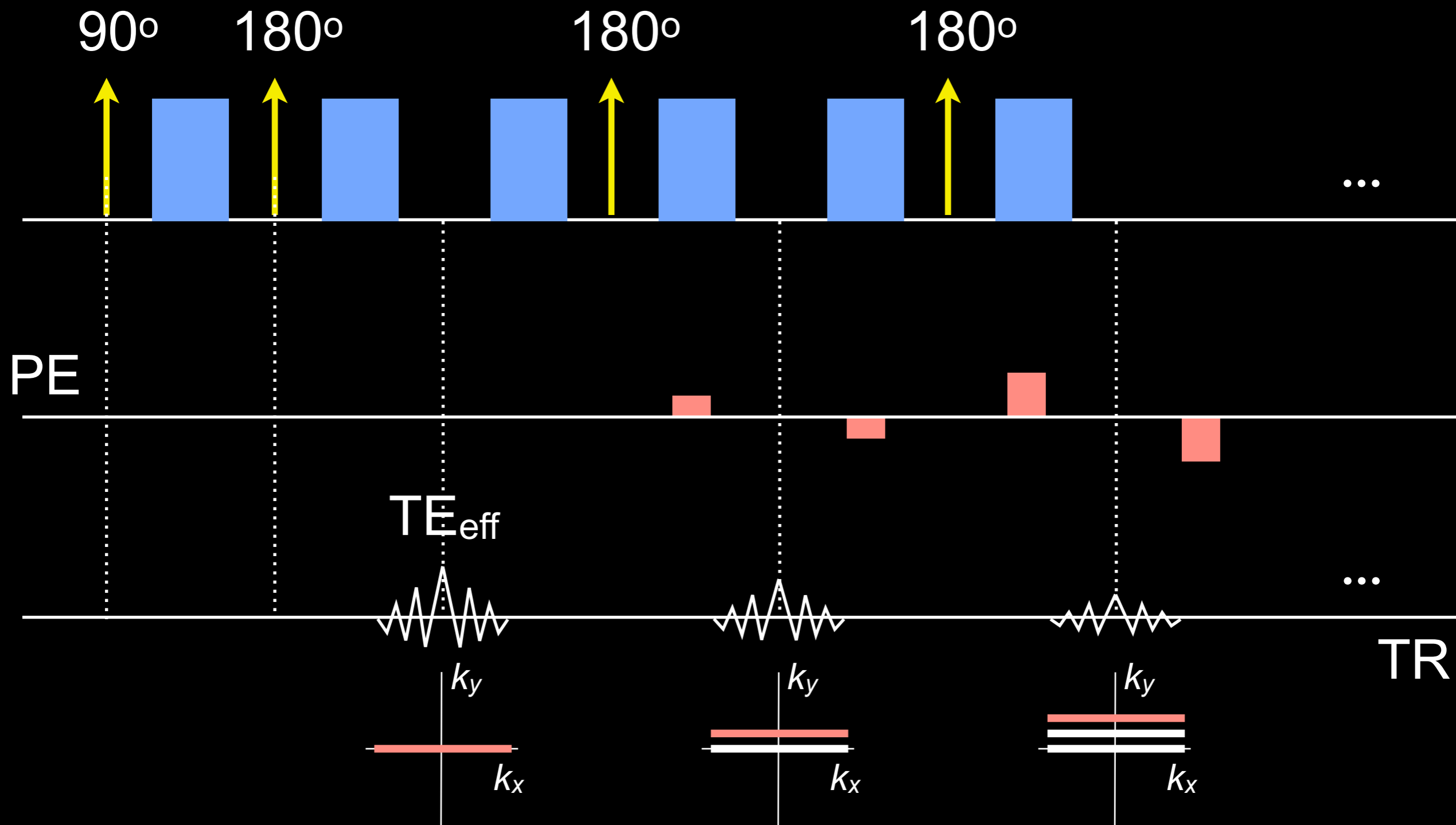
- Image contrast
 - Based on TE, TR
 - T1w, T2w, PDw
 - Can augment with prep pulses
- Scan time
 - $T_{SE} = N_{pe} \times TR$
 - TR = 1000 ms, $N_{pe} = 256$: $T_{SE} = 4+$ min
 - usually combined with 2D multislice acq

Multi-echo Spin Echo



Can perform T_2 mapping.

RARE (Turbo Spin Echo)



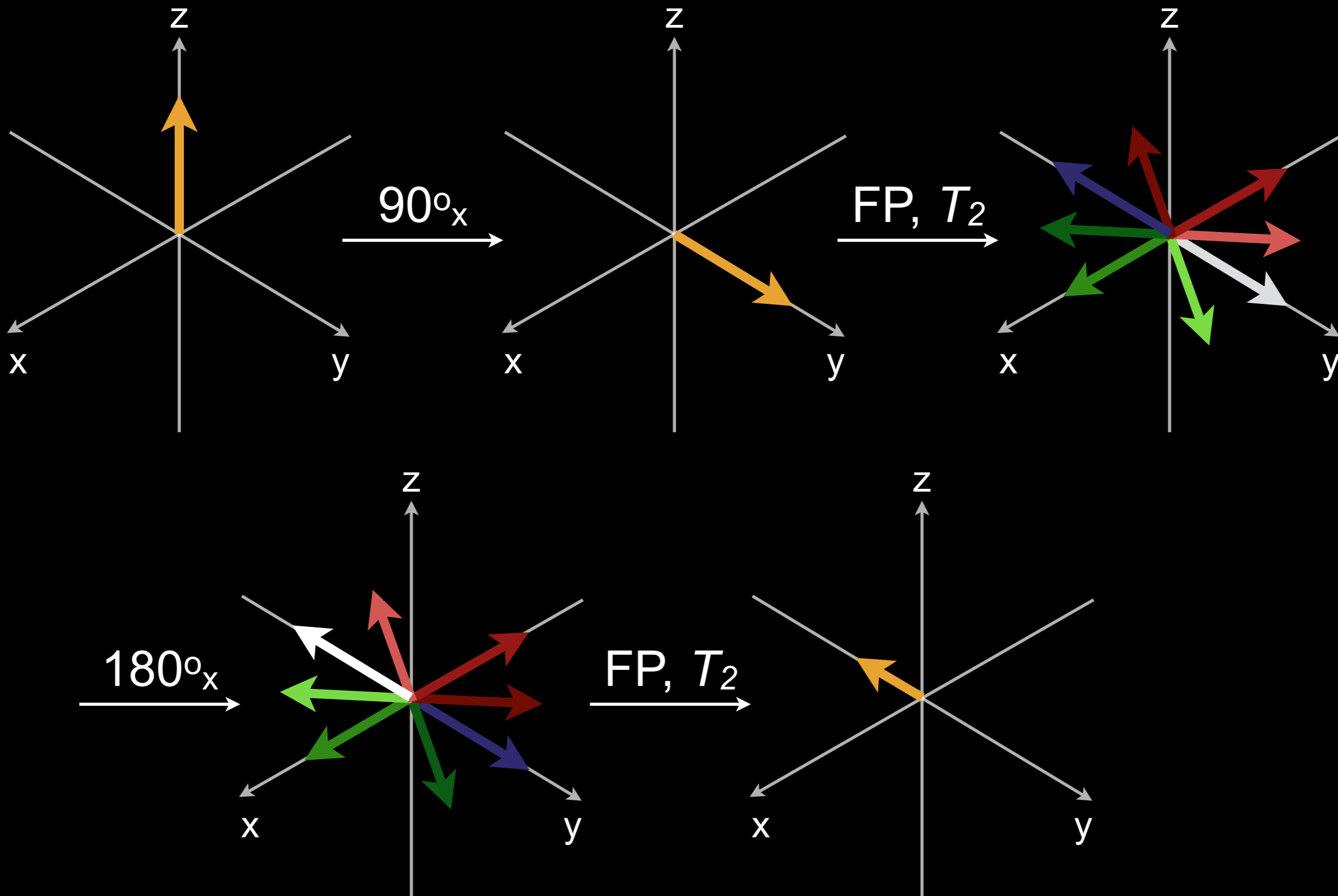
CPMG Conditions

- Carr-Purcell-Meiboom-Gill conditions
 - ensure echoes only occur at desired positions in the sequence, and
 - signals at each position have the same phase
- $90^\circ_x - \tau - 180^\circ_y - 2\tau - 180^\circ_y - 2\tau - 180^\circ_y \dots$
- Constant phase accrual btwn pulses
 - Same area for crusher pairs
 - Phase encode rewinder

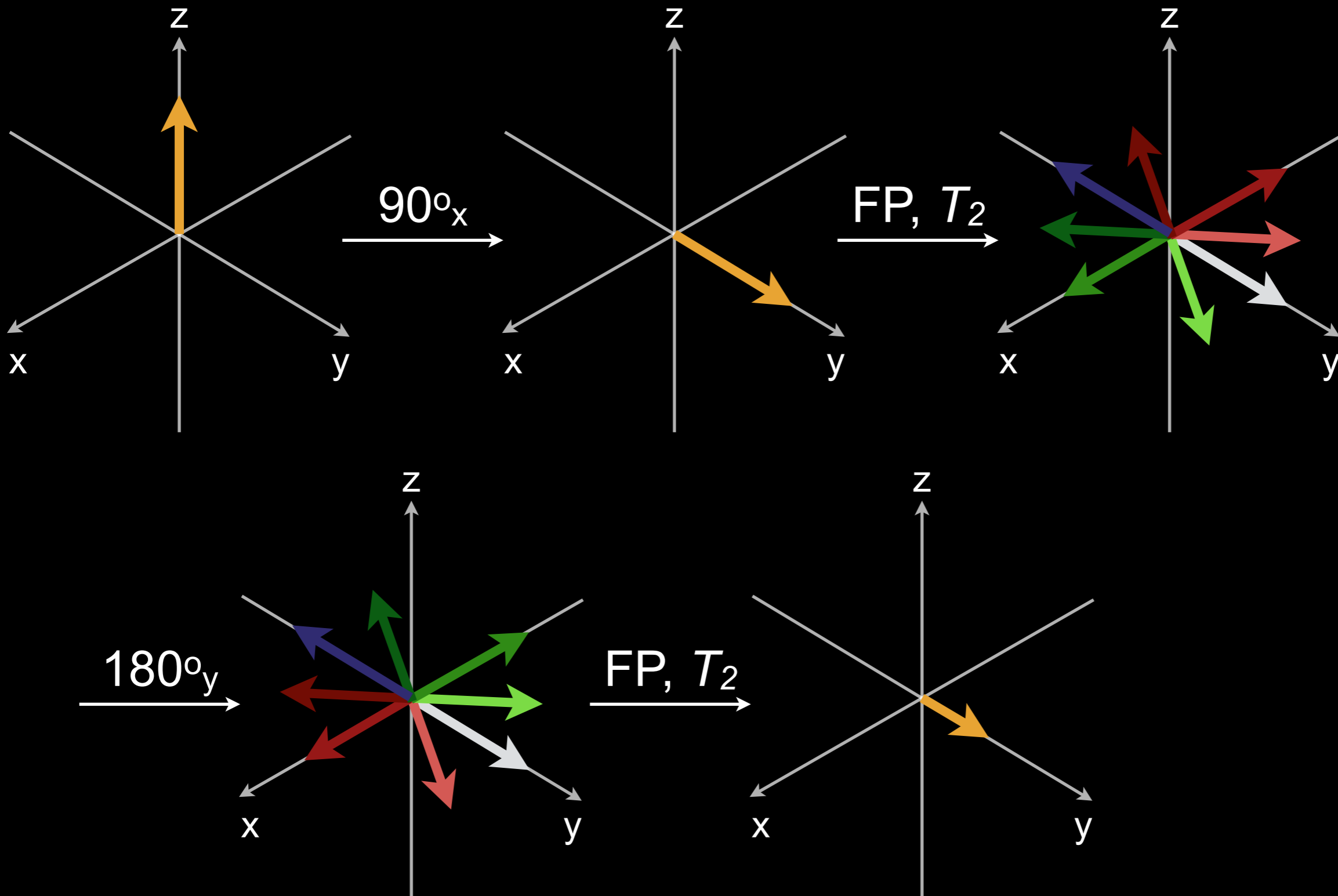
CPMG Conditions

- When satisfied
 - SE and STE coincide (same phase)
 - secondary SE and FID are crushed
- Moving spins can violate CPMG

