Pulse Sequences: RARE and Simulations

M229 Advanced Topics in MRI

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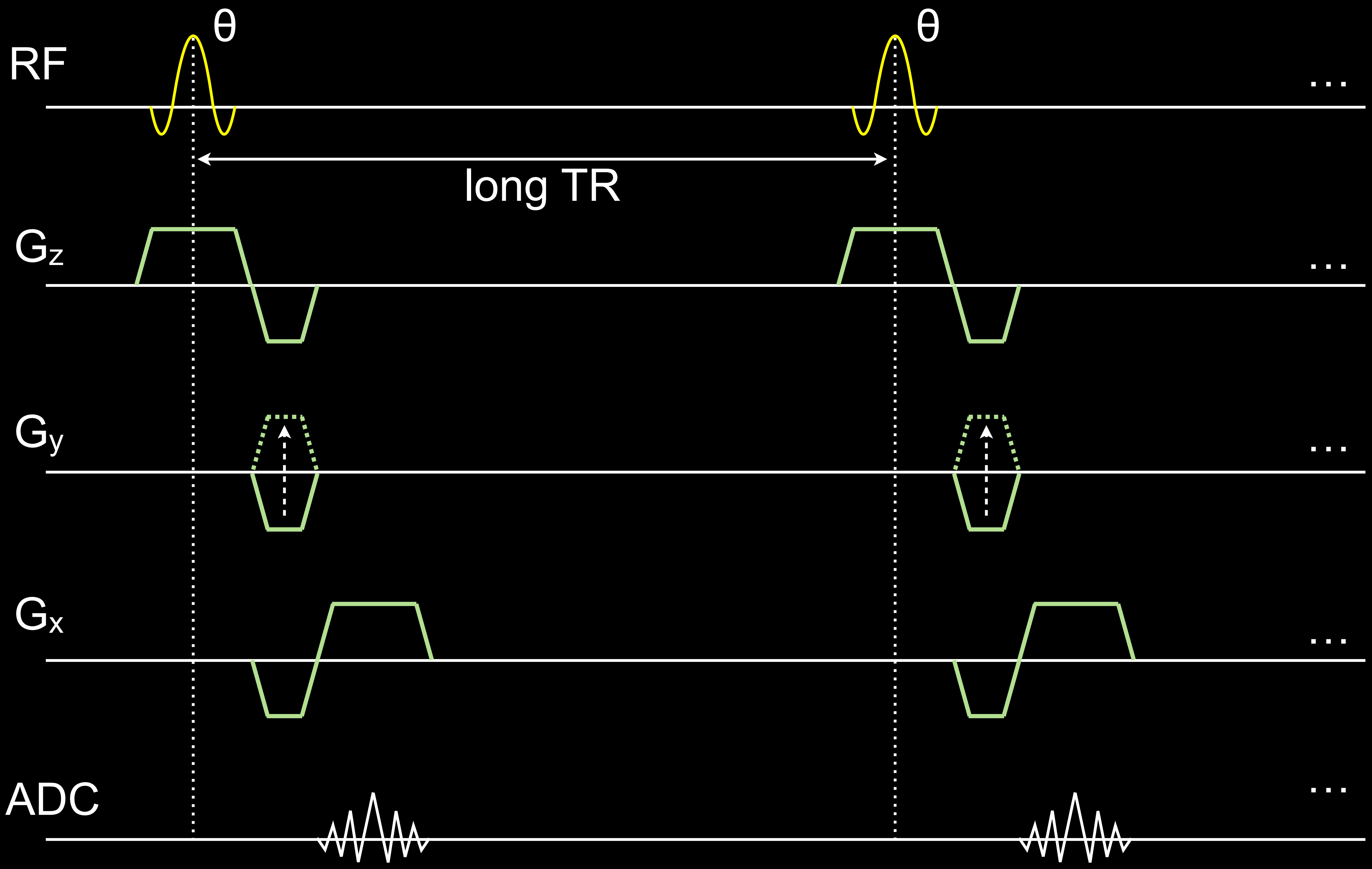
Class Business

- Office hours
  - Holden: Fri 10-11 am
  - Shu-Fu: Mon 2-4 pm
- Homework 1 due on 4/28 Fri
- Final project
  - Start thinking
  - Discuss over email or during office hours
  - Discussion in class on 4/27 Thu

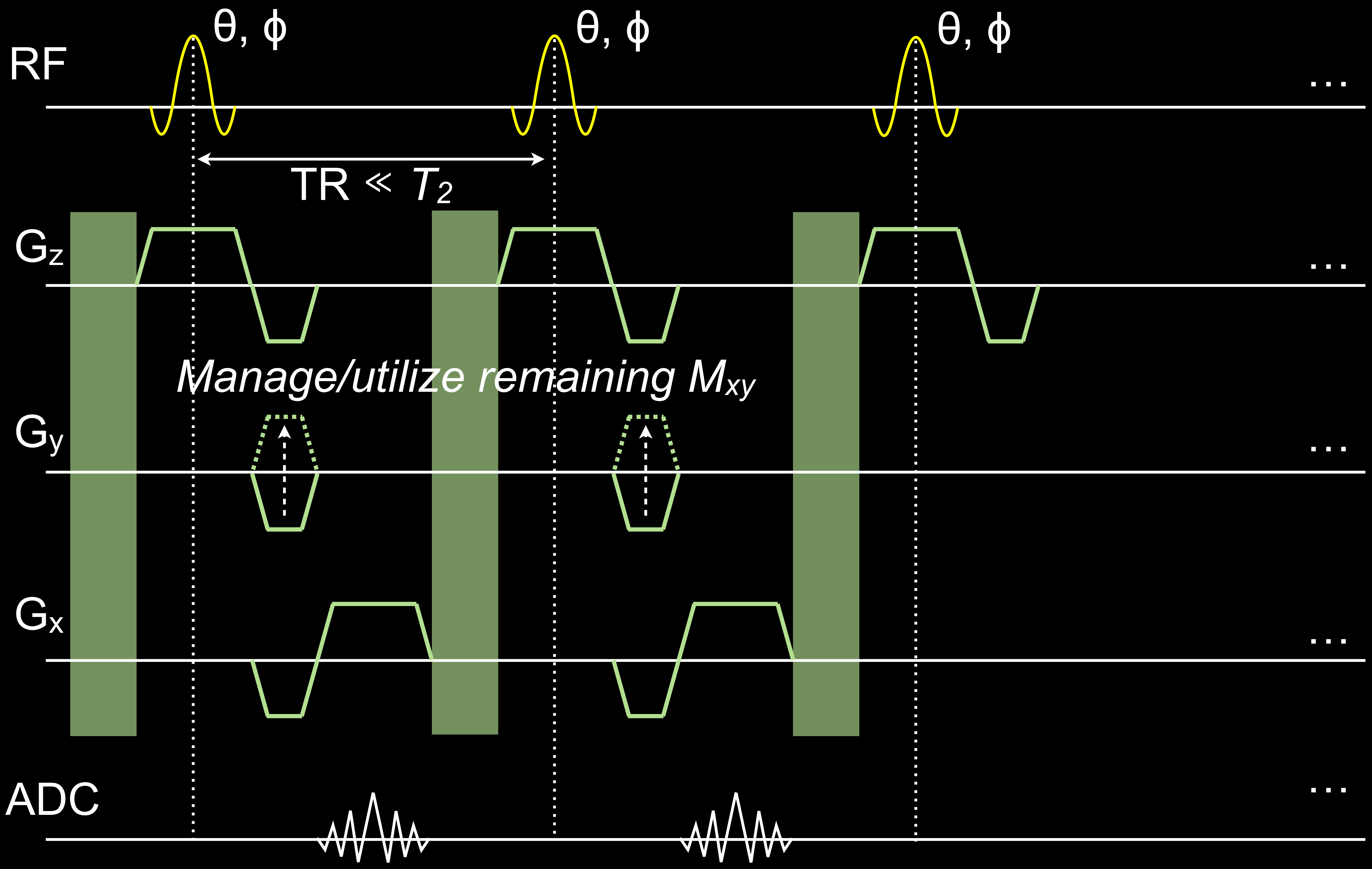
Outline

- Rapid GRE
  - Review
- RARE (aka FSE, TSE)
- Pulse sequence simulations
  - MATLAB Bloch simulations
  - Homework 1

Gradient Echo



Rapid Gradient Echo

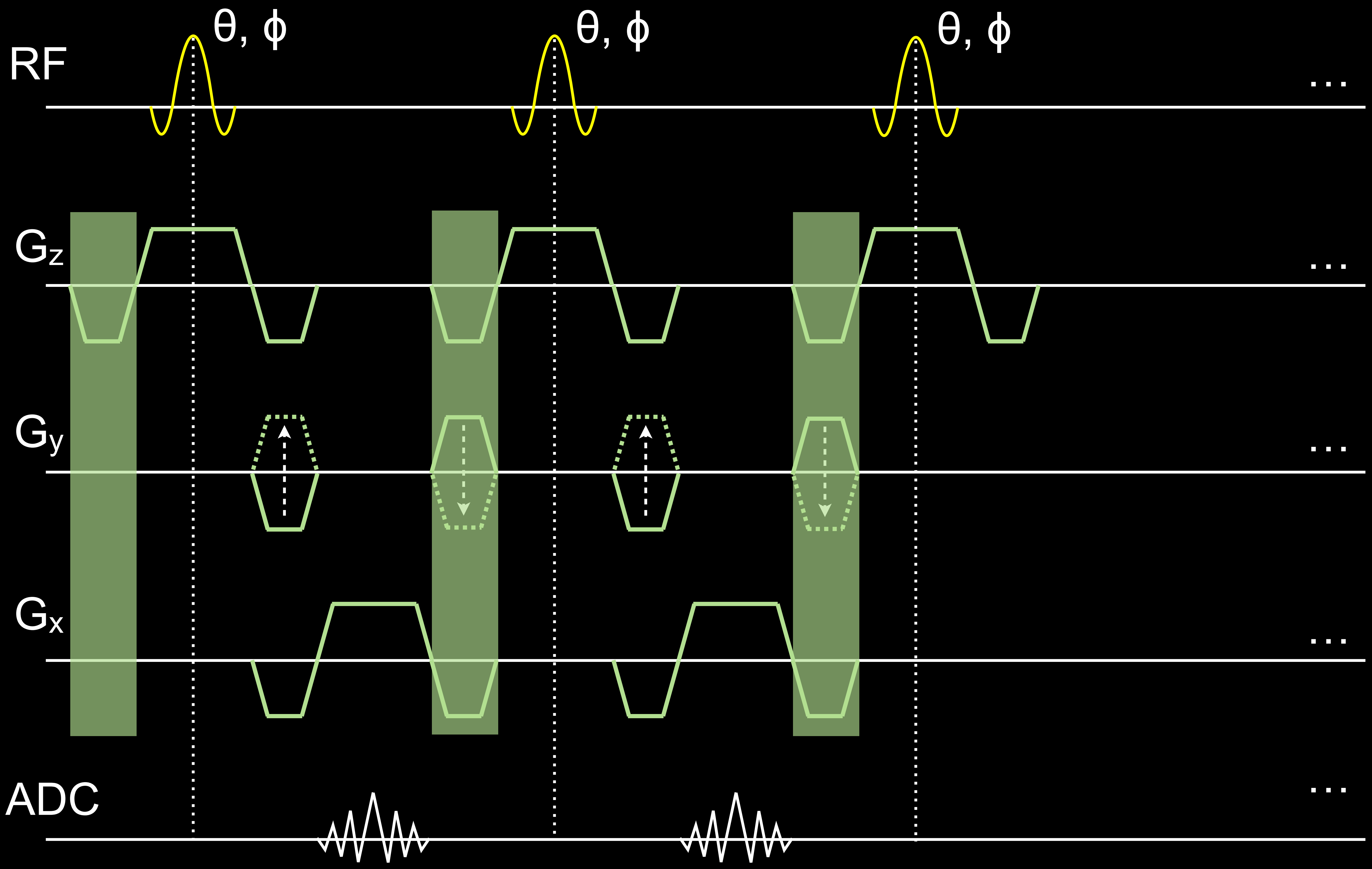


Rapid Gradient Echo

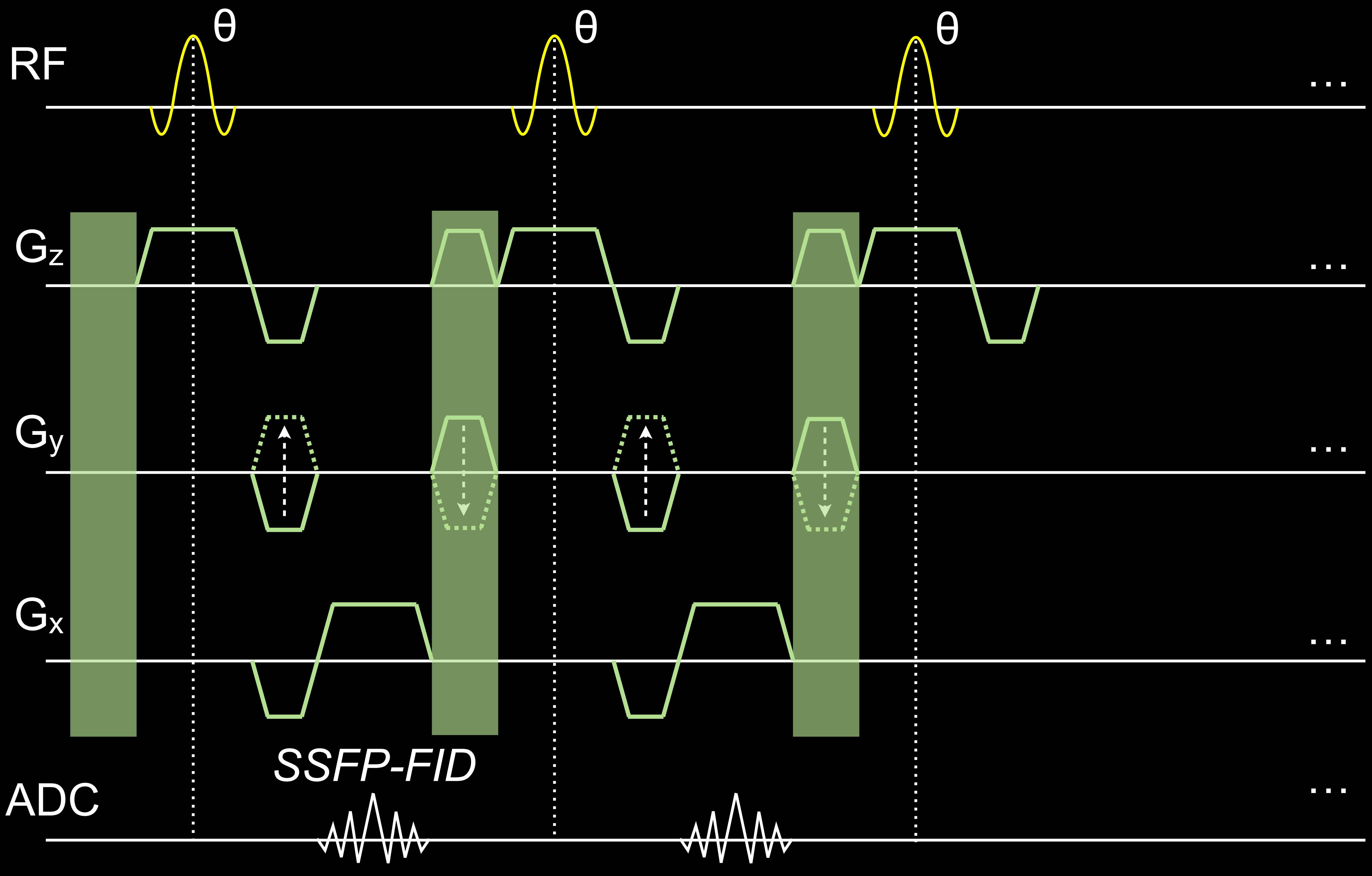
- Rapid imaging with TR $\ll T_2 < T_1$
- Steady state
  - Involves a mixture of M_z and M_{xy}
  - Necessary and sufficient conditions:
    1. Constant RF flip angle θ
    2. Constant TR
    3. Constant dephasing β between RF pulses
    4. RF phase $\phi_n = a + bn + cn^2$

Scheffler K, Con Magn Reson 1999; 11:291-304

Balanced SSFP

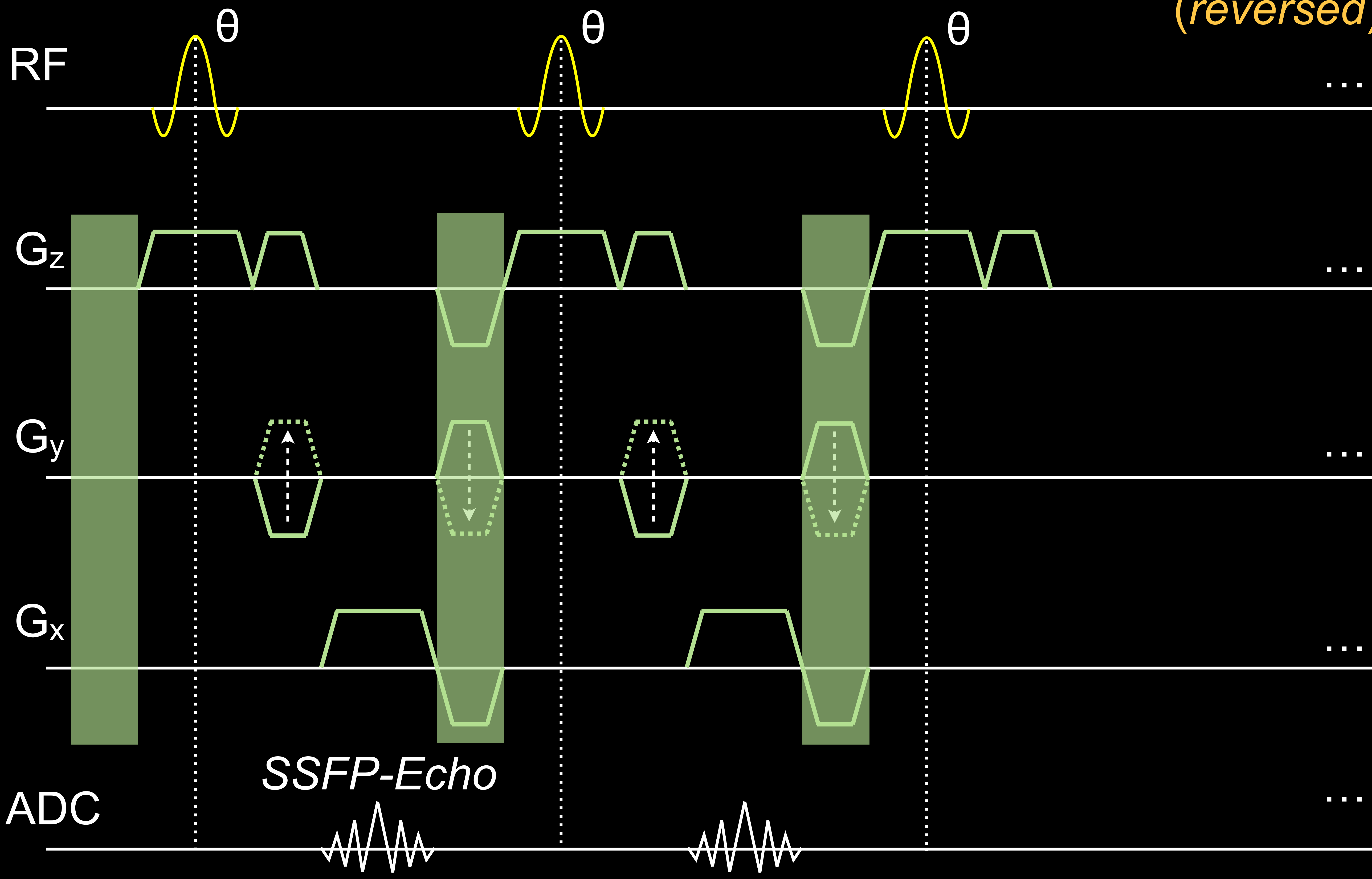


Gradient-spoiled GRE

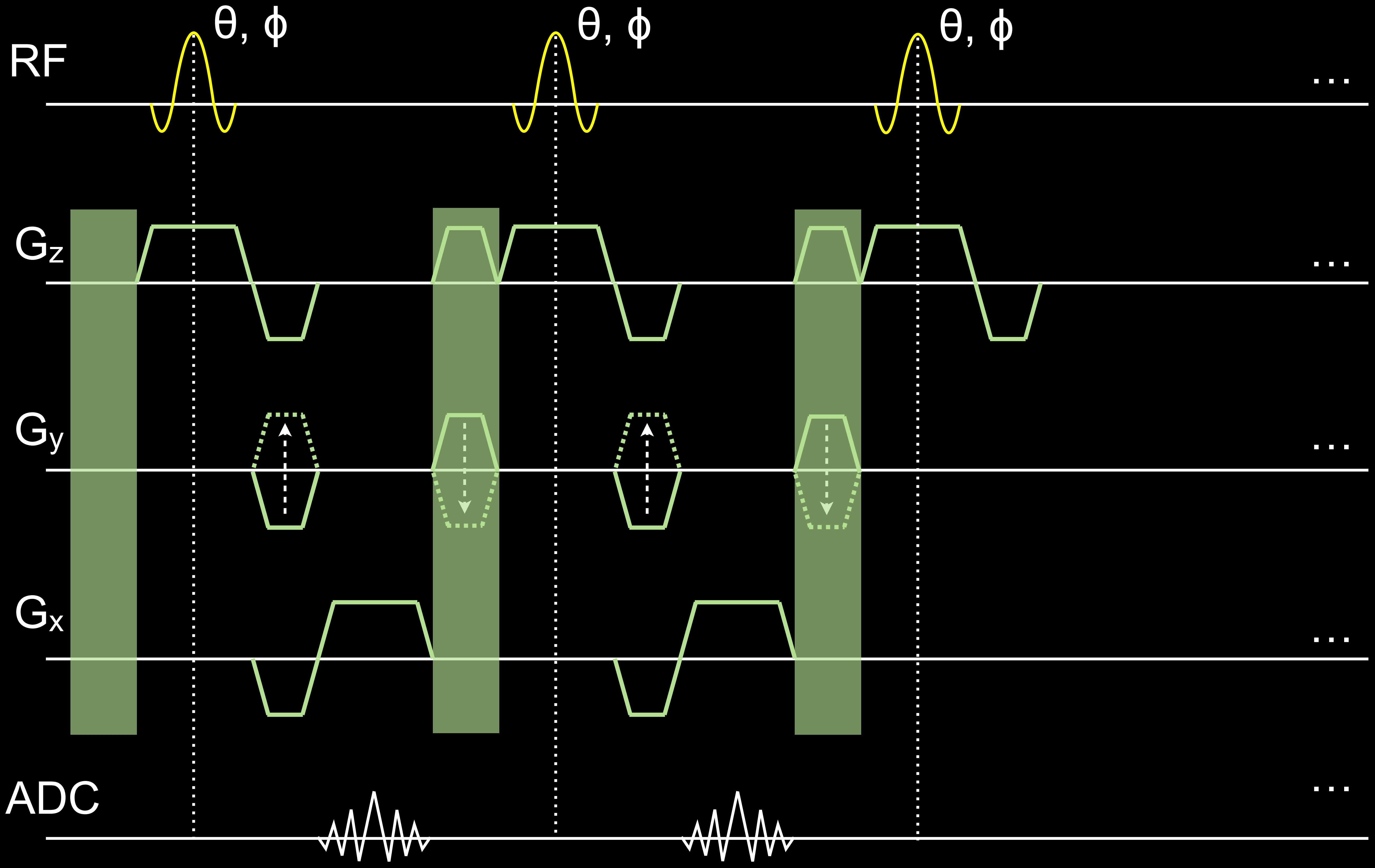


Gradient-spoiled GRE

(reversed)



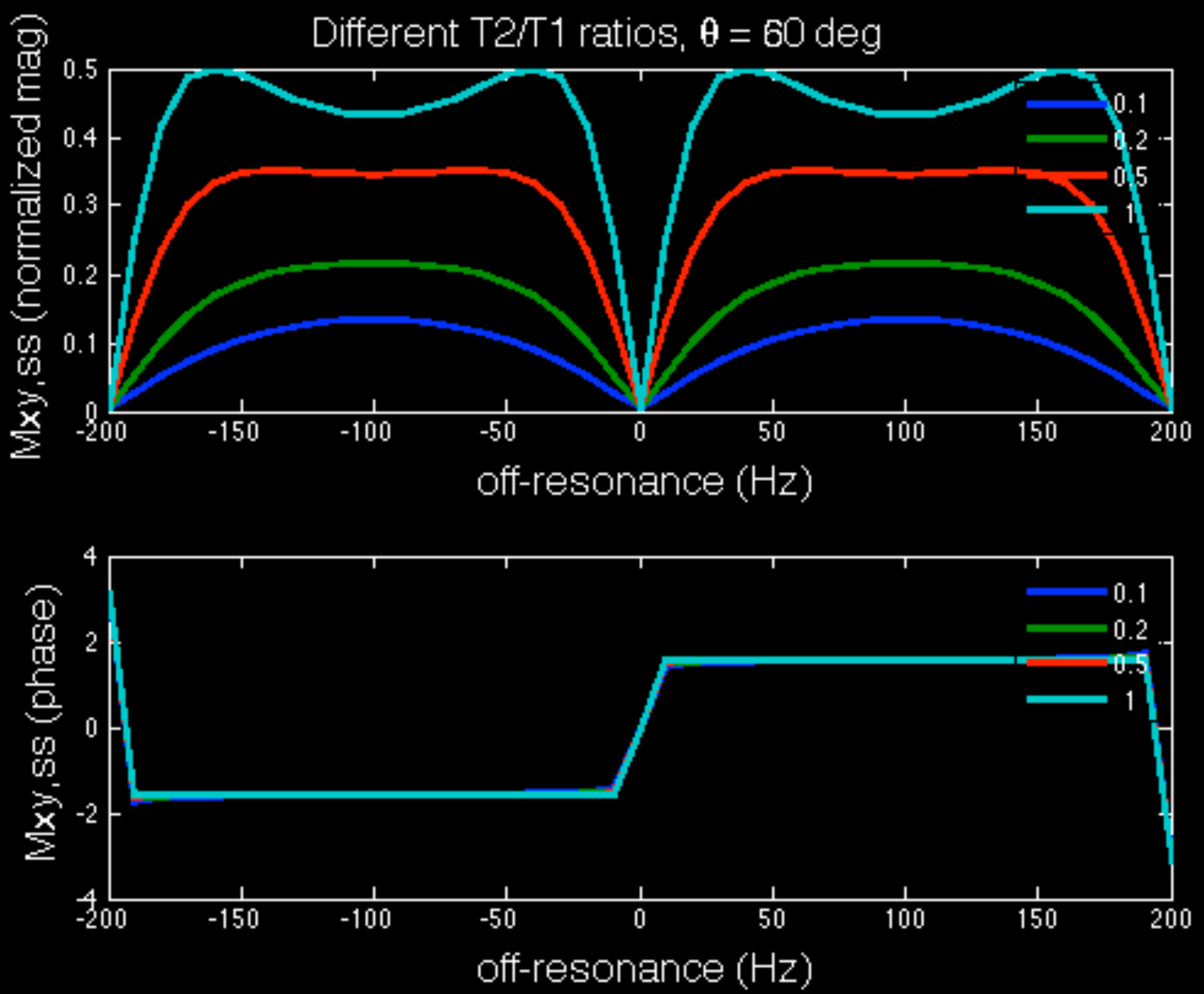
Gradient & RF-spoiled GRE



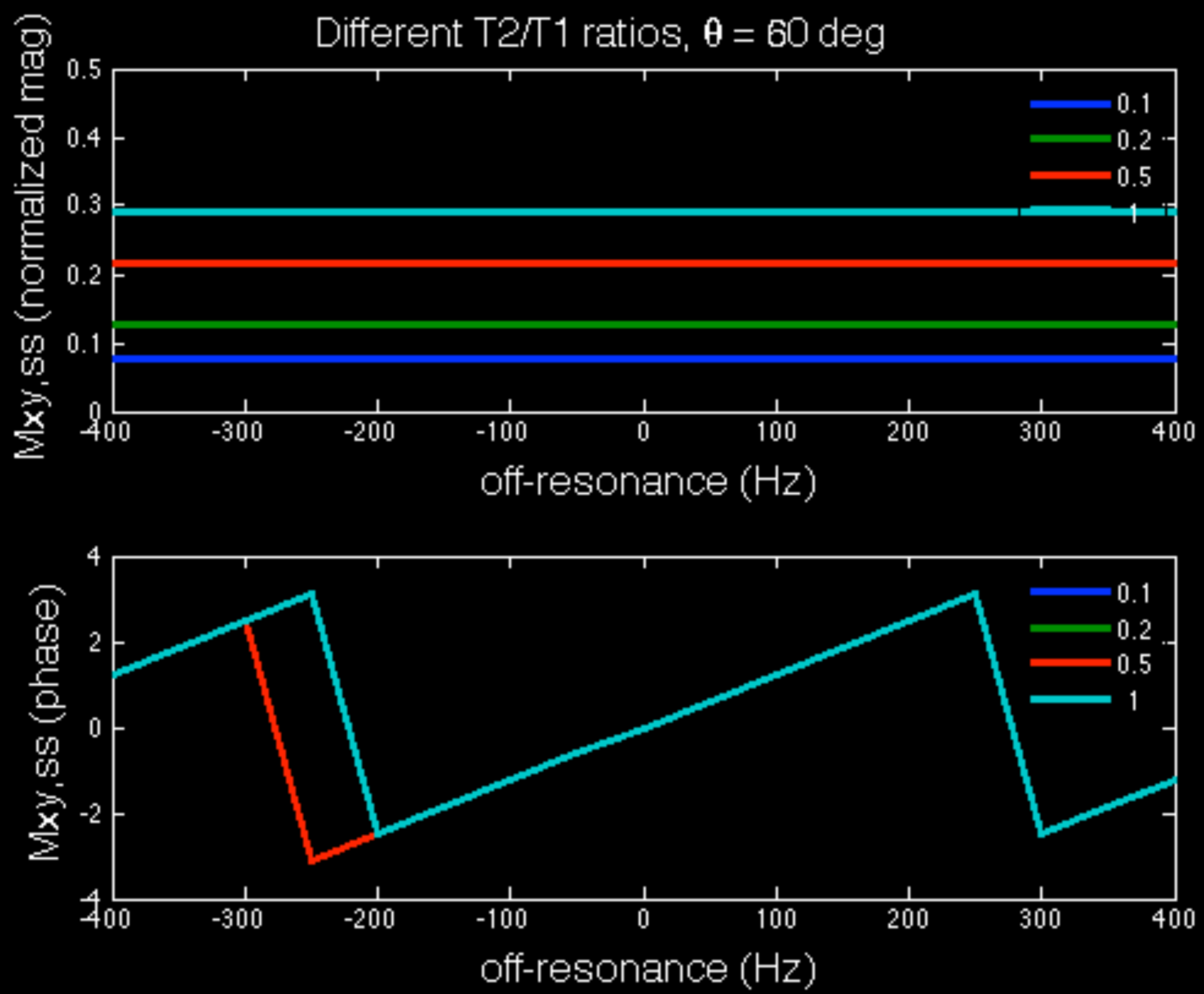
Gradient-spoiled GRE

SS signal as a function of off-resonance:

bSSFP



GRE (SSFP-FID)