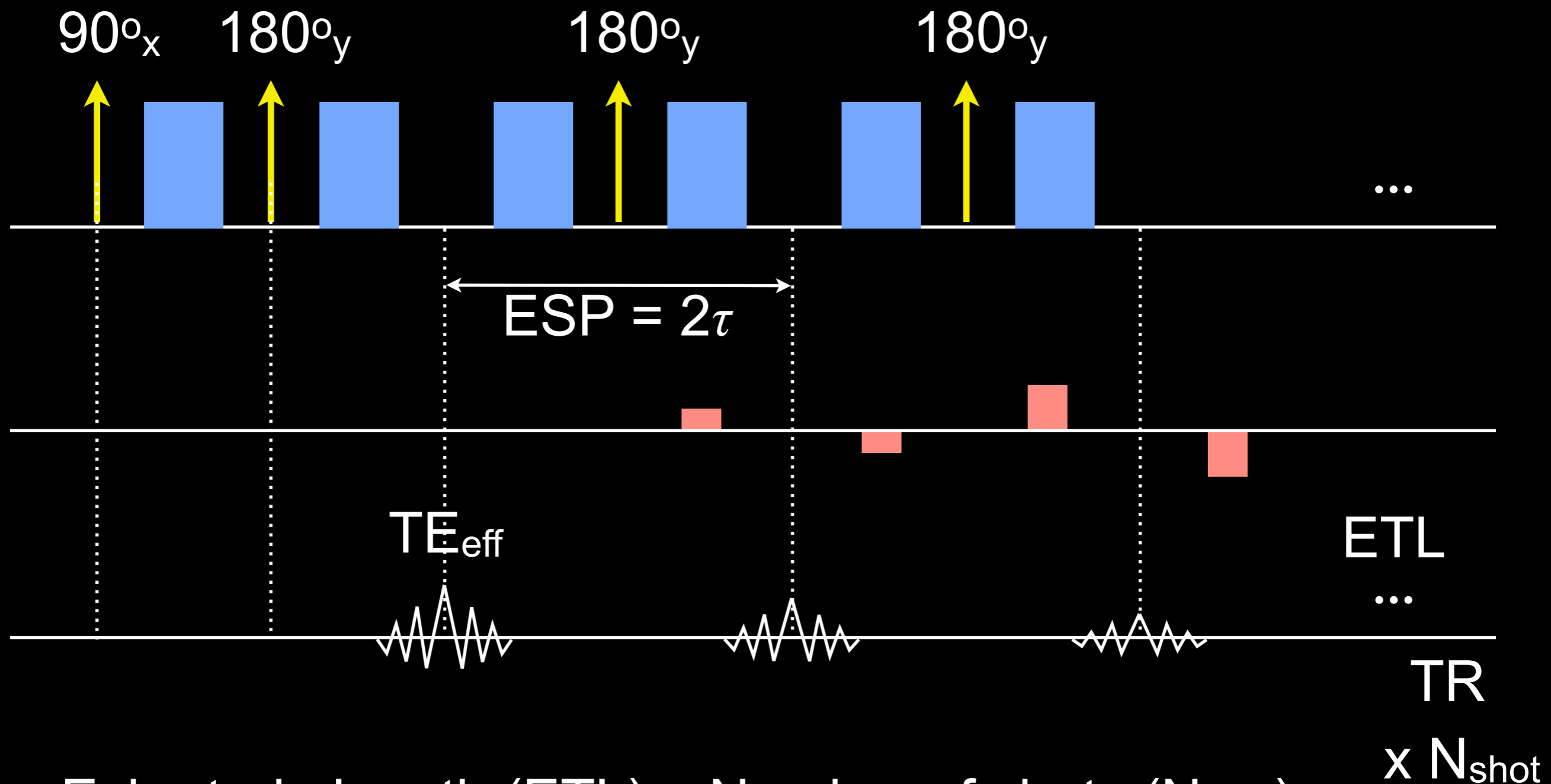
Spin Echo: $90^\circ_x - 180^\circ_x$



Spin Echo: $90^\circ_x - 180^\circ_y$



TSE Sequence Params



Echo train length (ETL)

Number of shots (N_{shot})

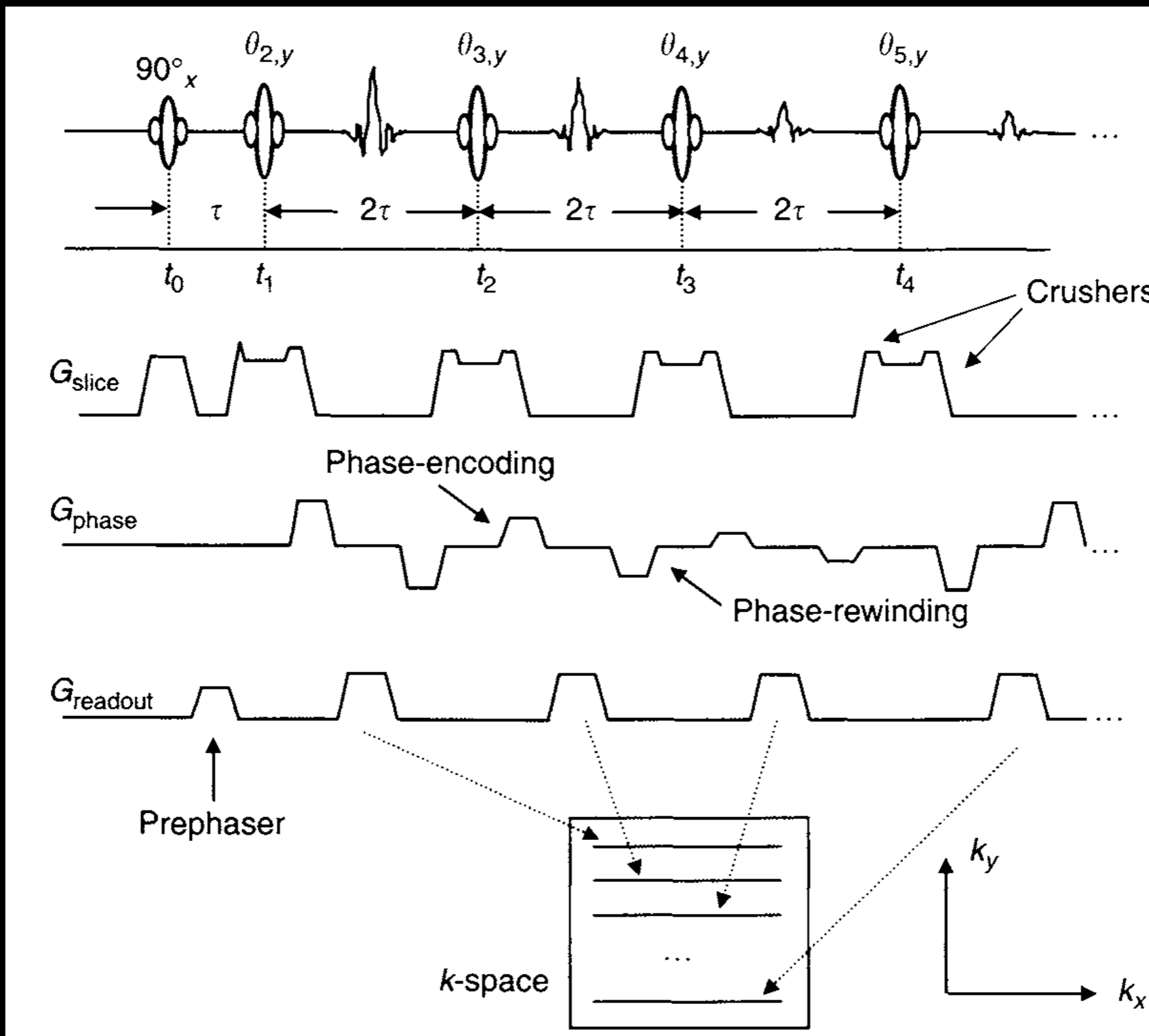
Echo spacing (ESP)

Effective TE (TE_{eff})

TSE Sequence Params

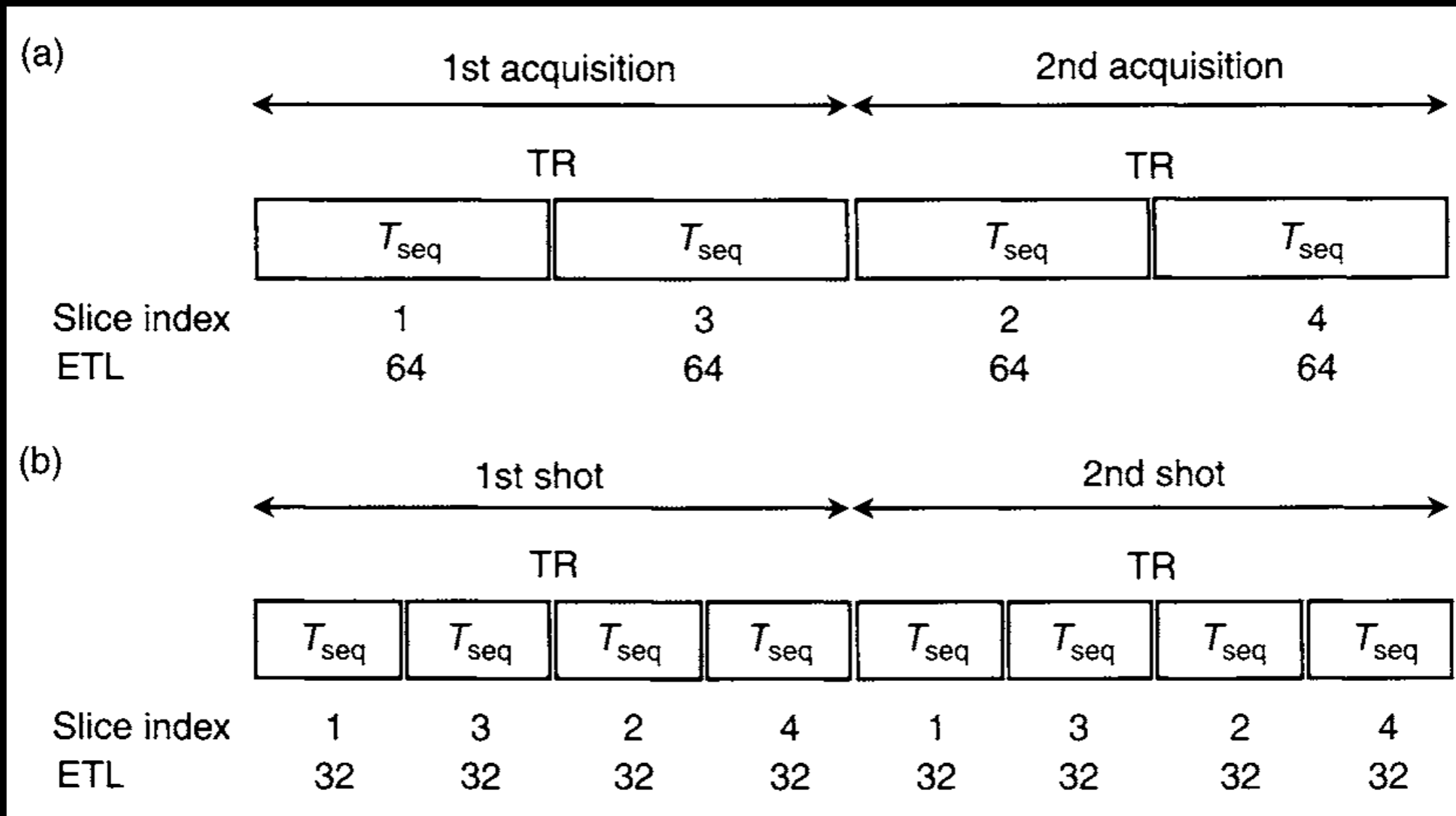
- ETL typically 4-16
 - Can't be too high, due to T_2 decay
- ESP typically <10 ms
 - Must accommodate RF, gradients, ADC
 - Short ESP facilitates high ETL
- Example: readout until $S = 0.2 S_0$
 - $S = S_0 * \exp(-t/T_2)$; assume $T_2 = 100$ ms
 - $t = 160.9$ ms
 - ESP = 8 ms; ETL = 20
 - ESP = 4 ms; ETL = 40