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

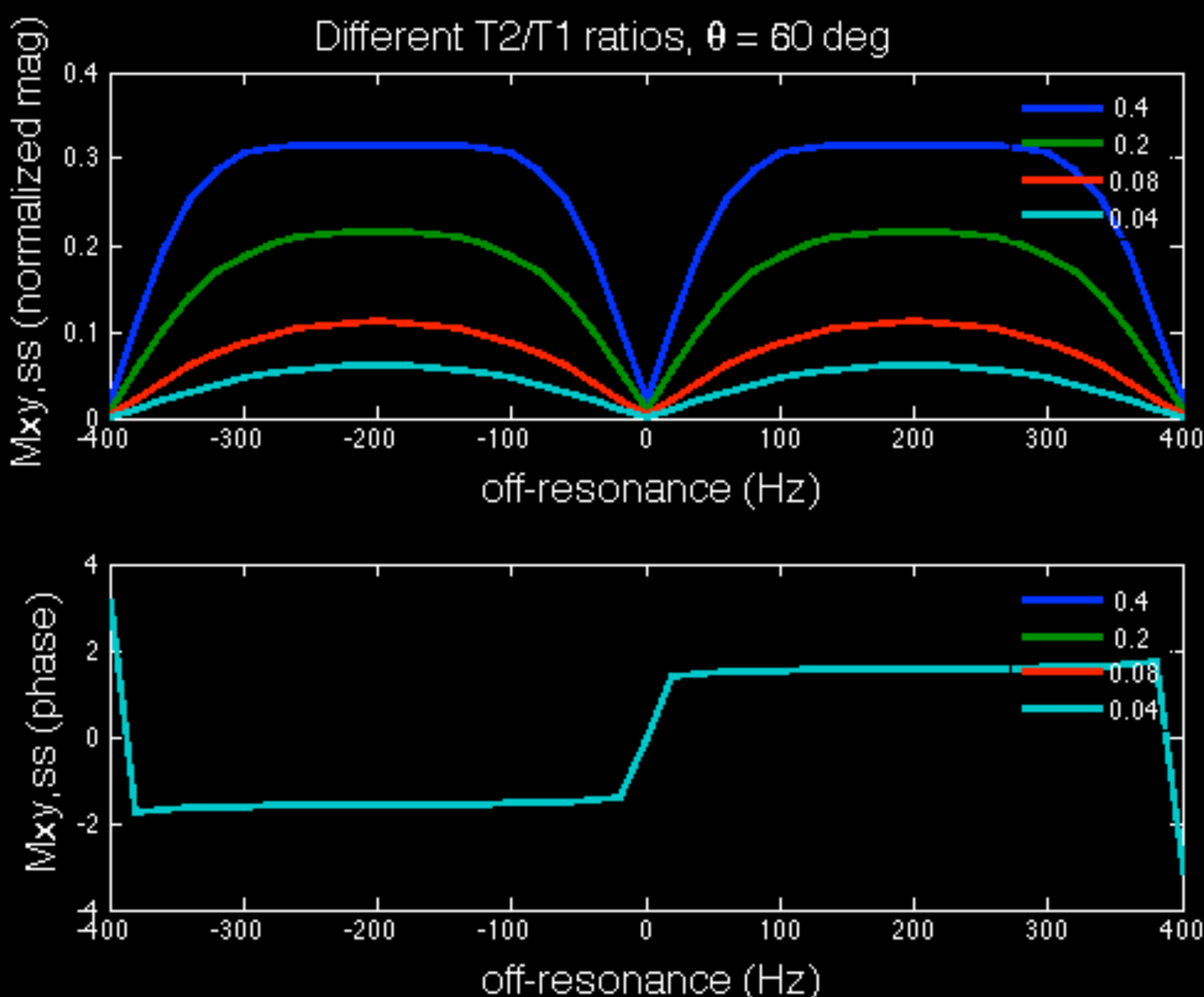
Gradient and RF-spoiled GRE

- RF spoiling (quadratic)
  - $\phi_n = \phi_{n-1} + n\phi_0 = (1/2)\phi_0(n^2 + n + 2)$
  - typically $\phi_0 = 50^o$ or 117^o
  - 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)

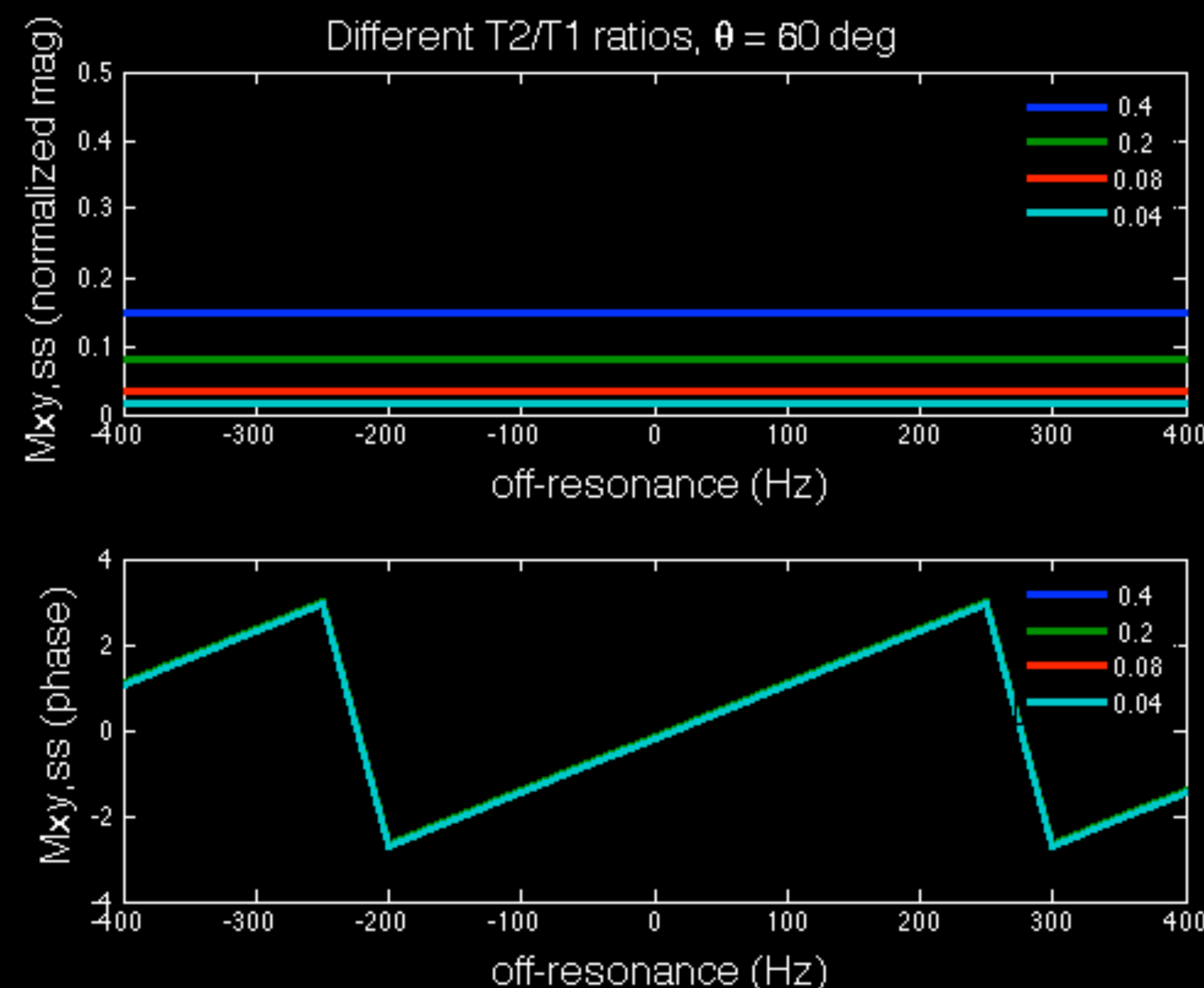
Gradient and RF-spoiled GRE

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

cf. Hargreaves B, JMRI 2012; 36:1300-1313

Why RARE (TSE)?

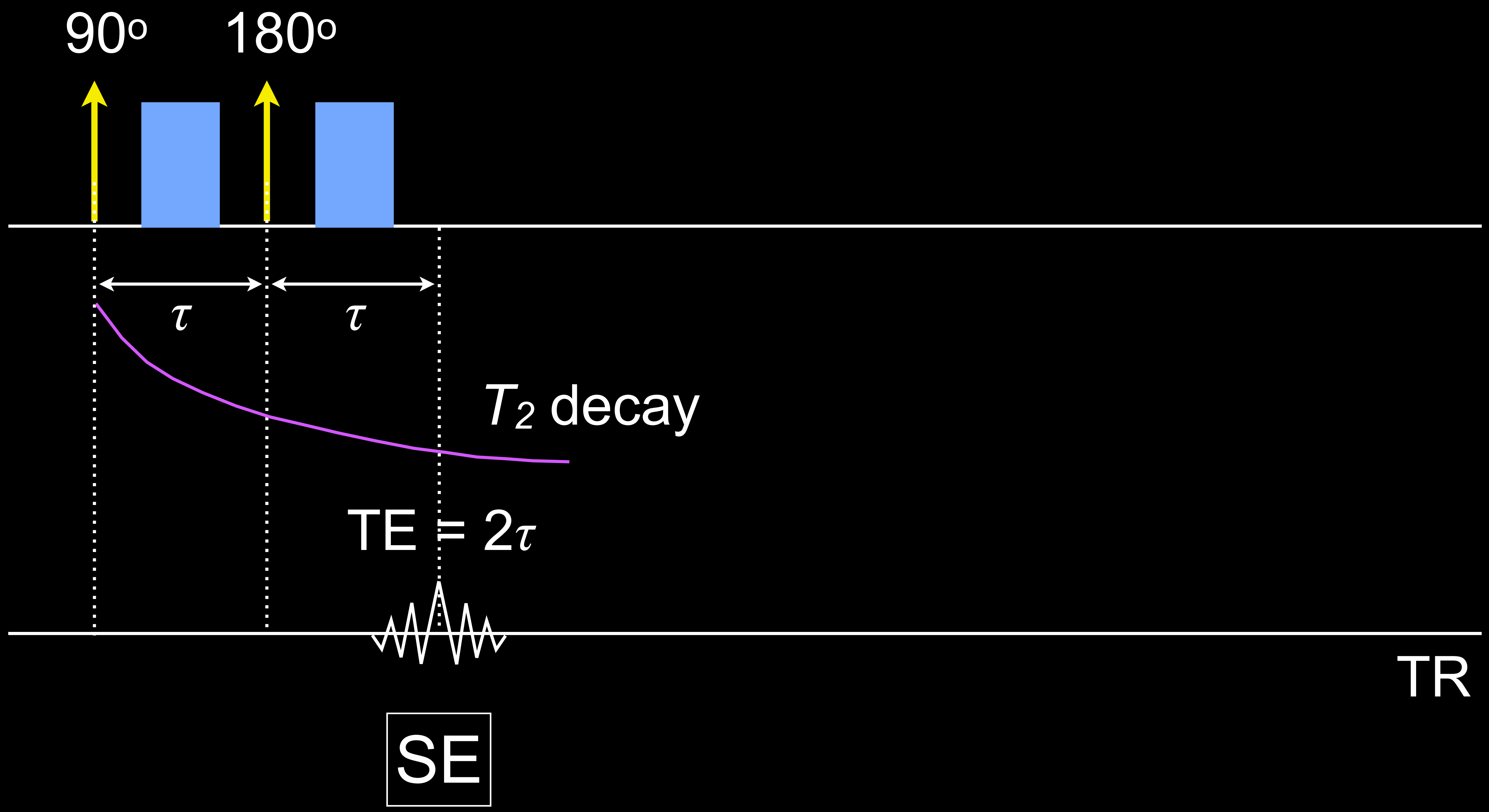
- Basic spin echo (SE) MRI is slow
  - TR on the order of 500 - 5000 ms
  - Data acquisition of one k-space line per TR, readout duration of 10 ms or less
  - Could acquire more lines before complete T_2 decay of M_{xy}

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)