2D RARE Sequence

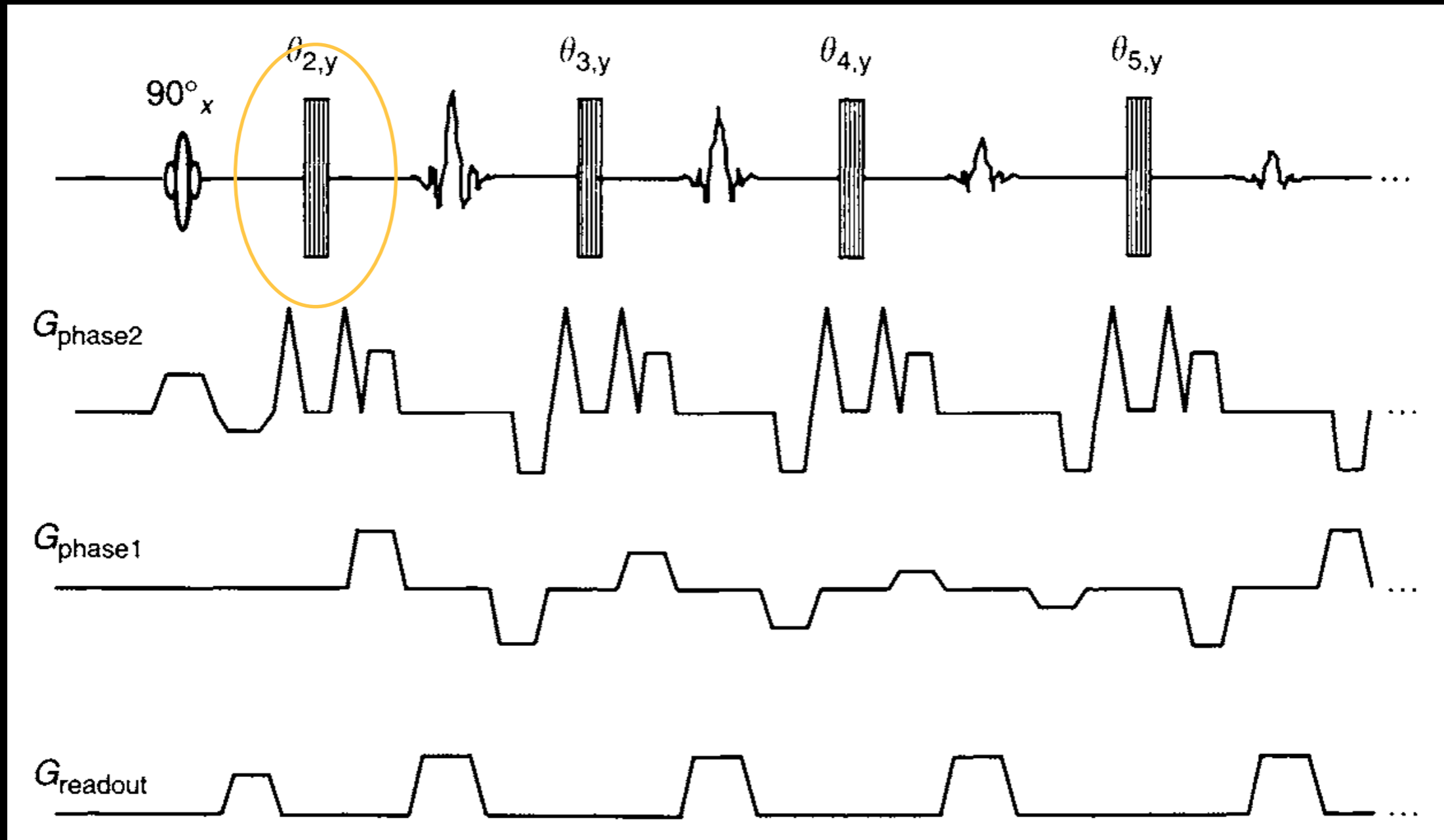


2D RARE Sequence

Interleaved 2D Multi-Slice Acquisition



3D RARE Sequence

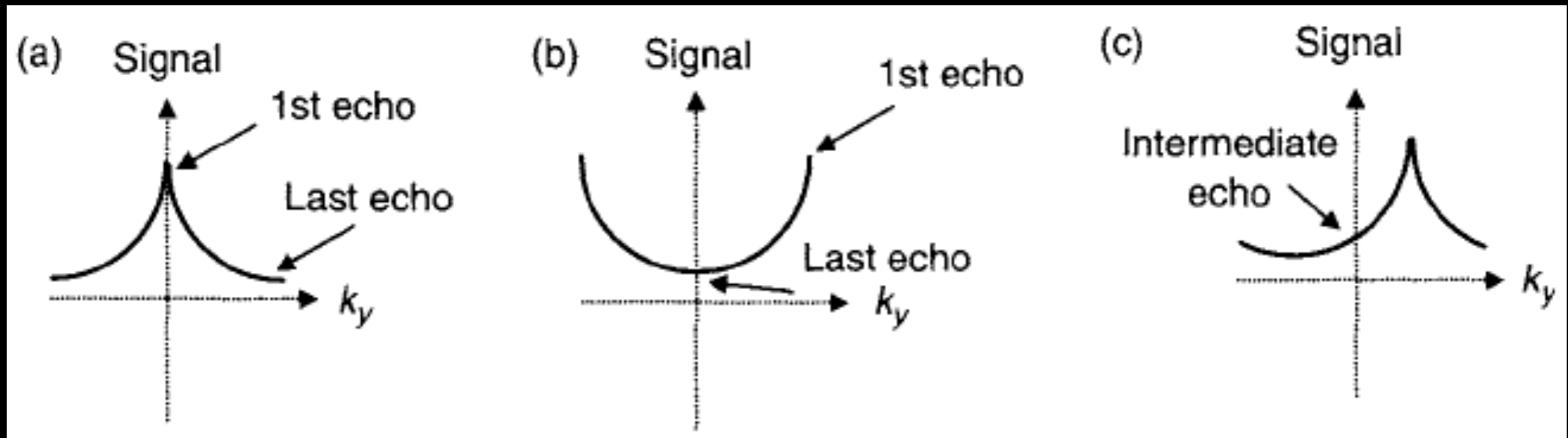


TSE Scan Time

- Scan time
 - Recall $T_{SE} = N_{pe} \times TR_{SE}$
 - $N_{shot} = N_{pe} / ETL$
 - $T_{TSE} = N_{shot} \times TR_{TSE} = (T_{SE} / ETL) \times (TR_{TSE}/TR_{SE})$
- Example: 2D single slice
 - $N_{pe} = 256$; $ETL = 16$; $N_{shot} = 16$
 - $TR = 1000$ ms: $T_{TSE} = 16$ sec
- Example: 3D volume
 - $N_{pe} = 256 \times 256$; $ETL = 32$; $N_{shot} = 2048$
 - $TR = 1000$ ms: $T_{TSE} = 34$ min

TSE Image Contrast

- TE_{eff} , TR
 - T1w, T2w, PDw
 - PE ordering affects TE_{eff}



TSE Image Contrast

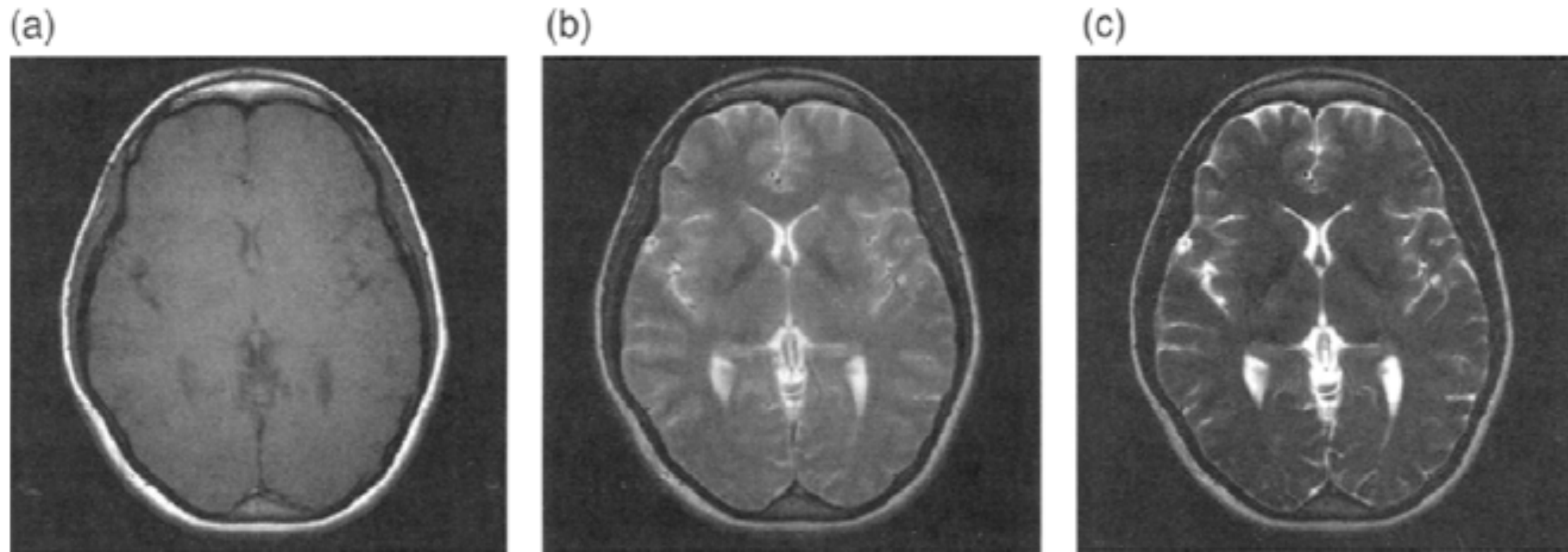


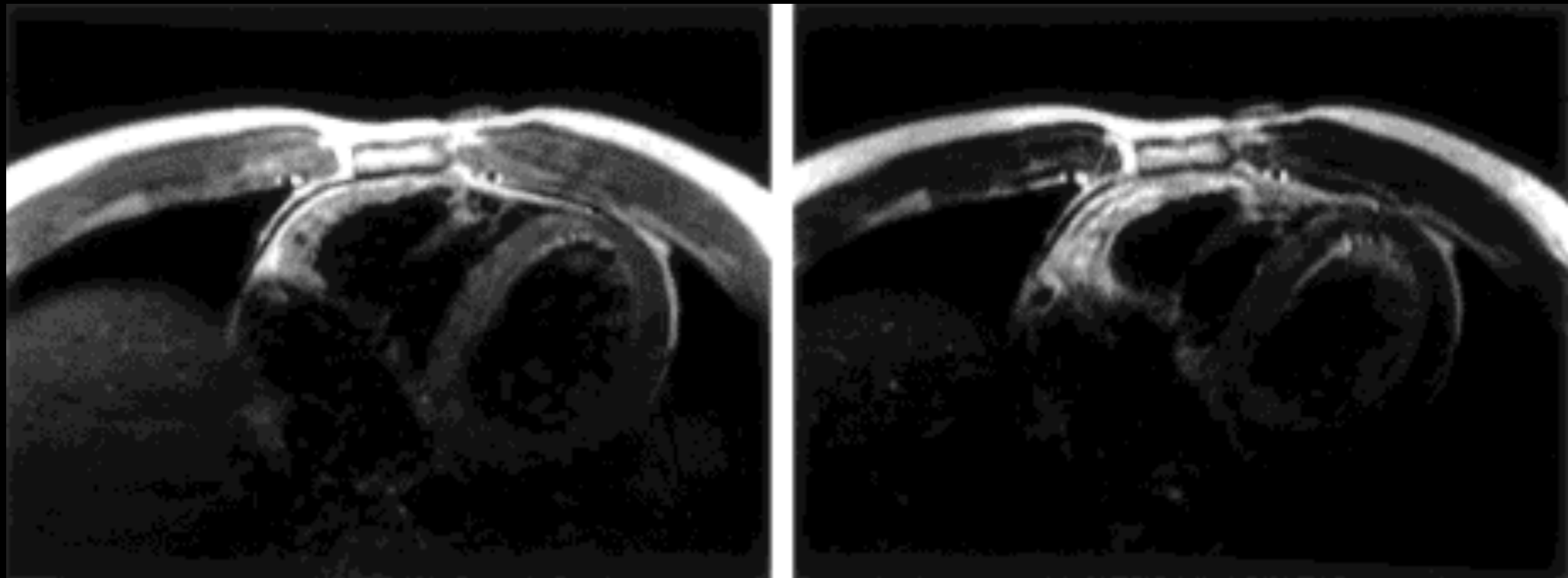
FIGURE 16.48 By using different echoes to sample the k-space center, considerably different image contrast can be obtained from a RARE sequence. (a) T_1 -weighted image with $TE = 11$ ms, $TR = 480$ ms, and $N_{\text{etl}} = 8$. (b) Moderately T_2 -weighted image with $TE = 77$ ms, $TR = 4000$ ms, and $N_{\text{etl}} = 16$. (c) Heavily T_2 -weighted image with $TE = 176$ ms, $TR = 4000$ ms, and $N_{\text{etl}} = 16$.

TSE Image Contrast

- Dual-echo PDw+T2w in same TR
- Mag-prep modules (IR, SR, FS, etc.)
- Inherent flow suppression
 - only static spins see multiple 180s
 - “dark/black blood” imaging

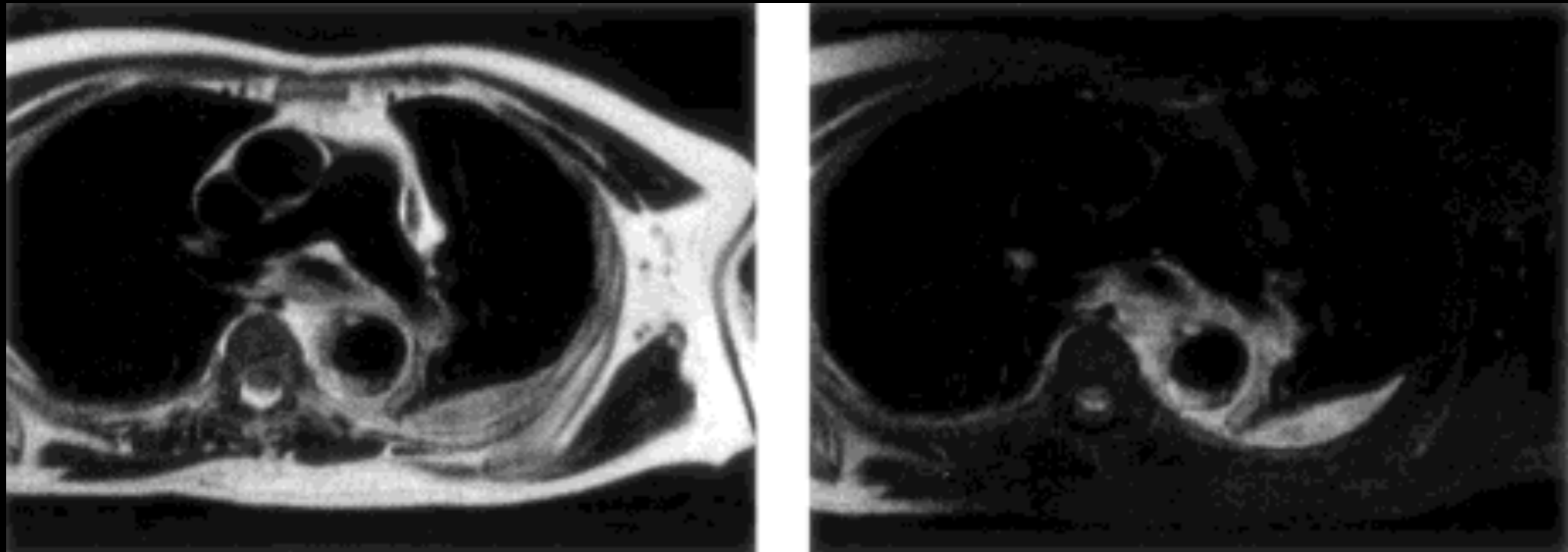
TSE Image Contrast

Dark Blood from Spin Echo



TSE Image Contrast

Dark Blood from Double Inversion-Recovery TSE



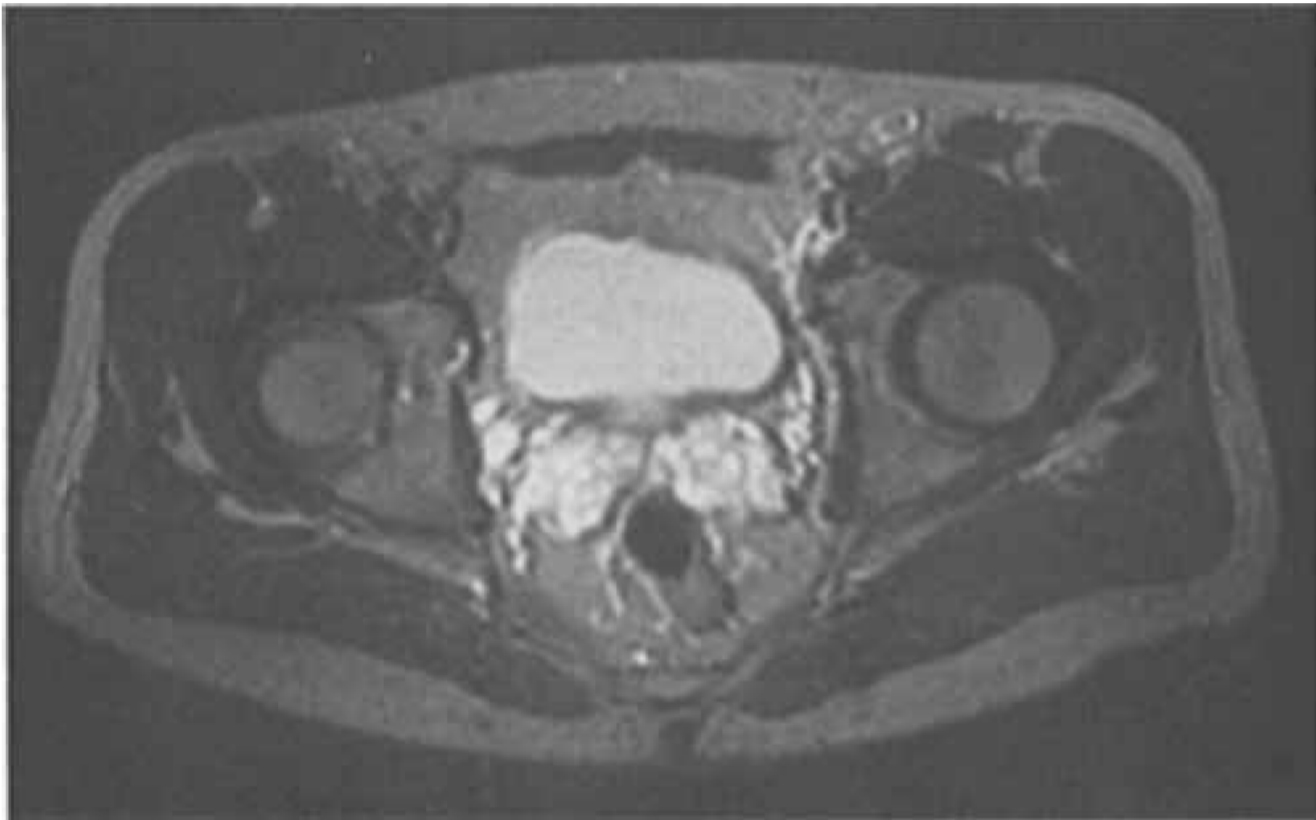
TSE Image Contrast

- Bright fat
 - J-coupling of protons in lipids (CH₃-CH₂-);
 $f_{CS} \sim 25 \text{ Hz}$, $f_J \sim 7 \text{ Hz @ } 1.5 \text{ T}$
 - $S = S_0 * \exp(-t/T_2) * \cos(n_{ech} \pi f_J ESP)$
 - Shortening of apparent T_2 (in SE)

 - J-coupling negligible when
 $ESP \leq 1/[2 \sqrt{f_{CS}^2 + f_J^2}] \sim 20 \text{ ms @ } 1.5 \text{ T}$
 - In TSE, short ESP avoids attenuation by J-coupling, thus brighter fat signal

TSE Image Contrast

Spin Echo



Turbo Spin Echo



Bright Fat

TSE Image Contrast

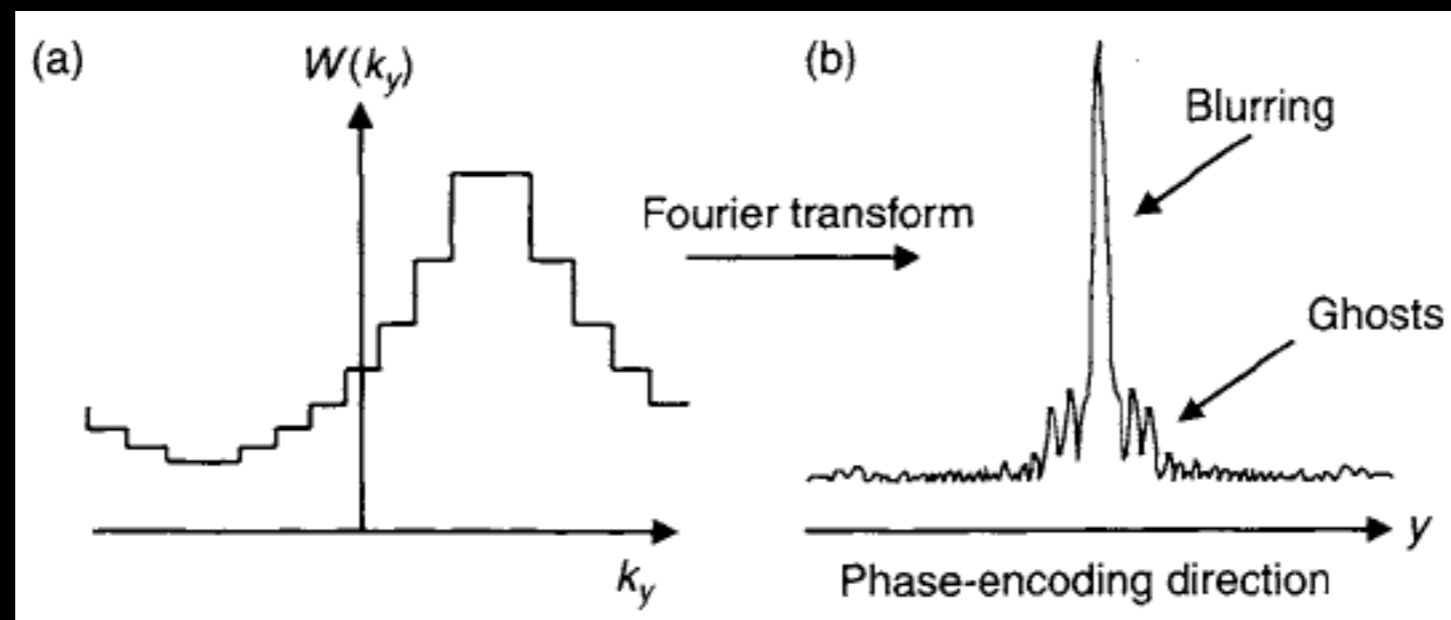
- Magnetization transfer
 - MT effect
 - multiple refocusing pulses in TSE
 - off-resonance excitation in other slices; can lead to MT-induced signal loss

TSE Advantages

- Image contrast very similar to SE
- Robust to off-resonance effects (SE)
- Much faster scan than SE

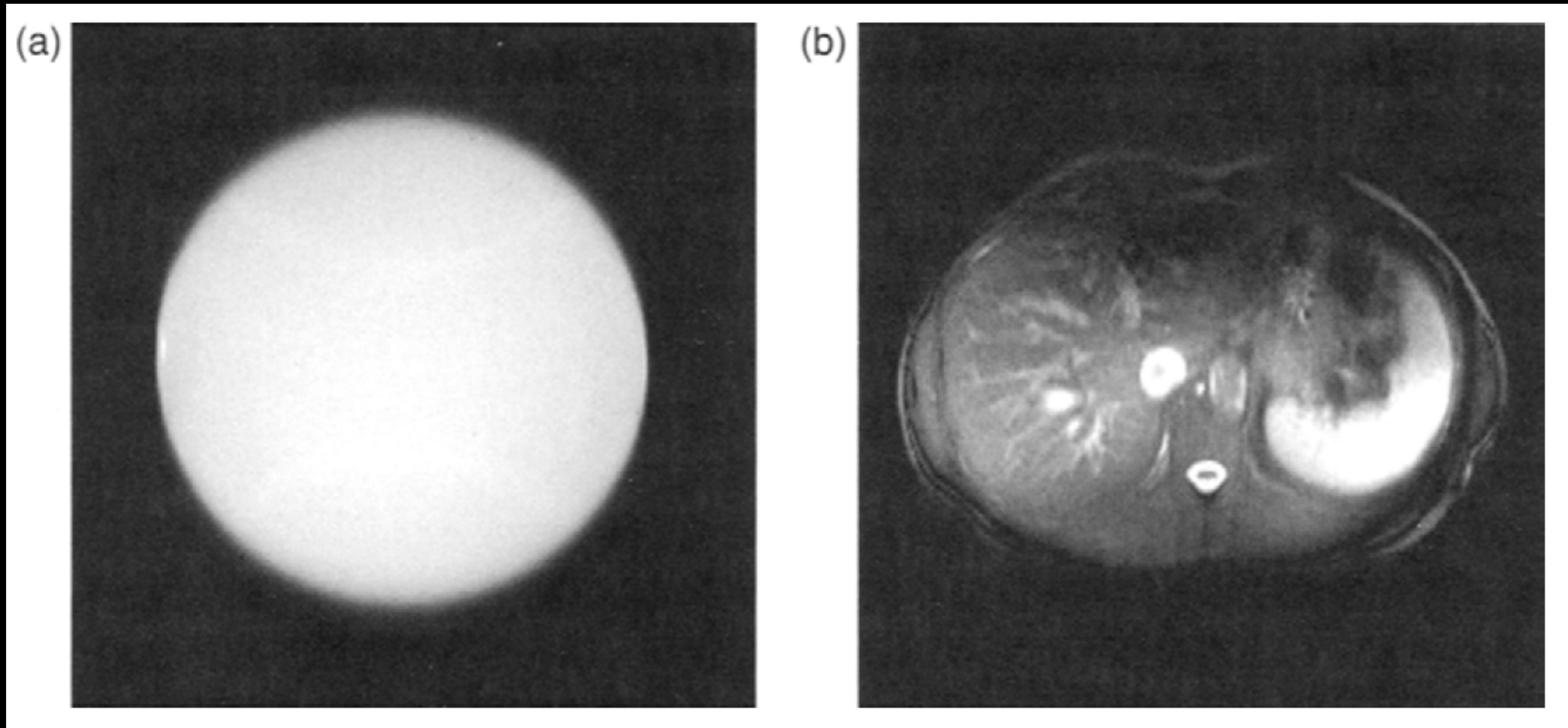
TSE Challenges

- Blurring; edge enhancement; ghosting;
 - attention to PE ordering and ETL



TSE Challenges

T₂ blurring (PE) in single-shot TSE



TSE Challenges

- RF power deposition increased
 - Specific Absorption Rate (SAR) W/kg;
 $SAR \propto \theta^2 (B_0)^2$
 - use reduced refocusing flip angles,
e.g., $\theta = 130^\circ$ instead of 180°