[1]Hennig J et al., MRM 1986

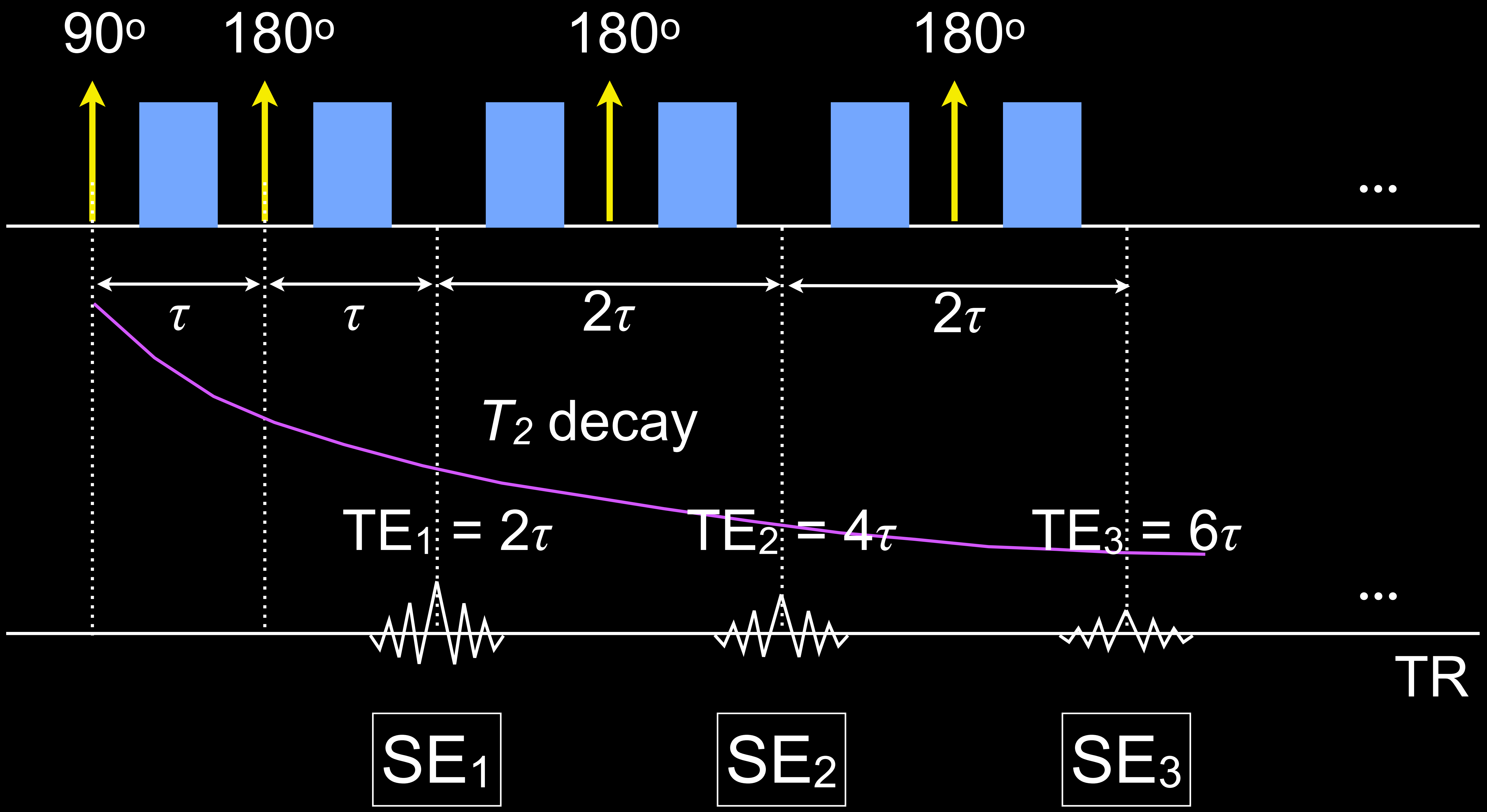
Spin Echo



Spin Echo

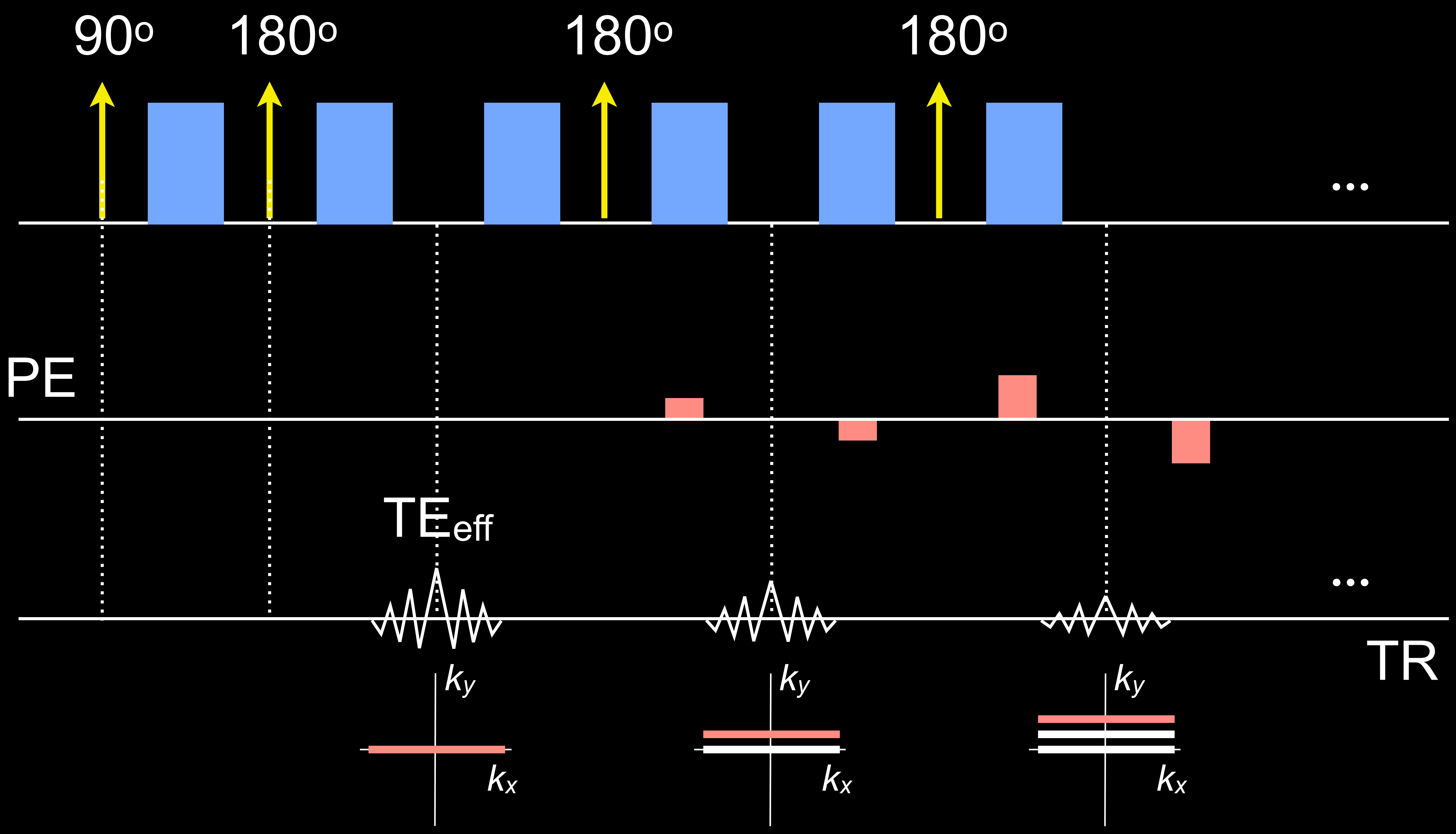
- Image contrast
  - Based on TE, TR
  - T1w, T2w, PDw
  - Can augment with prep pulses
- Scan time
  - $T_{SE} = N_{pe} \times TR$
  - TR = 1000 ms, N_{pe} = 256: T_{SE} = 4+ min
  - usually combined with 2D multislice acq

Multi-echo Spin Echo



Can perform T_2 mapping.

RARE (Turbo Spin Echo)



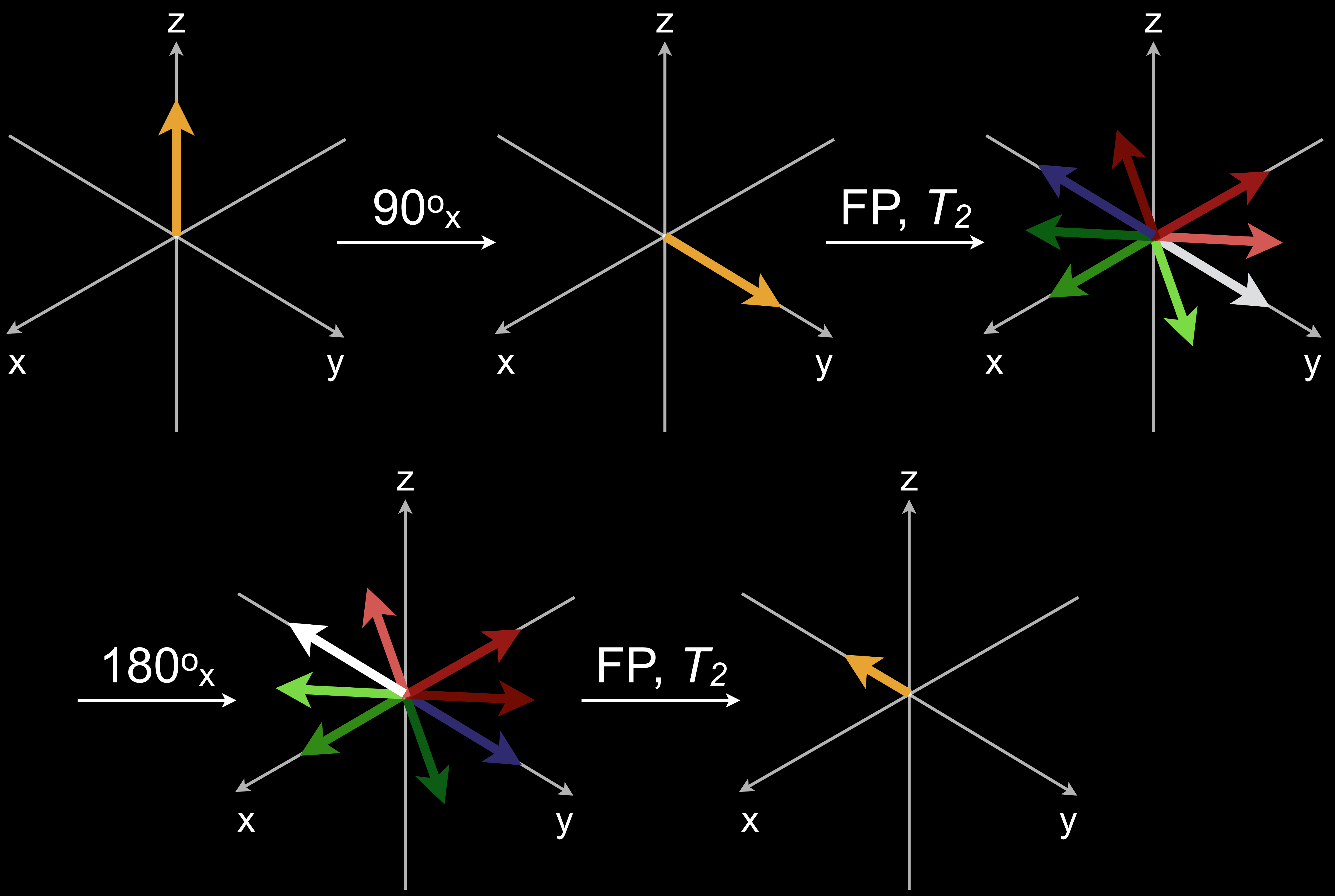
CPMG Conditions

- 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^o_x - τ - 180^o_y - 2τ - 180^o_y - 2τ - 180^o_y ...
- Constant phase accrual btwn pulses
  - Same area for crusher pairs
  - Phase encode rewinder

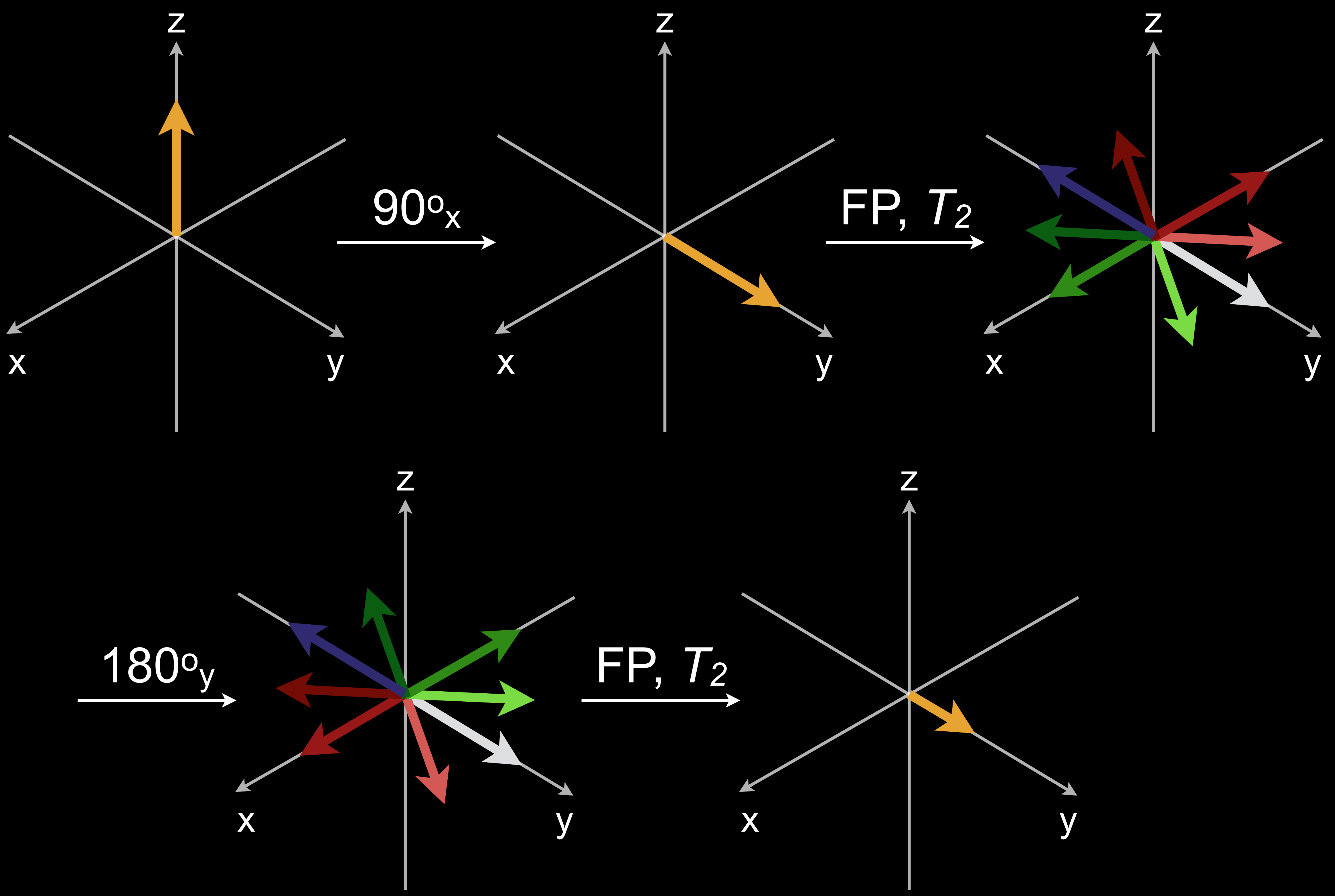
CPMG Conditions

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

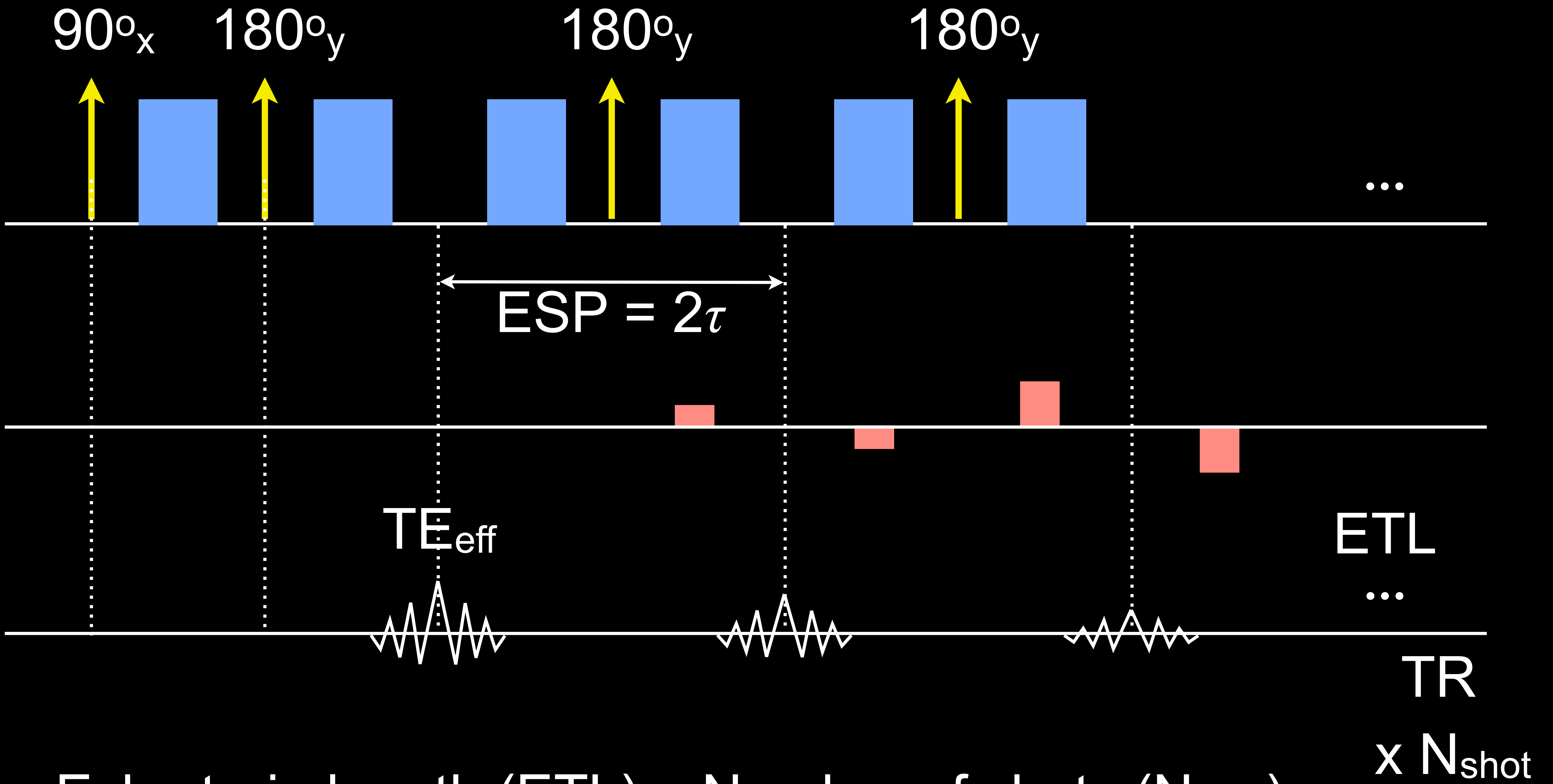
Spin Echo: 90^o_x - 180^o_x



Spin Echo: 90^o_x - 180^o_y



TSE Sequence Params



Echo train length (ETL)

Echo spacing (ESP)

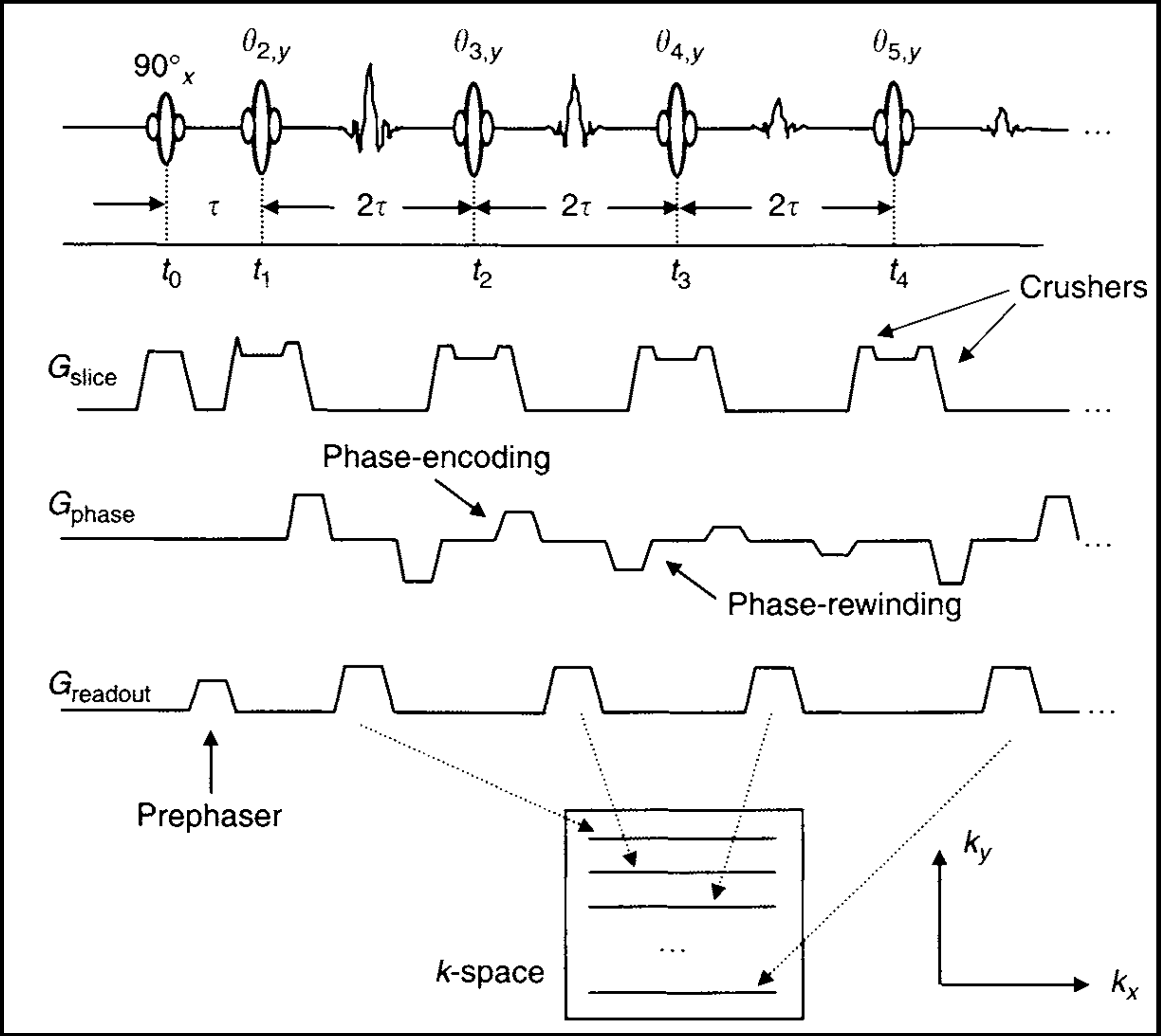
Number of shots (N_{shot})

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

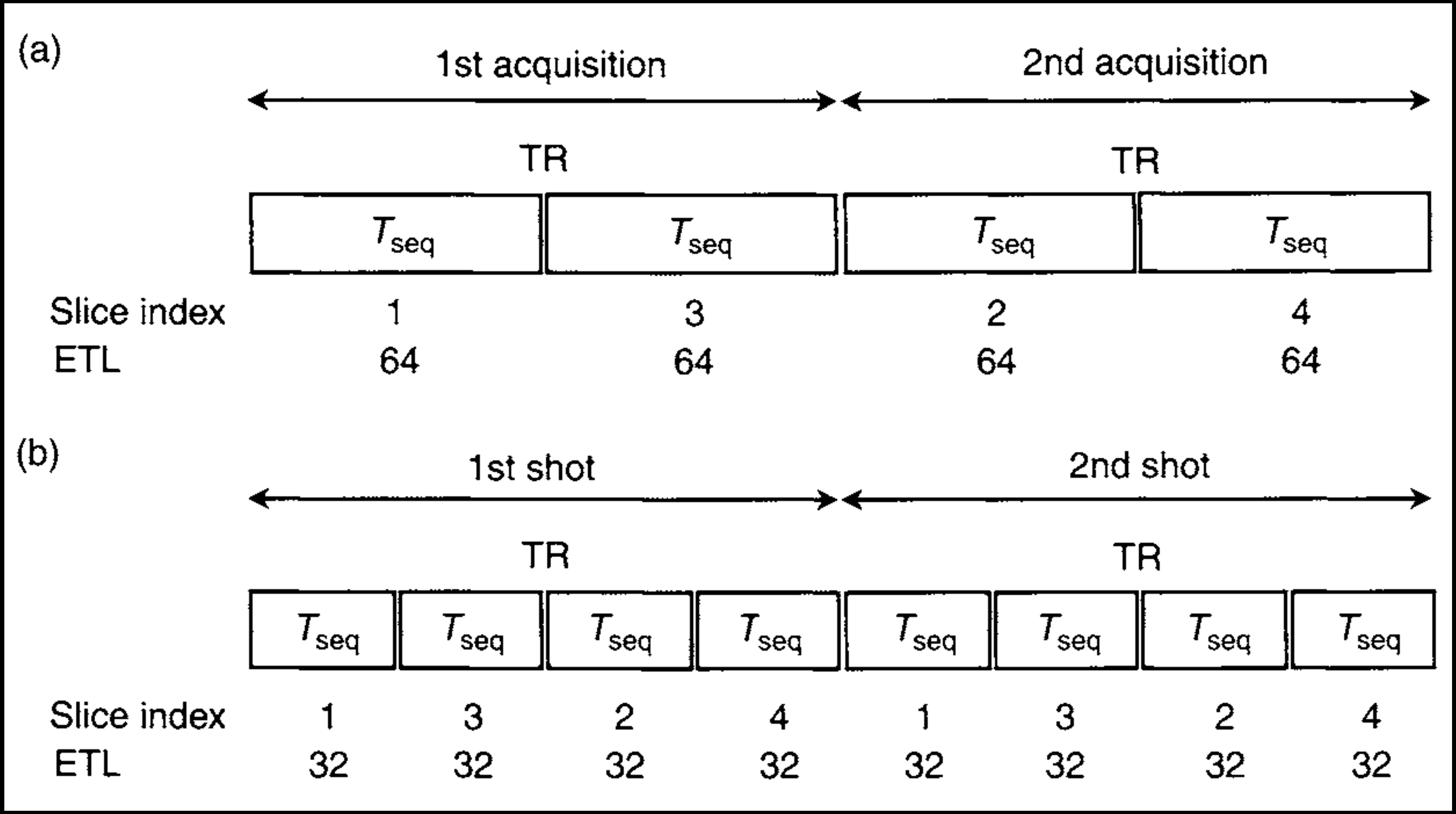
2D RARE Sequence



Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

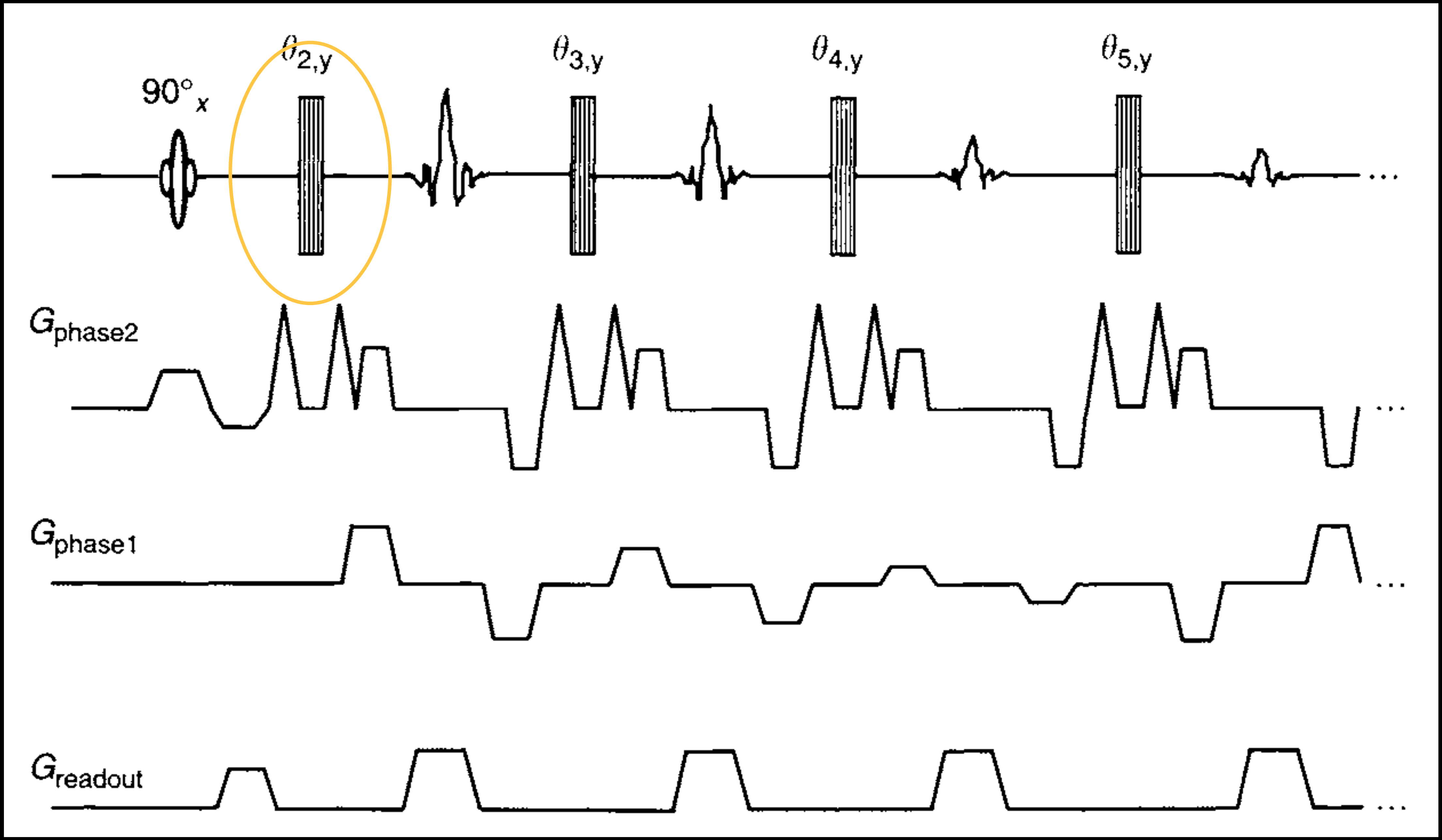
2D RARE Sequence

Interleaved 2D Multi-Slice Acquisition



Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

3D RARE Sequence



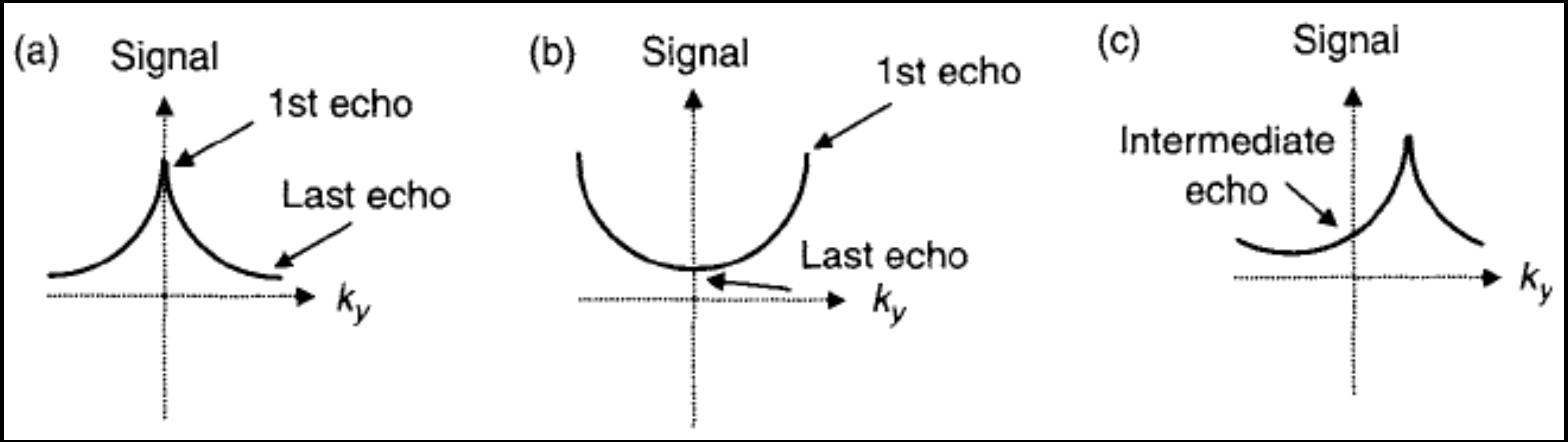
Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