Extensions and Variations

- Partial echo
- Multi-echo
- Mag-prep

Extensions and Variations

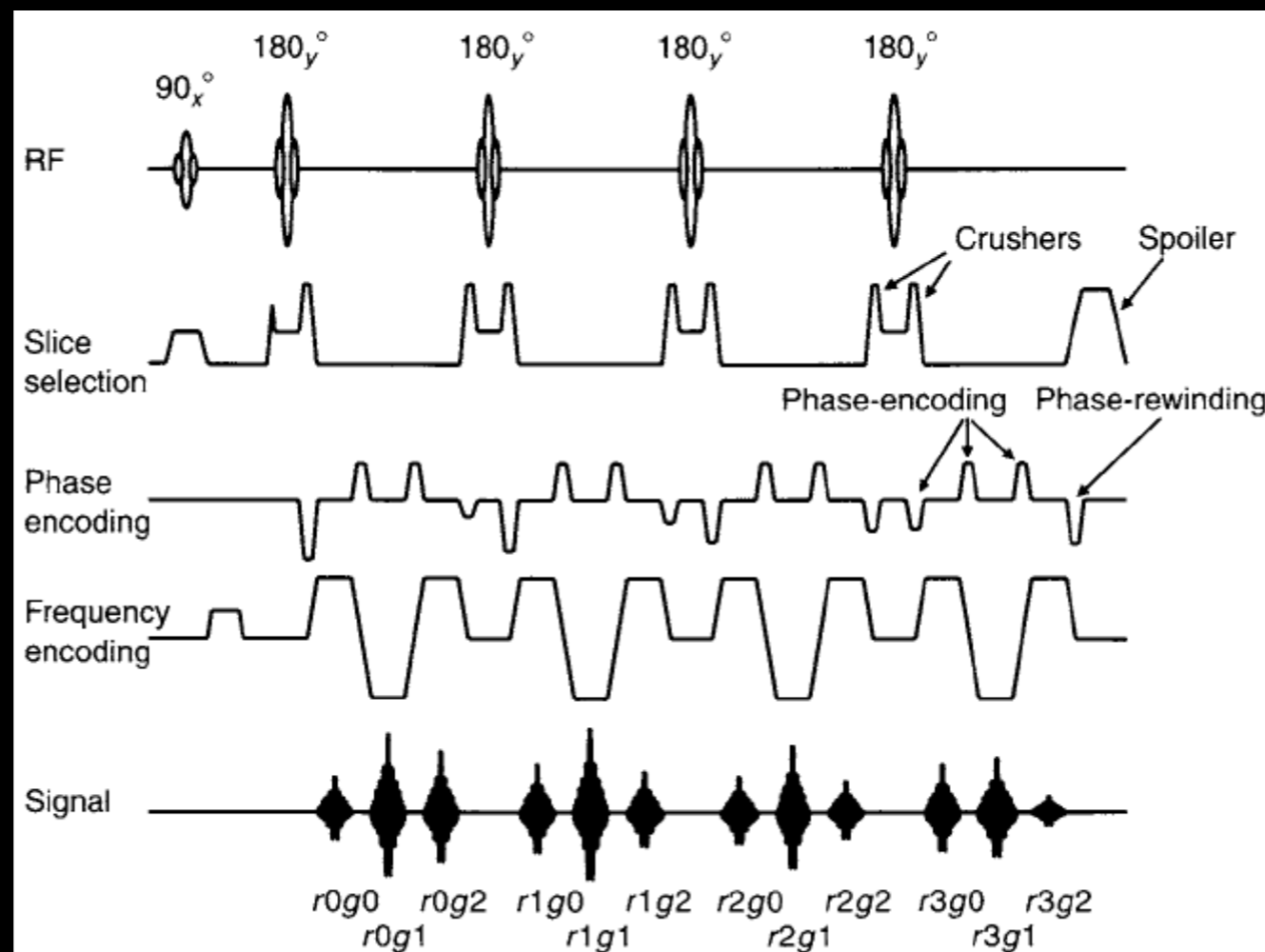
- Partial Fourier
 - Sample ~half of k-space data, reconstruct assuming Hermitian symmetry (real-valued MR images)
 - reduce refocusing pulses, reduce SAR
 - better control of TE_{eff}
- Parallel imaging
 - Undersample k-space data, reconstruct using information from multiple coils
 - reduce refocusing pulses, reduce SAR

Related Sequences

- TSE + non-Cartesian trajectories
 - radial, rings, spiral, cylinders, etc.
- TSE-Dixon to separate bright fat
- Half-Fourier acquired single-shot turbo spin echo (HASTE)
- Variable flip angle 3D TSE (SPACE, CUBE, etc.) to manage SAR, ETL

Related Sequences

Gradient And Spin Echo (GRASE)¹,
aka Turbo gradient spin echo (TGSE)



¹Oshio K et al., *MRM* 1991

Bernstein et al., *Handbook of MRI Pulse Sequences*, Ch 16.2

Clinical Applications

- The bread and butter sequence!
 - Brain
 - Body
 - Cardiac
 - Musculoskeletal
 - and more ...

More About TSE

- FID, SE, secondary SE, Stimulated Echoes (STE) ...
- Practical conditions
 - Reduced refocusing pulse angles
 - Non-uniform slice profiles
 - B_1 inhomogeneity

Summary

- RARE (Turbo Spin Echo)
 - multiple RF pulses
 - efficient use of M_{xy}
 - shares robustness of SE
 - core clinical sequence
 - challenges with SAR

- EPG next time!

Pulse Sequence Simulations

Outline

- Bloch Equation Simulations
 - basic operations (matrix form)
 - MATLAB implementation
 - examples: rapid GRE
 - homework

Bloch Simulation

- Bloch Equations
 - RF excitation
 - T_1 , T_2 decay
 - free precession
 - gradient pulse

Bloch Simulation

Rotation:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \quad R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}$$

$$R_z(\theta) = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

```
function Rx=xrot(phi)
Rx = [1 0 0; 0 cos(phi) -sin(phi); 0 sin(phi) cos(phi)];
```

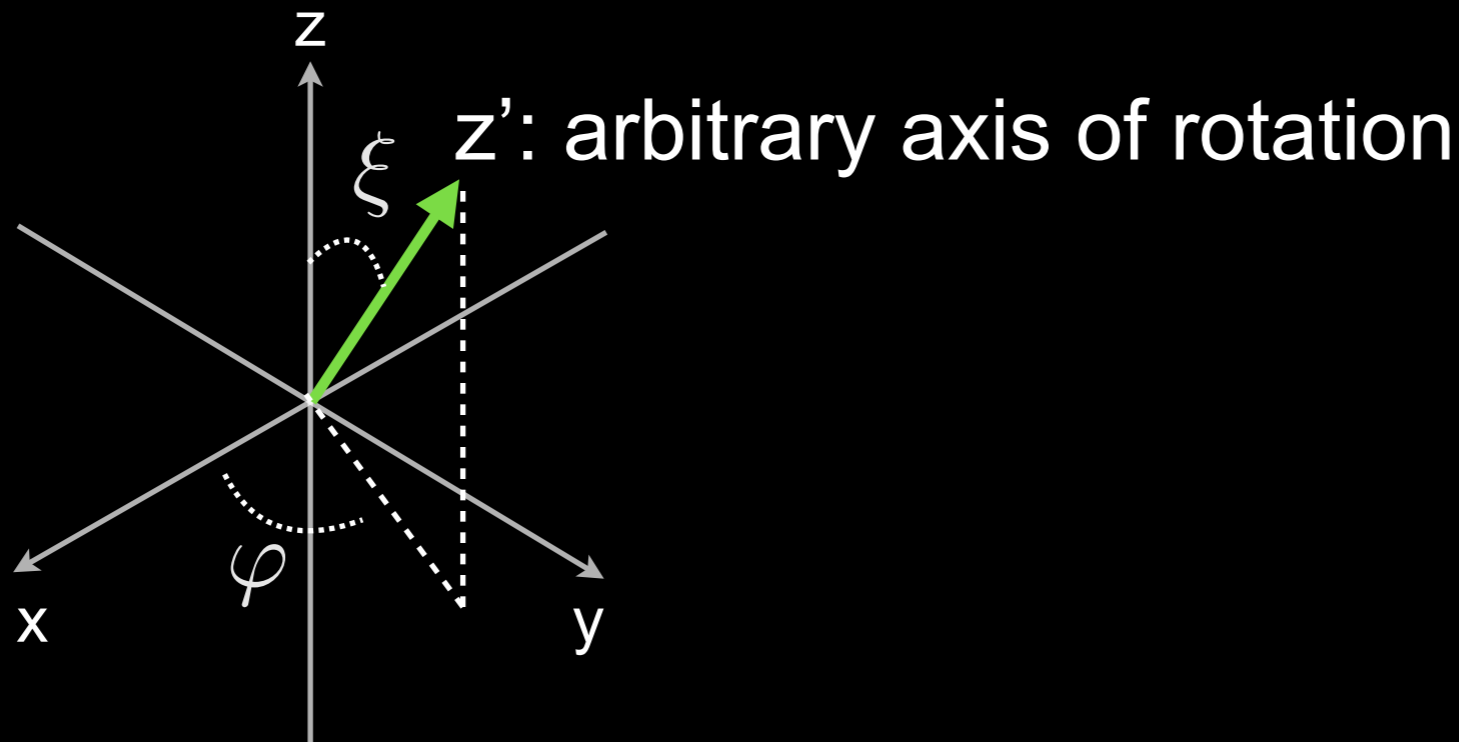
Bloch Simulation

Free precession:

$$R_z(\omega_0 t) = \begin{bmatrix} \cos \omega_0 t & \sin \omega_0 t & 0 \\ -\sin \omega_0 t & \cos \omega_0 t & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Bloch Simulation

General Rotation:



$$R_{\{\varphi, \xi\}}(\theta) = R_z(-\varphi)R_y(-\xi)R_z(\theta)R_y(\xi)R_z(\varphi)$$

Bloch Simulation

Relaxation + Free Precession:

$$M(t) = \begin{bmatrix} e^{-t/T_2} & 0 & 0 \\ 0 & e^{-t/T_2} & 0 \\ 0 & 0 & e^{-t/T_1} \end{bmatrix} R_z(\Delta\omega t) M(0) + \begin{bmatrix} 0 \\ 0 \\ M_0(1 - e^{-t/T_1}) \end{bmatrix}$$

$AM(0) + B$

```
function [Afp,Bfp]=freeprecess(T,T1,T2,df)
% T, T1, T2 in ms
% df in Hz

% Relaxation
M0 = 1;
A = [exp(-T/T2) 0 0; 0 exp(-T/T2) 0; 0 0 exp(-T/T1)];
B = M0*[0 0 1-exp(-T/T1)]';

% df in Hz
phi = 2*pi * df*T*10^-3; %omega = 2pi * f, in radians
Rz = zrot( phi );

Afp = A*Rz;
% Bfp = B*Rz;
% same as:
Bfp = B;
```


Bloch Simulation

- Transient state; steady state
- Different seq/tissue params
- Brian's MATLAB Bloch sim tutorial
 - <http://www-mrsrl.stanford.edu/~brian/bloch/>

Bloch Simulation

- Example 1: Gradient Echo (long TR)
 - xrot.m, yrot.m, zrot.m, throt.m
 - freeprecess.m
 - Sim_SatRecovery.m
 - add gradient rewinders / spoilers, RF phase cycling to simulate rapid GRE sequences

Bloch Simulation

- Example 2: Balanced SSFP
 - xrot.m, yrot.m, zrot.m, throt.m
 - freeprecess.m
 - sssignal.m
 - BalancedSSFP_freqresp.m

 - consider different flip angle, T_1 , T_2
 - change TR and look at freq response