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
  - $N_{pe} = 256*256$; $ETL = 32$; $N_{shot} = 2048$
  - TR = 1000 ms: $T_{TSE} = 34$ min

TSE Image Contrast

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



Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

TSE Image Contrast

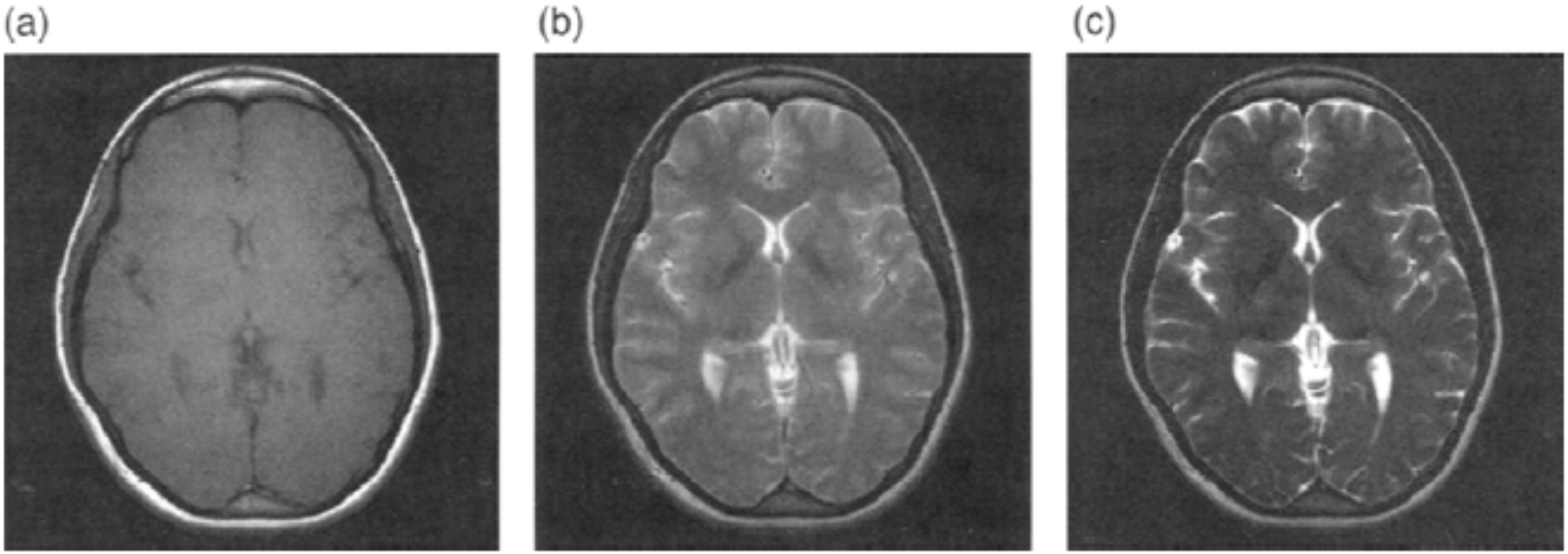


FIGURE 16.48 By using different echoes to sample the k-space center, considerably different image contrast can be obtained from a RARE sequence. (a) T_1-weighted image with TE = 11 ms, TR = 480 ms, and $N_{etl} = 8$. (b) Moderately T_2-weighted image with TE = 77 ms, TR = 4000 ms, and $N_{etl} = 16$.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

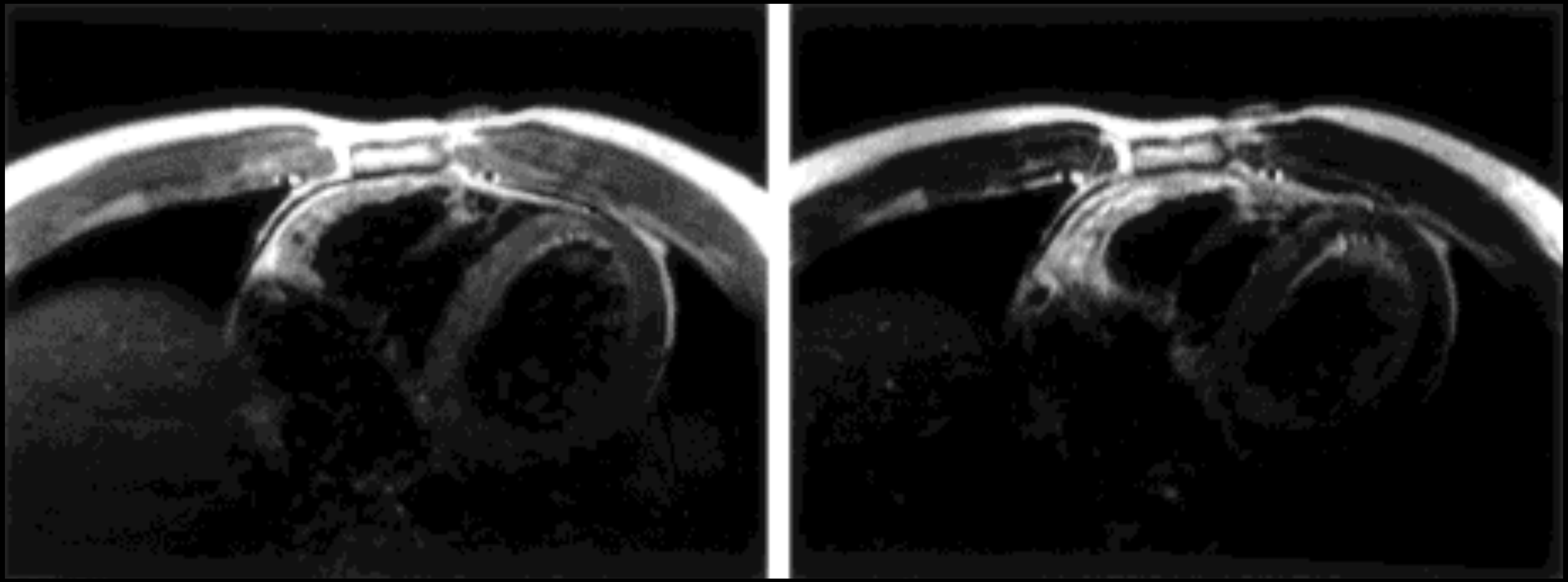
Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

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

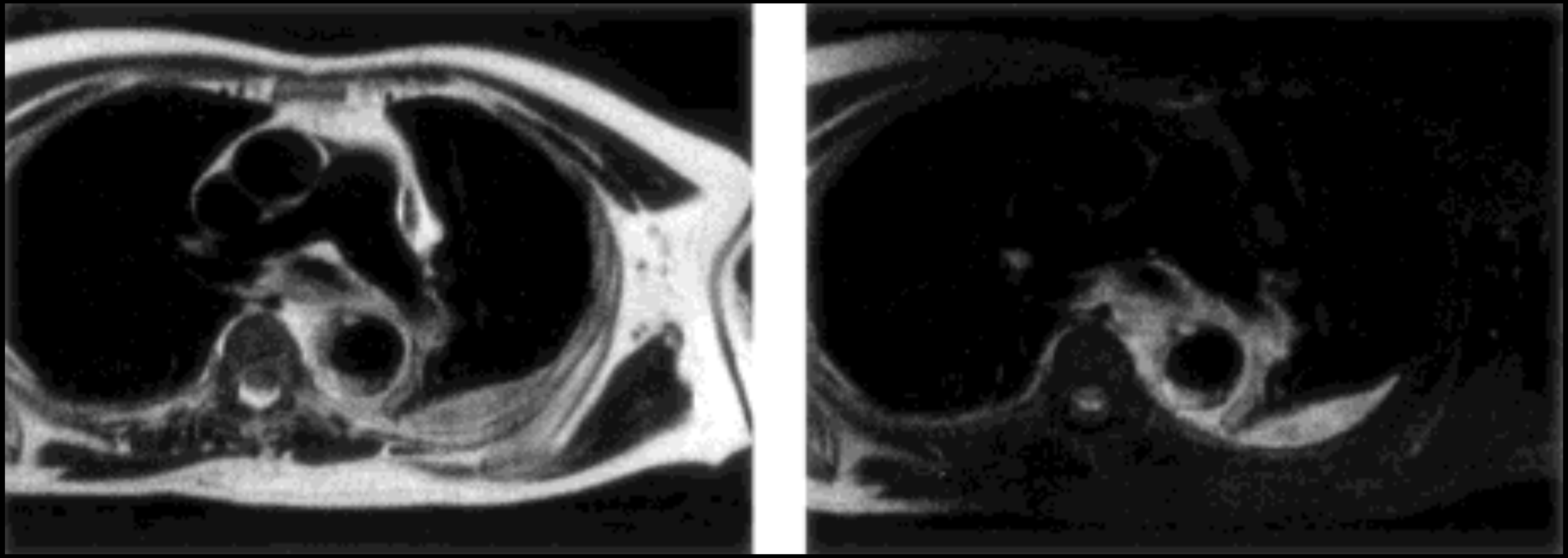
Dark Blood from Spin Echo



[1]Pettigrew RI et al., JMRI 1999

TSE Image Contrast

Dark Blood from Double Inversion-Recovery TSE



[1]Pettigrew RI et al., JMRI 1999

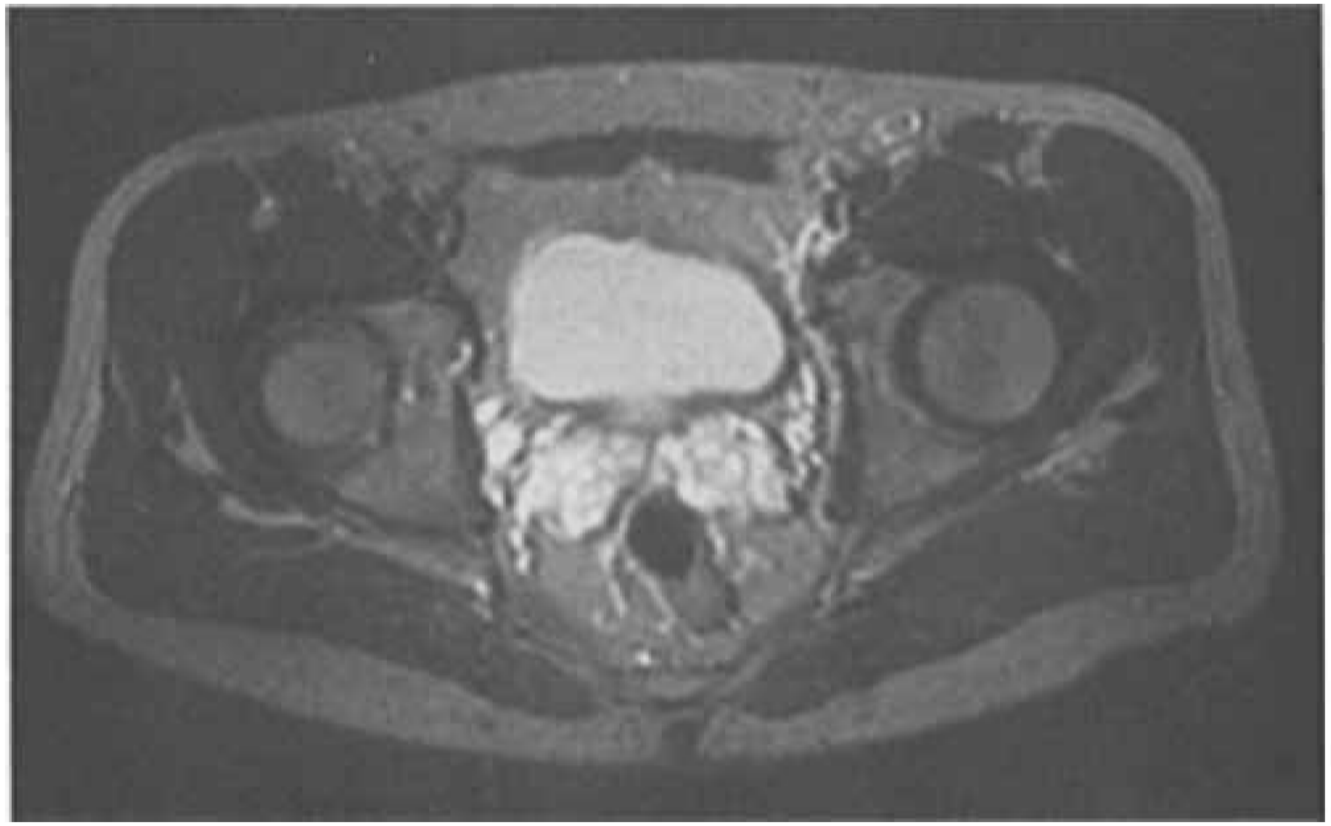
TSE Image Contrast

- Bright fat
  - J-coupling of protons in lipids (CH_3-CH_2-); f_{CS} ~ 25 Hz, f_J ~ 7 Hz @ 1.5 T
  - $S = S_0 * \exp(-t/T_2) * \cos(n_{ech}\, \pi\, f_J\, ESP)$
  - Shortening of apparent T_2 (in SE)

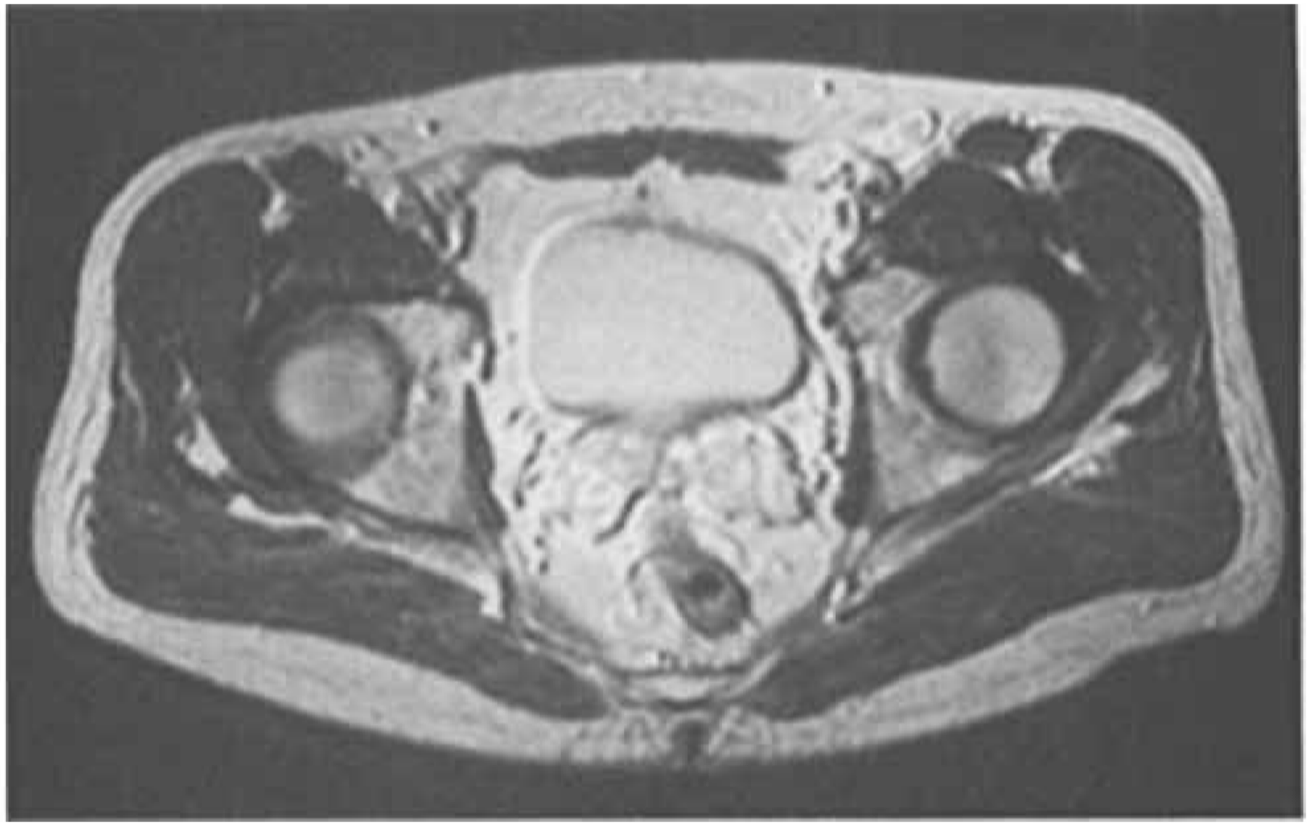
  - J-coupling negligible when $ESP \leq 1/[2\ \mathrm{sqrt}(f_{CS}^2 + f_J^2)]$ ~ 20 ms @ 1.5 T
  - In TSE, short ESP avoids attenuation by J-coupling, thus brighter fat signal

TSE Image Contrast

Spin Echo



Turbo Spin Echo



Bright Fat

[1]Henkelman R et al., JMRI 1992

TSE Image Contrast

- Magnetization transfer
  - MT effect

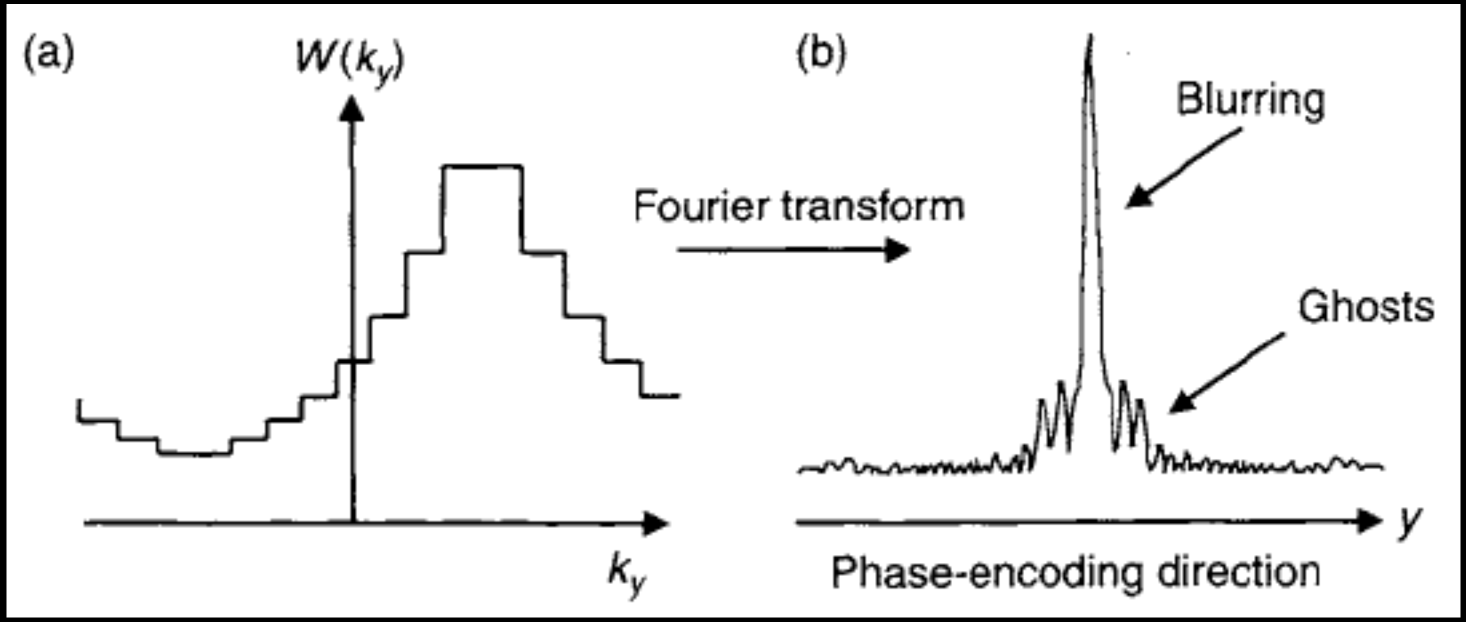
  - multiple refocusing pulses in TSE
  - off-resonance excitation in other slices; can lead to MT-induced signal loss

TSE Advantages

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

TSE Challenges

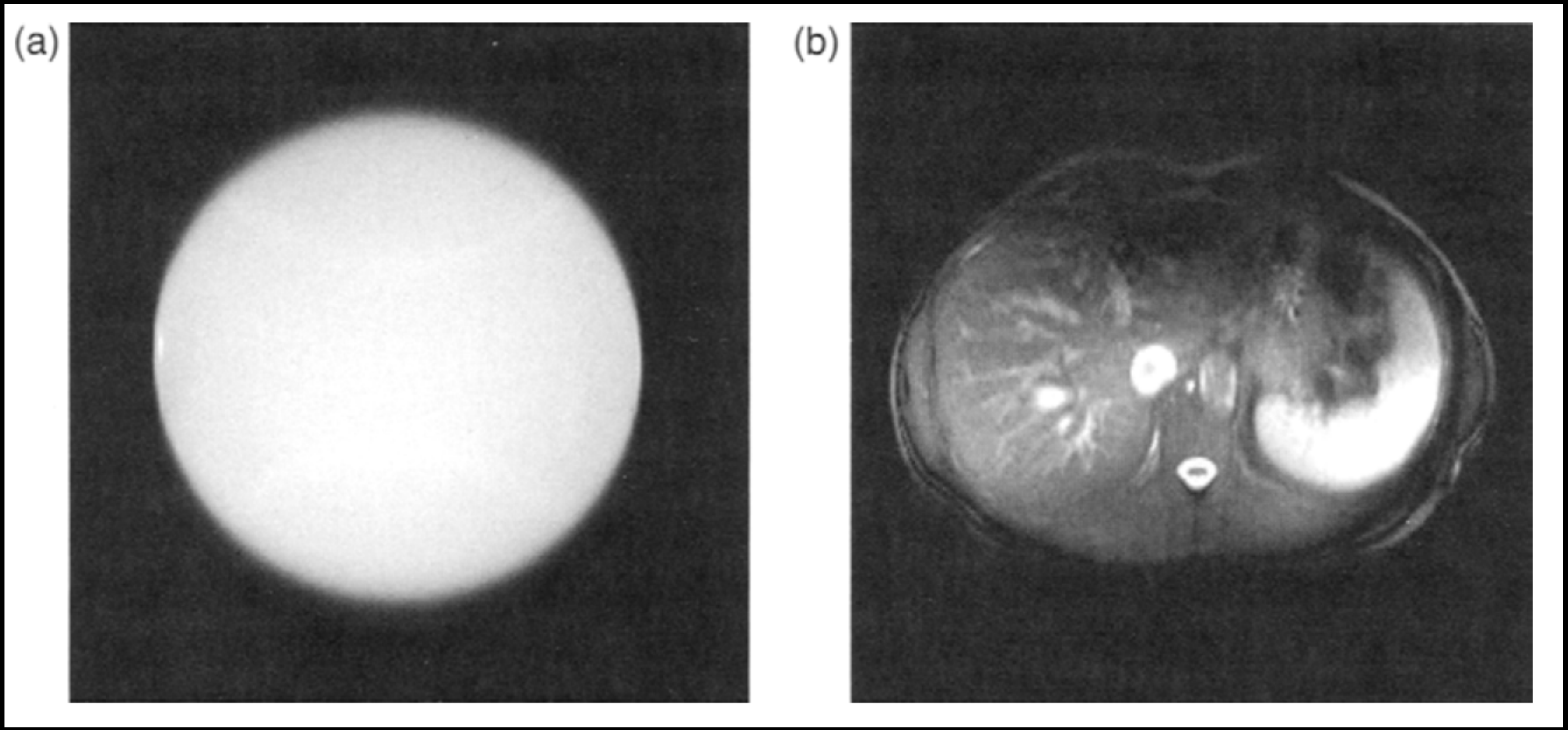
- Blurring; edge enhancement; ghosting;
  - attention to PE ordering and ETL



Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

TSE Challenges

T_2 blurring (PE) in single-shot TSE



Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4

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., $\theta = 130^o$ instead of 180^o

Extensions and Variations

- Partial echo
- Multi-echo
- Mag-prep

Extensions and Variations

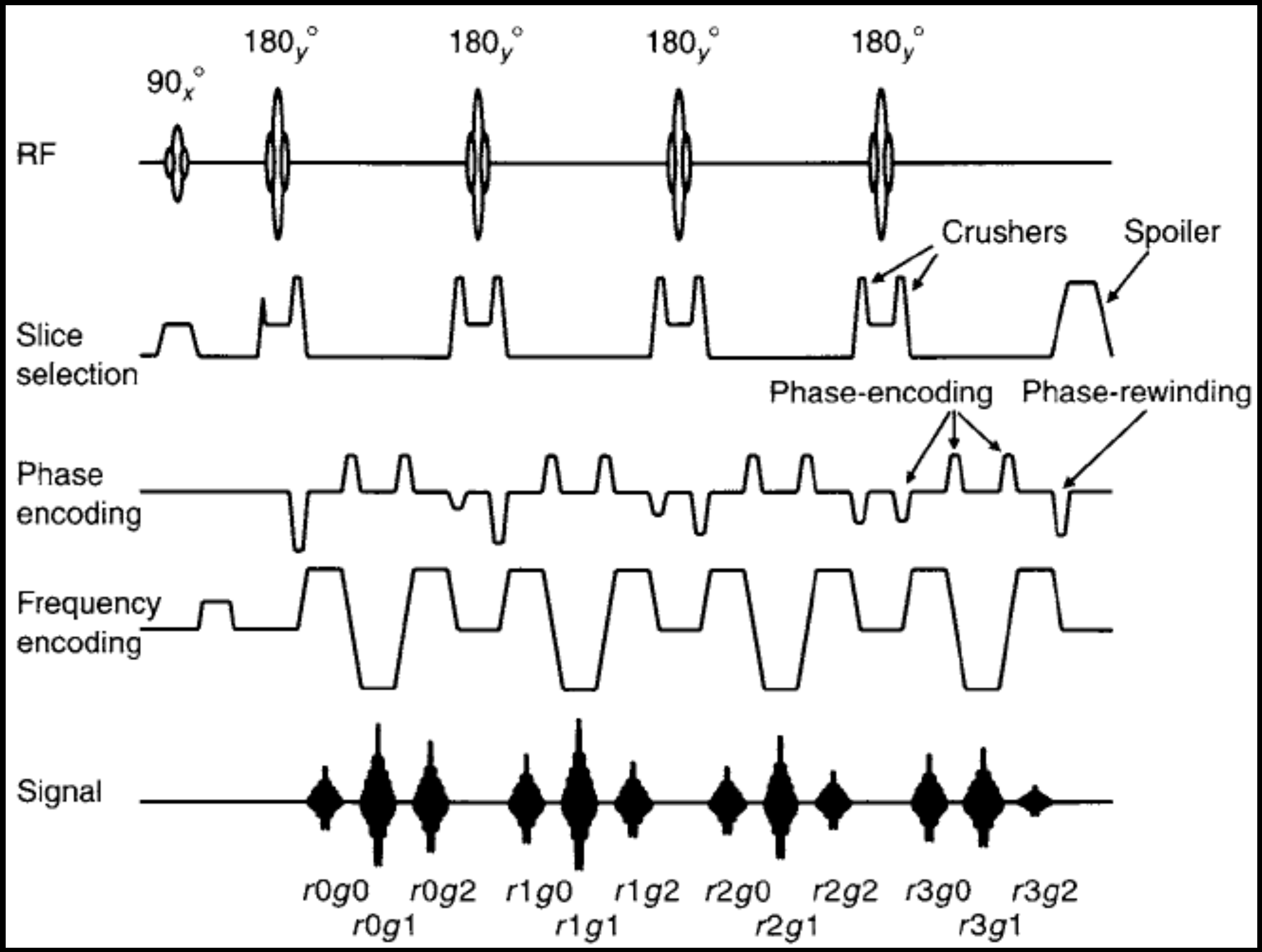
- Partial Fourier
  - Sample ~half of k-space data, reconstruct assuming Hermitian symmetry (real-valued MR images)
  - reduce refocusing pulses, reduce SAR
  - better control of TE_{eff}
- Parallel imaging
  - Undersample k-space data, reconstruct using information from multiple coils
  - reduce refocusing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



[1] *Oshio 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:

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

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

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

Nishimura, Principles of MRI, Ch. 2
Hargreaves, MATLAB Bloch Simulator

Bloch Simulation

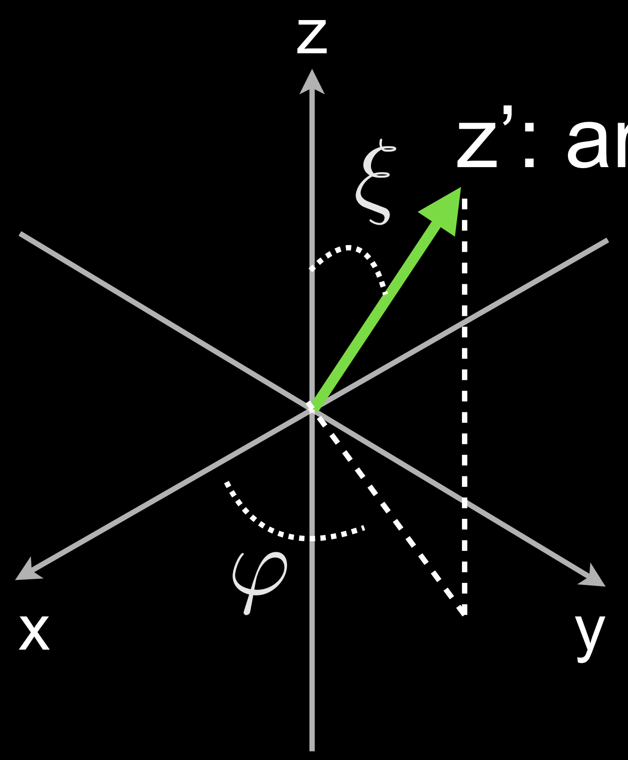
Free precession:

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

Nishimura, Principles of MRI, Ch. 2

Bloch Simulation

General Rotation:



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

Nishimura, Principles of MRI, Ch. 2

Bloch Simulation

Relaxation + Free Precession:

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

```
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;
```