Bloch Simulation

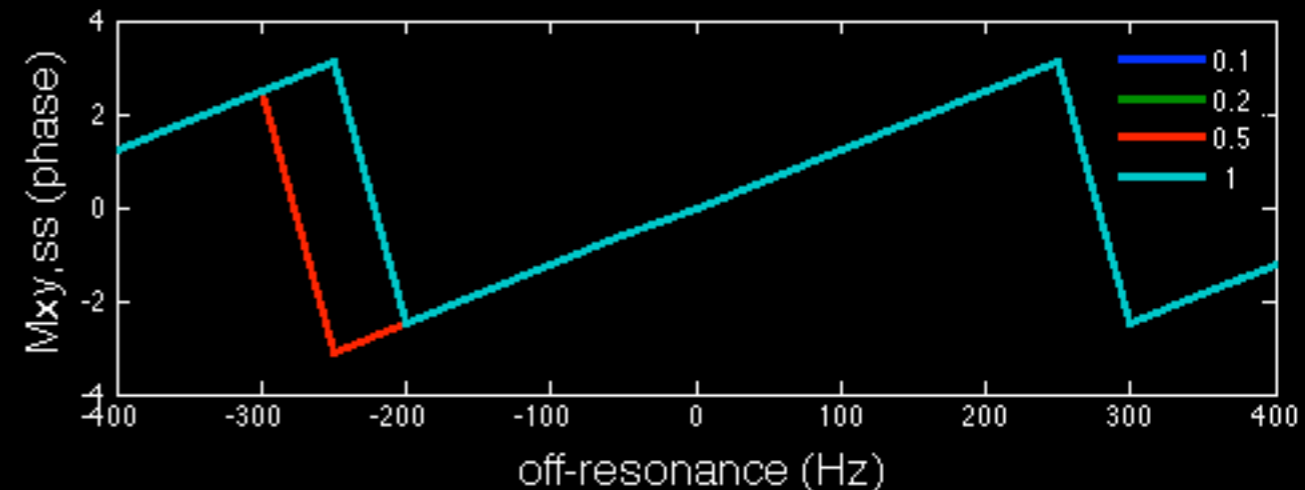
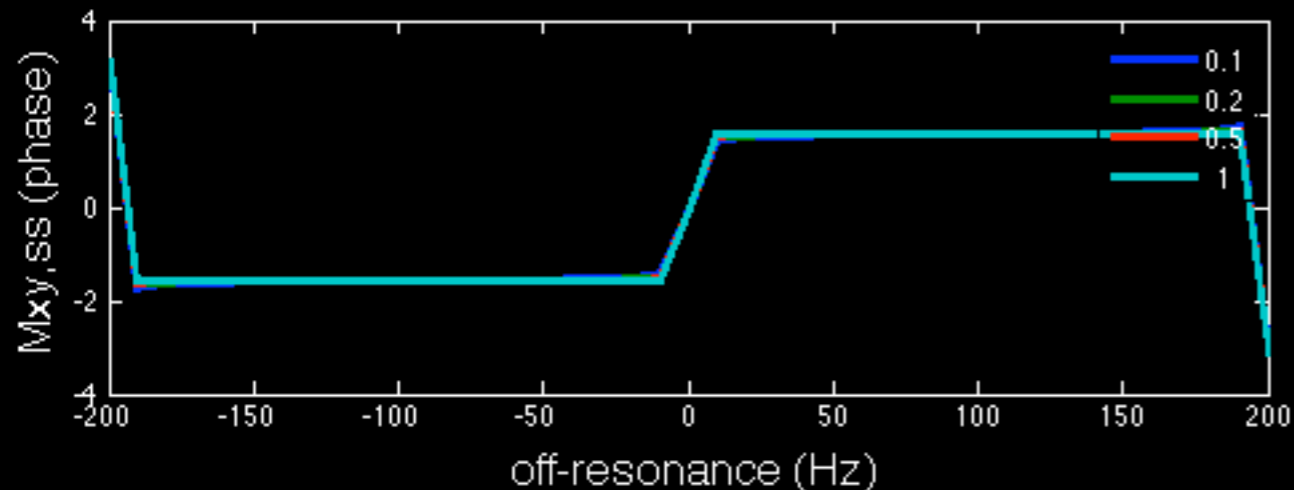
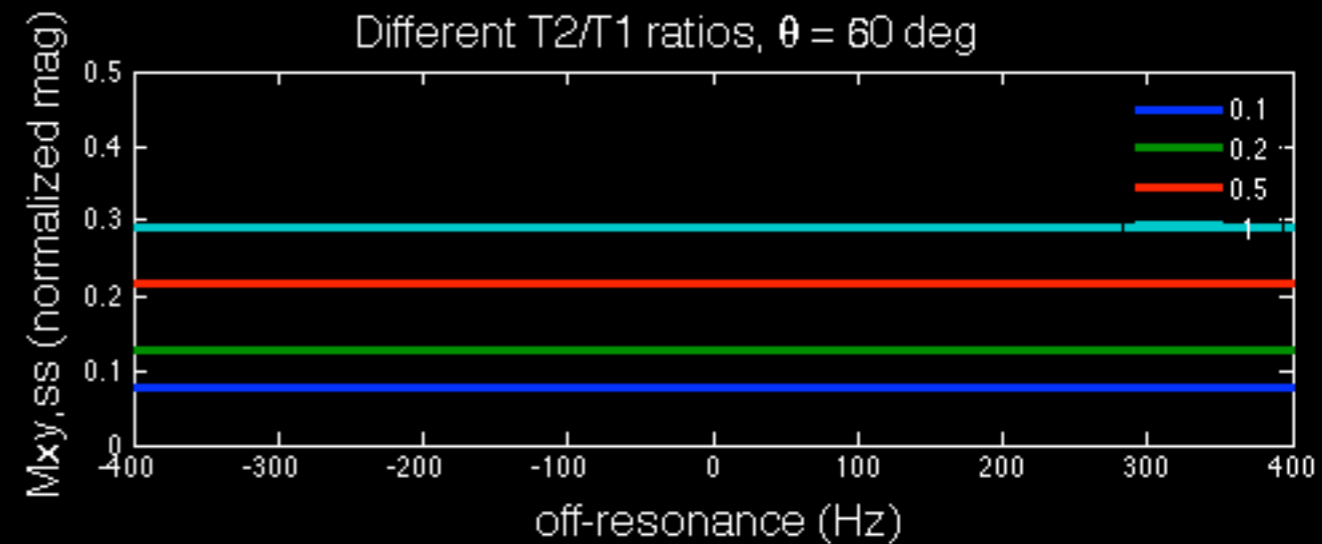
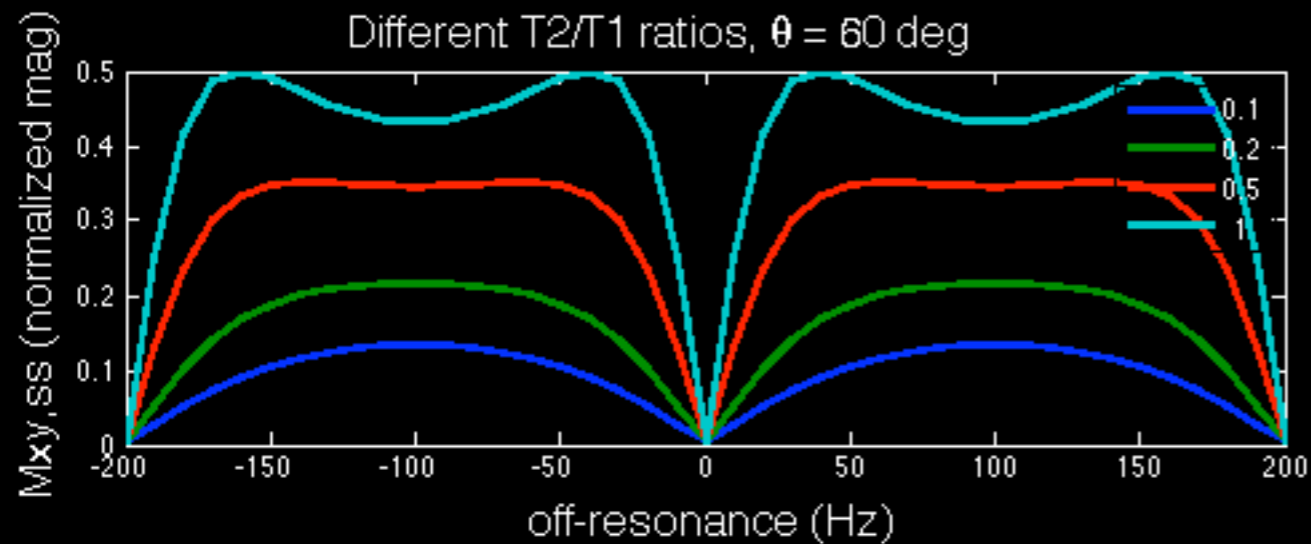
- Homework 2, part 1A
 - Steady state for bSSFP, SSFP-FID and SSFP-Echo

Gradient-spoiled GRE

SS signal as a function of off-resonance:

bSSFP

GRE (SSFP-FID)



$T_1 = 1000$ ms, $T_2 = 100, 200, 500, 1000$ ms

Gradient-spoiled GRE

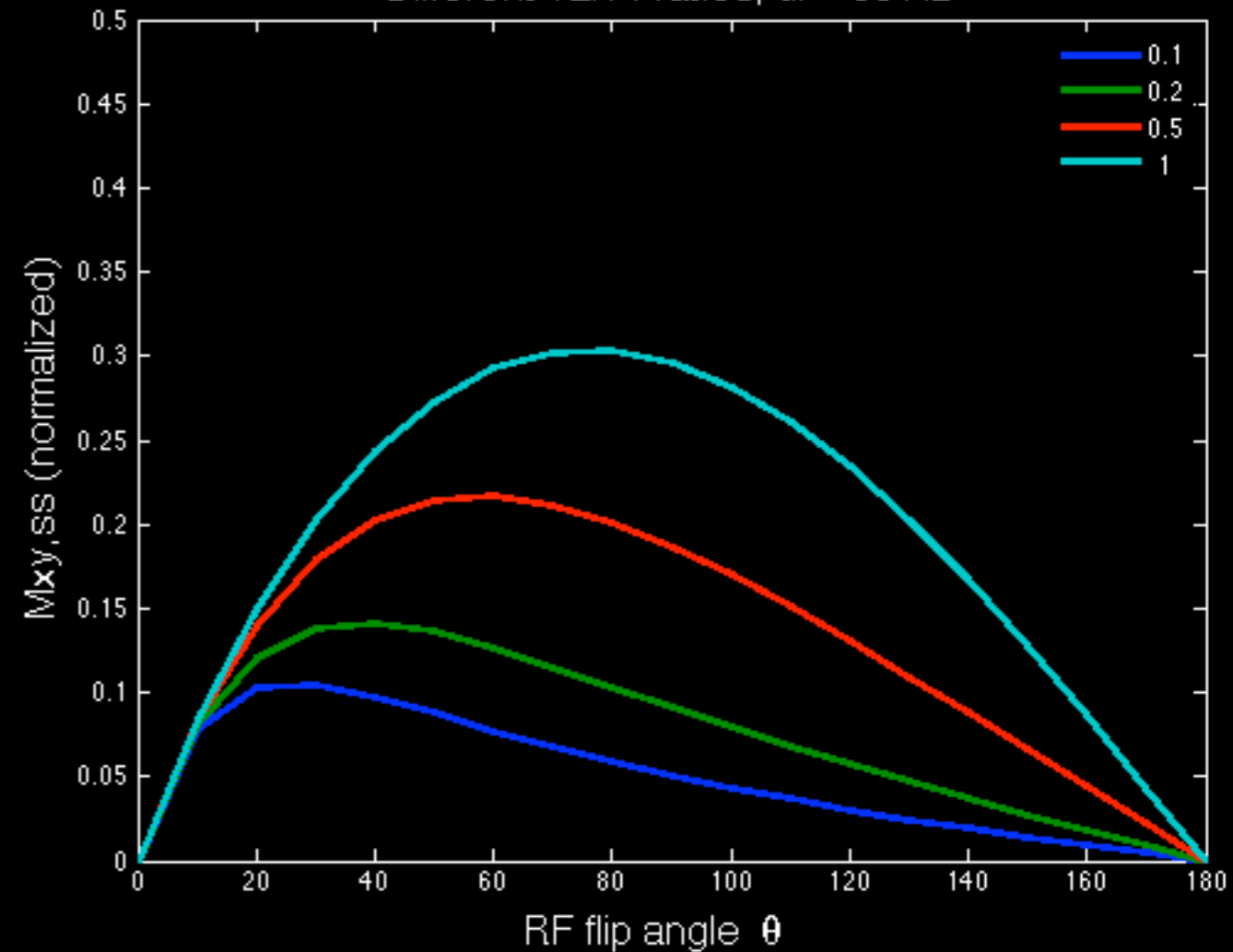
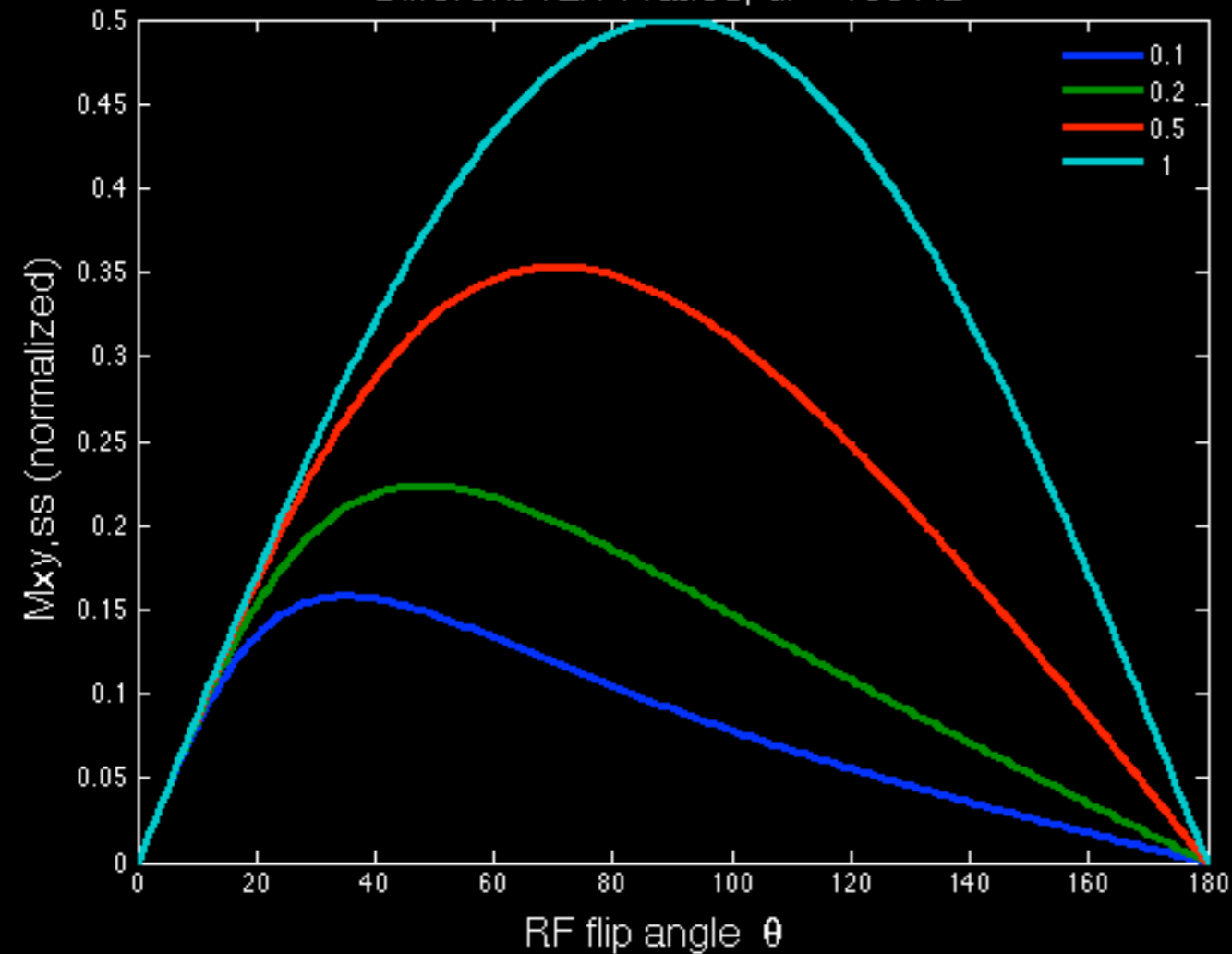
SS signal as a function of flip angle:

bSSFP

GRE (SSFP-FID)

Different T₂/T₁ ratios, df = 100 Hz

Different T₂/T₁ ratios, df = 50 Hz



$T_1 = 1000$ ms, $T_2 = 100, 200, 500, 1000$ ms

Gradient-spoiled GRE

(reversed)

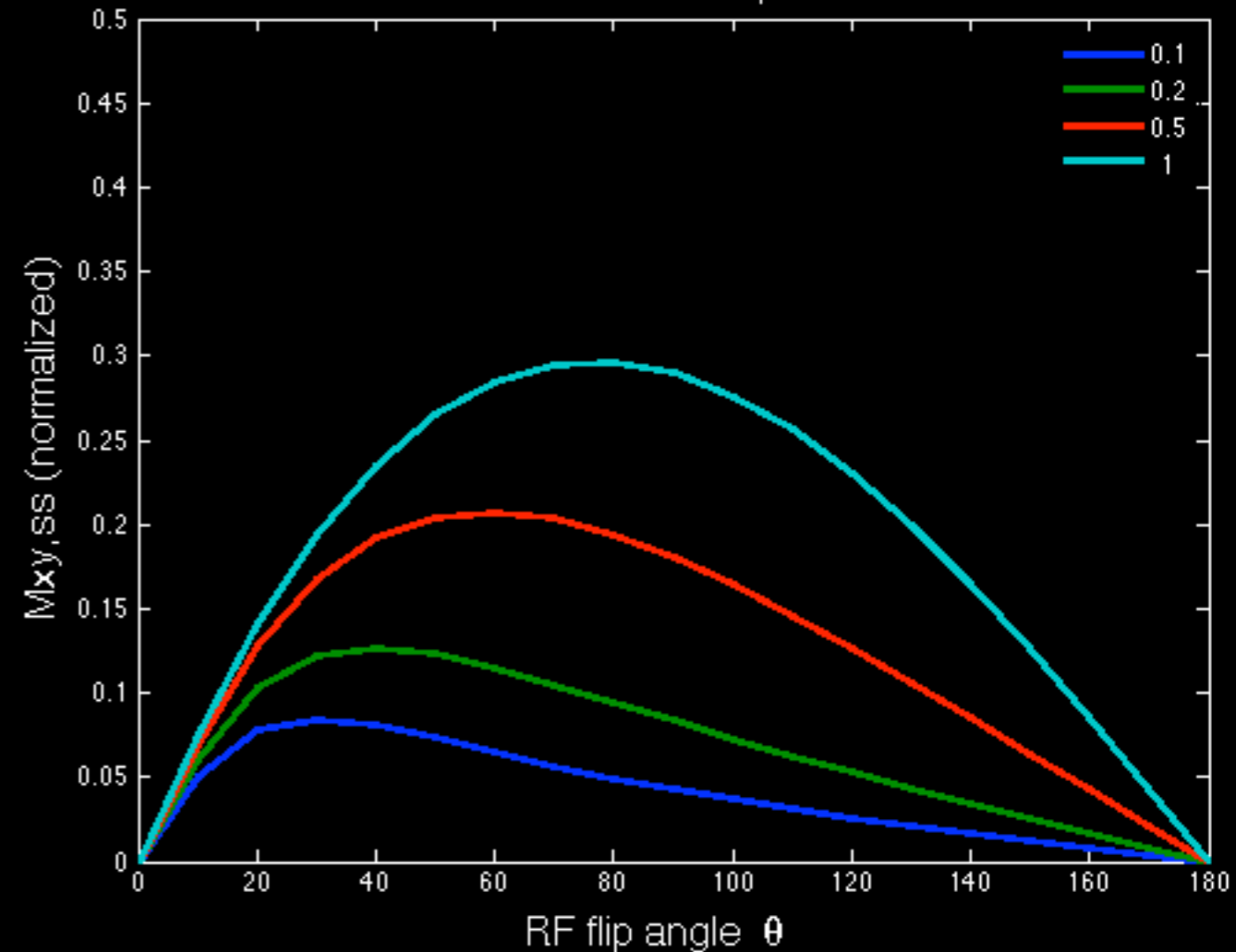
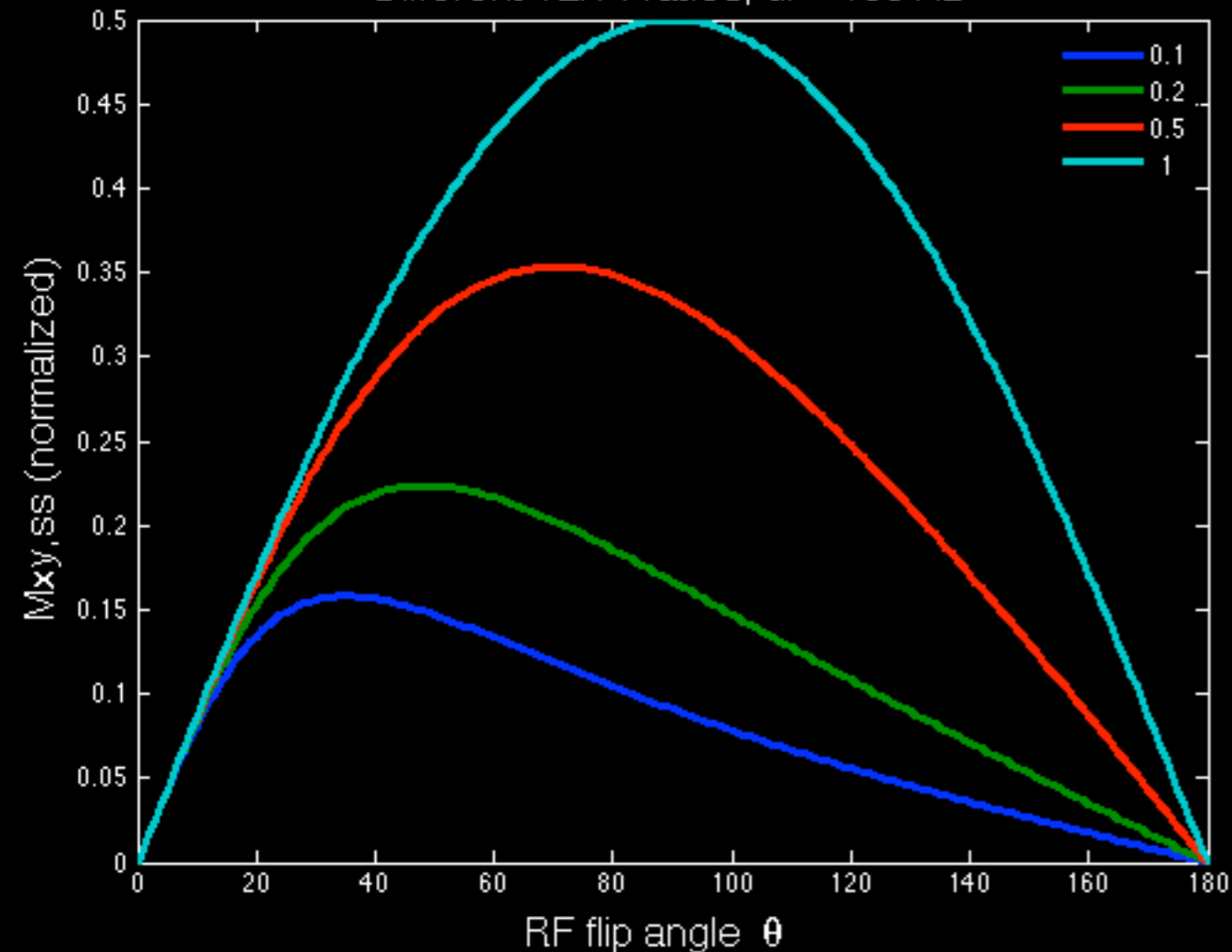
SS signal as a function of flip angle:

bSSFP

GRE (SSFP-Echo)

Different T2/T1 ratios, df = 100 Hz

Different T2/T1 ratios, df = 50 Hz



$T_1 = 1000$ ms, $T_2 = 100, 200, 500, 1000$ ms

Bloch Simulation

- Homework 2, part 1B
 - Transition to steady state for bSSFP
 - catalyzation schemes

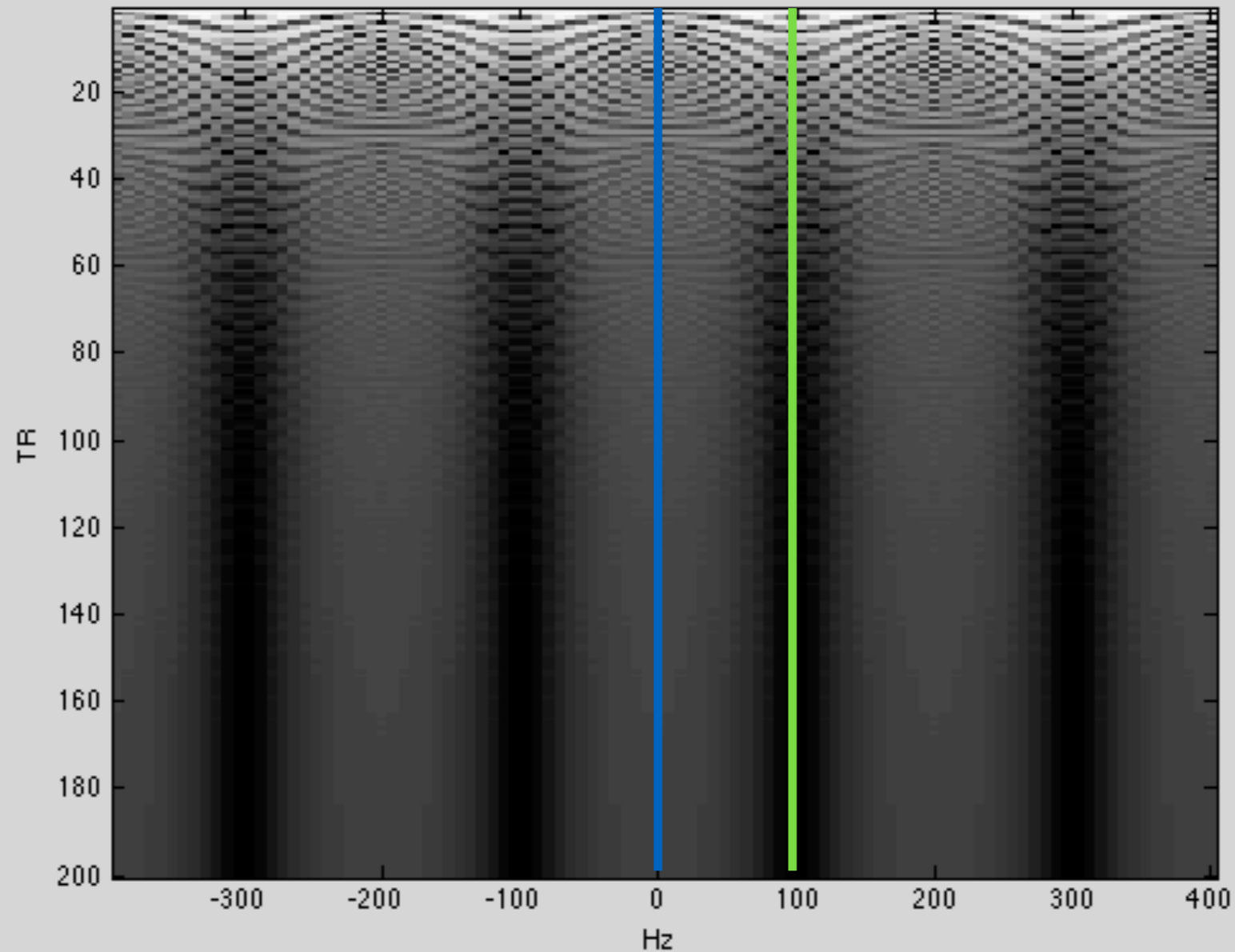
Balanced SSFP

Transition to steady state:

$TR = 5 \text{ ms}$

$\Delta\phi = \pi$

$\theta = 60^\circ$



$T_1 = 600 \text{ ms}, T_2 = 100 \text{ ms}$

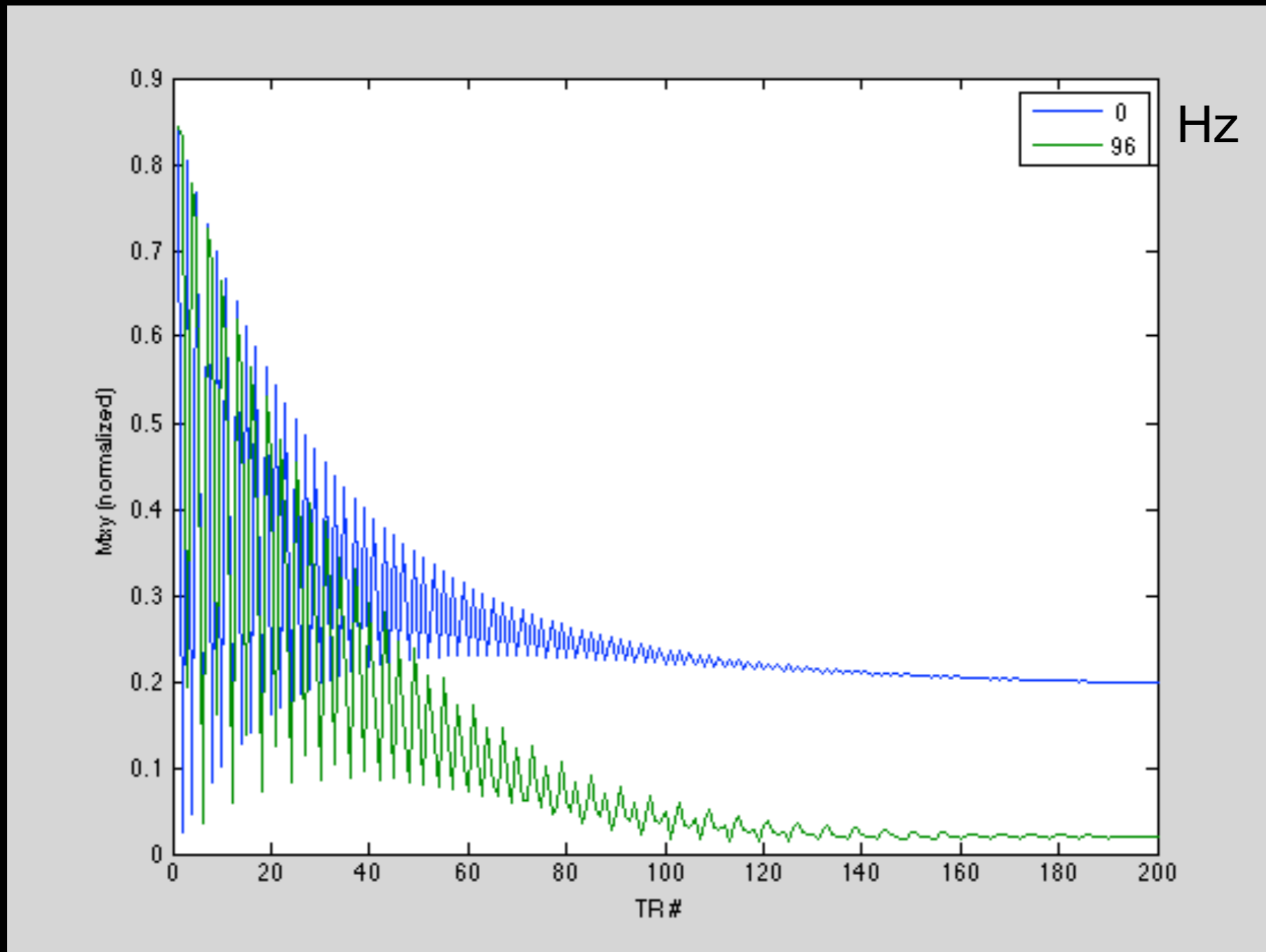
Balanced SSFP

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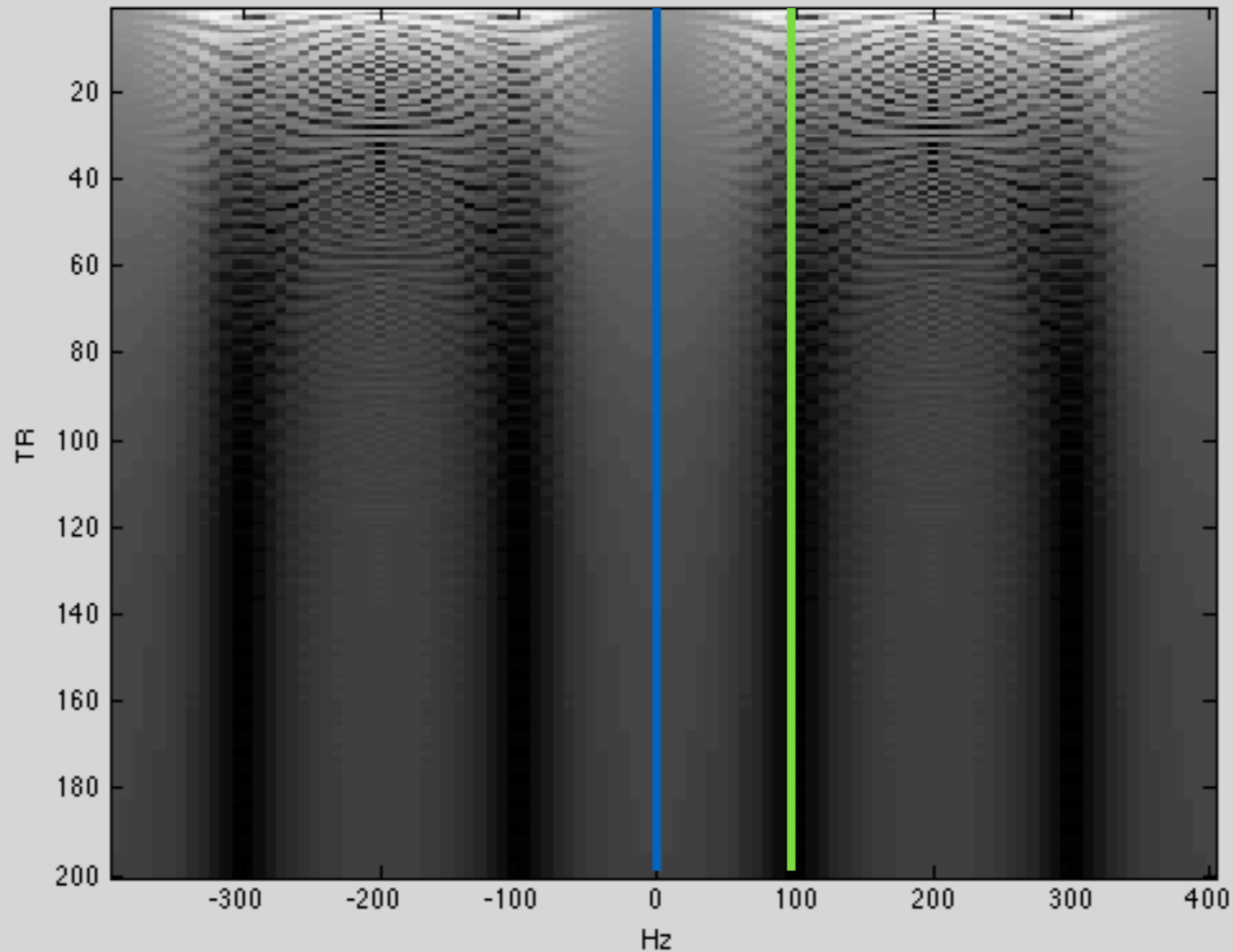
Balanced SSFP

Transition to steady state ($\theta/2$ -TR/2 prep):

TR = 5 ms

$\Delta\phi = \pi$

$\theta = 60^\circ$



$T_1 = 600\text{ ms}, T_2 = 100\text{ ms}$

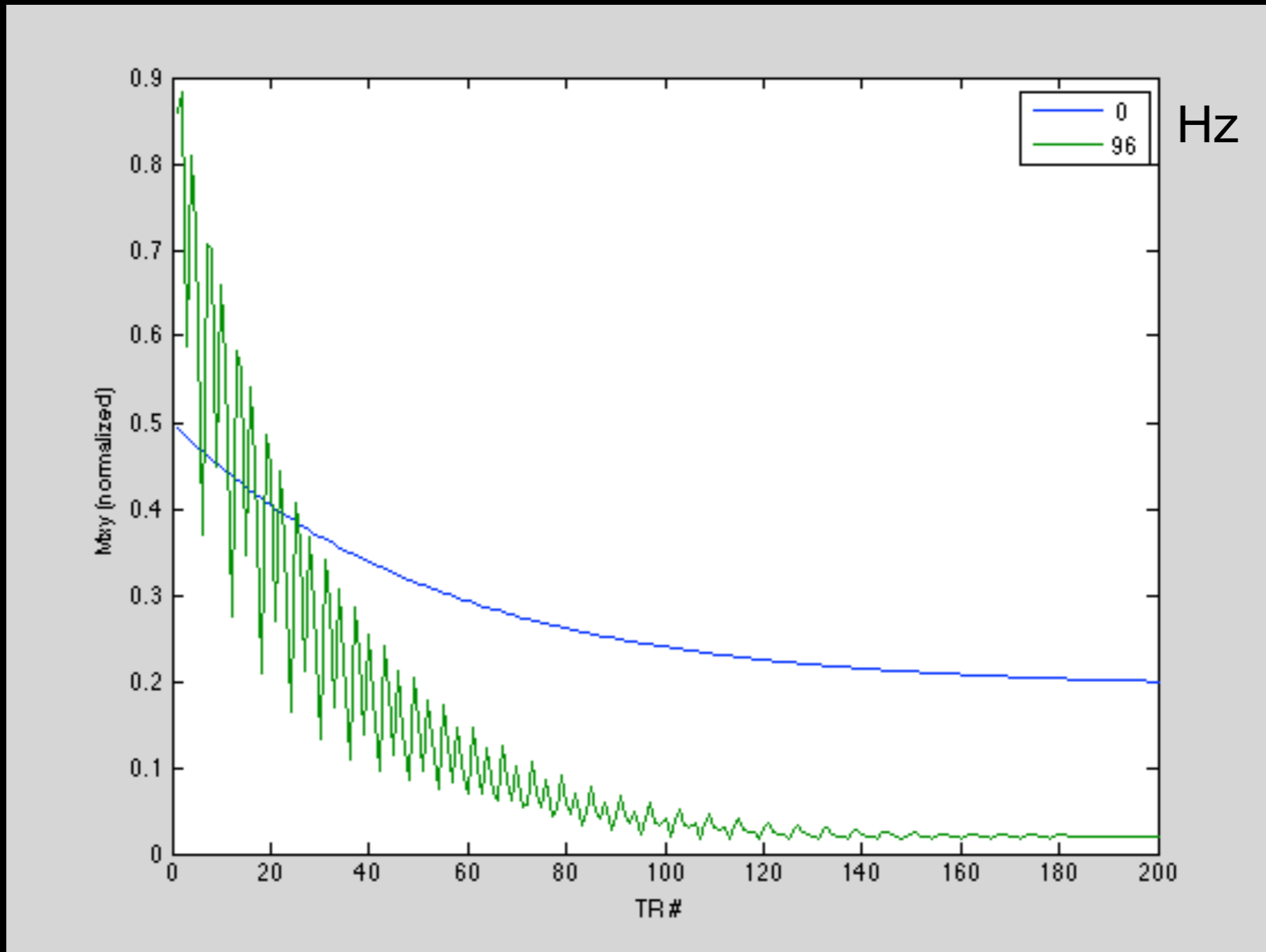
Balanced SSFP

Transition to steady state ($\theta/2$ -TR/2 prep):

TR = 5 ms

$\Delta\phi = \pi$

$\theta = 60^\circ$



$T_1 = 600$ ms, $T_2 = 100$ ms

Balanced SSFP

- Linear ramp-up catalyzation
 - initial train of $\theta \cdot [1:N]/N$ (same TR)
 - Example:
 $\theta = 60^\circ$, $N = 5$
ramp up pulses $\theta_{lin} = [12^\circ, 24^\circ, 36^\circ, 48^\circ, 60^\circ]$

Homework 2

- Pulse Sequence Simulations
 - 1. Bloch: Steady state comparison, bSSFP transient state and catalyzation
 - 2. EPG: SSFP-FID, RF-spoiled GRE
- Due 5 pm, 4/29 Mon by email
 - PDF and MATLAB code

Thanks!

- Web resources
 - ISMRM 2010 Edu: Miller, Weigel
 - ISMRM 2011 Edu: Miller, Weigel
- Further reading
 - Bernstein et al., Handbook of MRI Sequences
 - Haacke et al., Magnetic Resonance Imaging
 - Scheffler, Concepts in MR 1999; 11:291-304
 - Hennig, JMR 1988; 78:397-407

Thanks!

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- Next lecture
 - EPG and MATLAB demo

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