Hargreaves, MATLAB Bloch Simulator

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

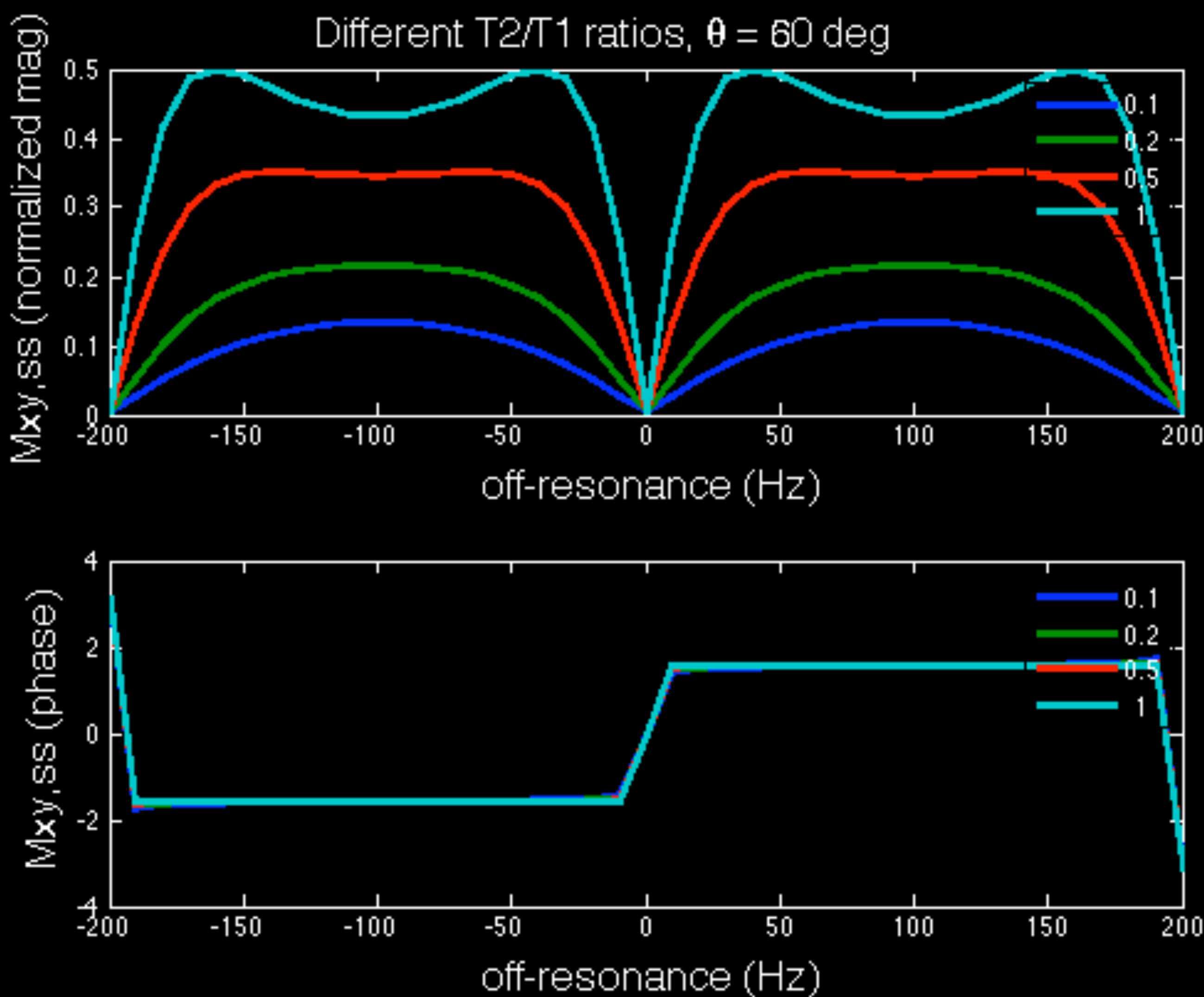
Bloch Simulation

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

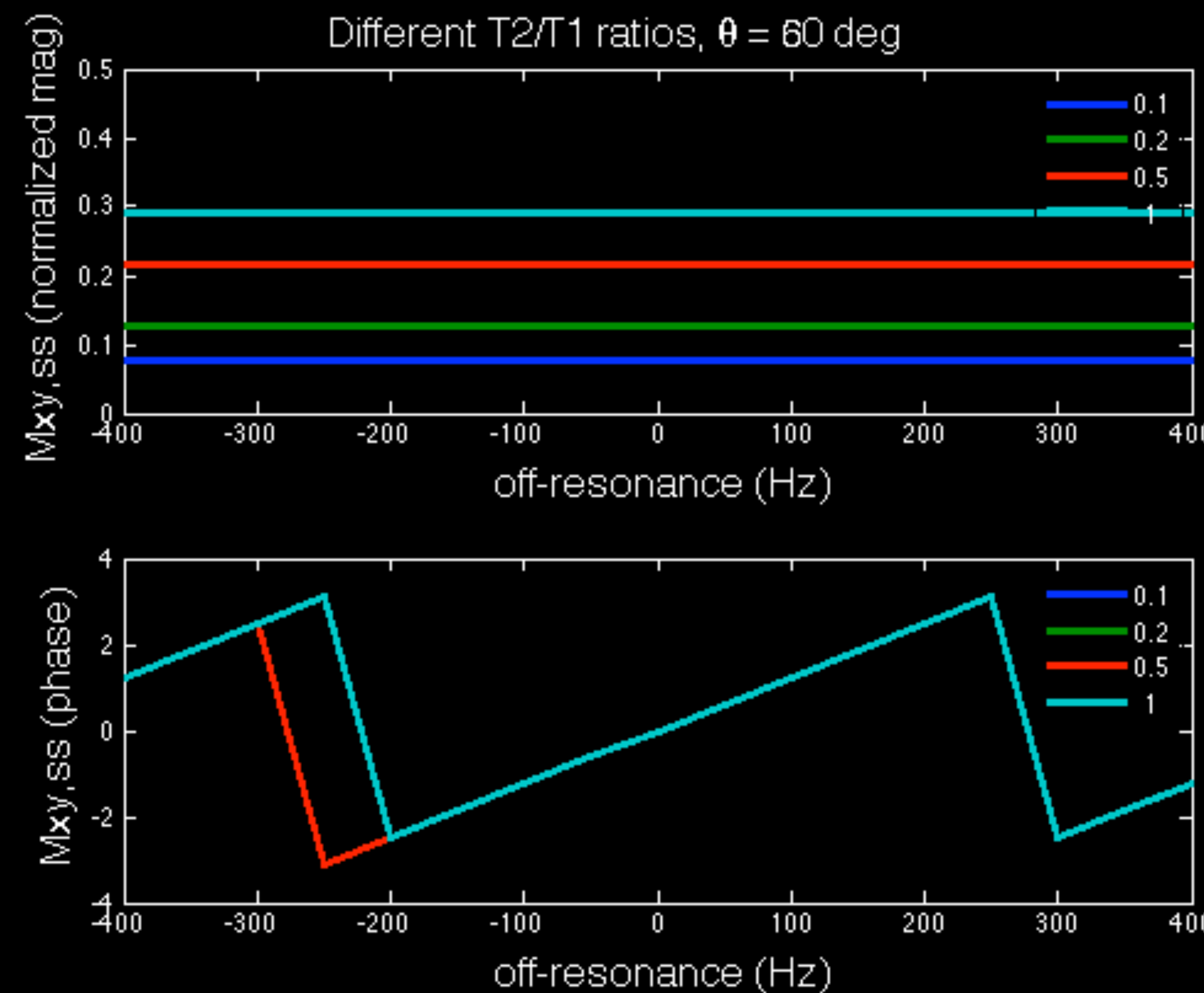
Gradient-spoiled GRE

SS signal as a function of off-resonance:

bSSFP



GRE (SSFP-FID)

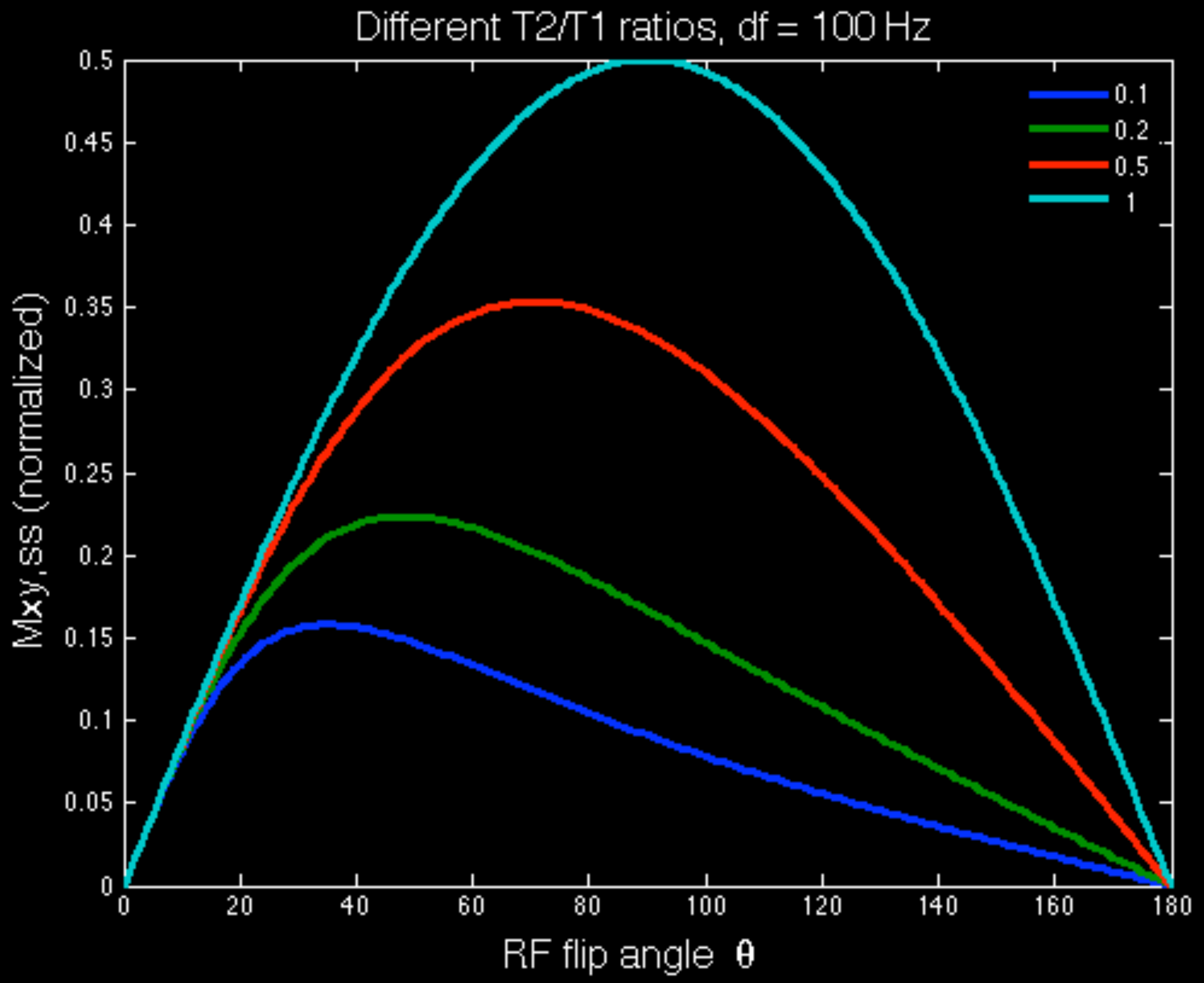


T_1 = 1000 ms, T_2 = 100,200,500,1000 ms

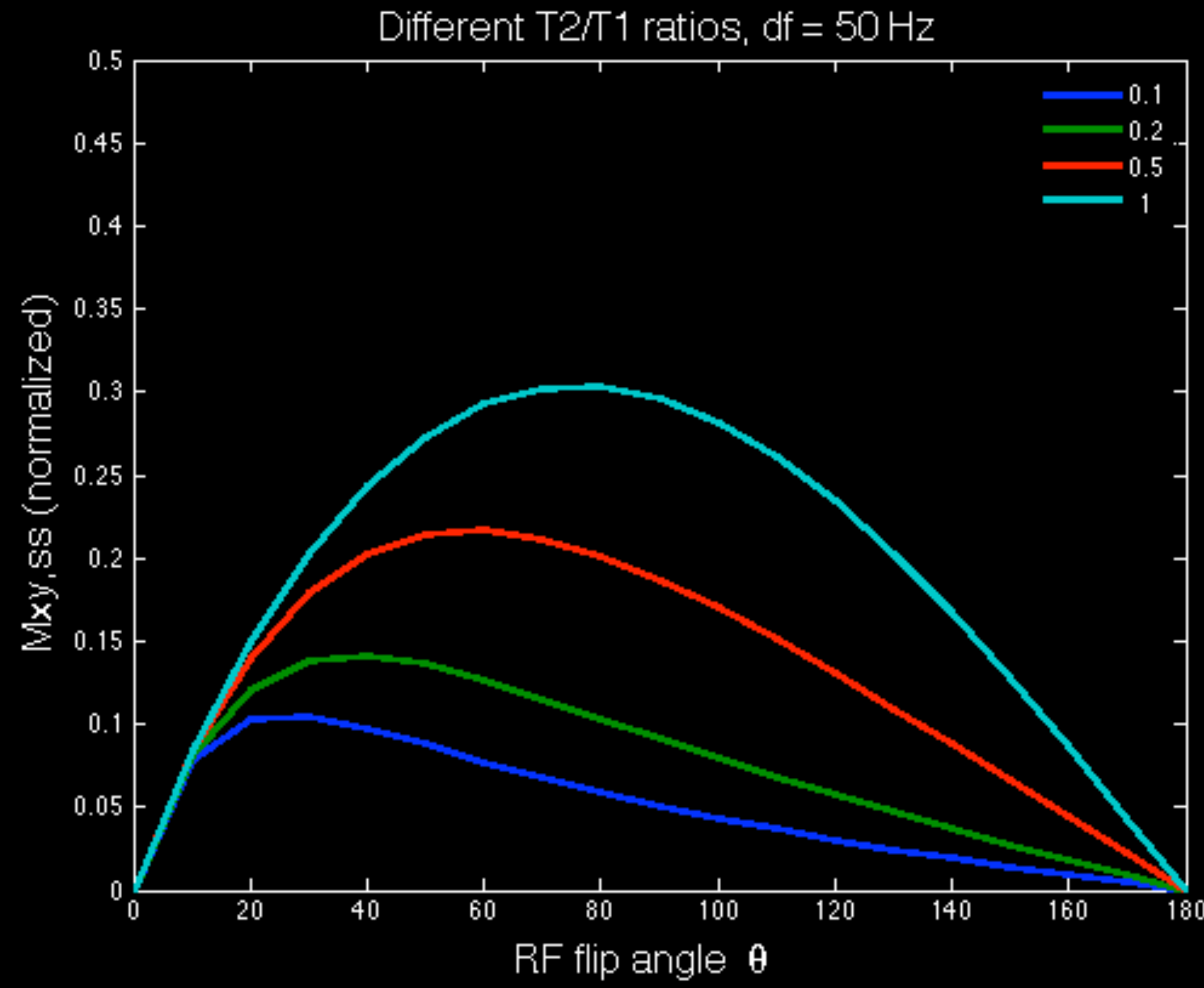
Gradient-spoiled GRE

SS signal as a function of flip angle:

bSSFP



GRE (SSFP-FID)



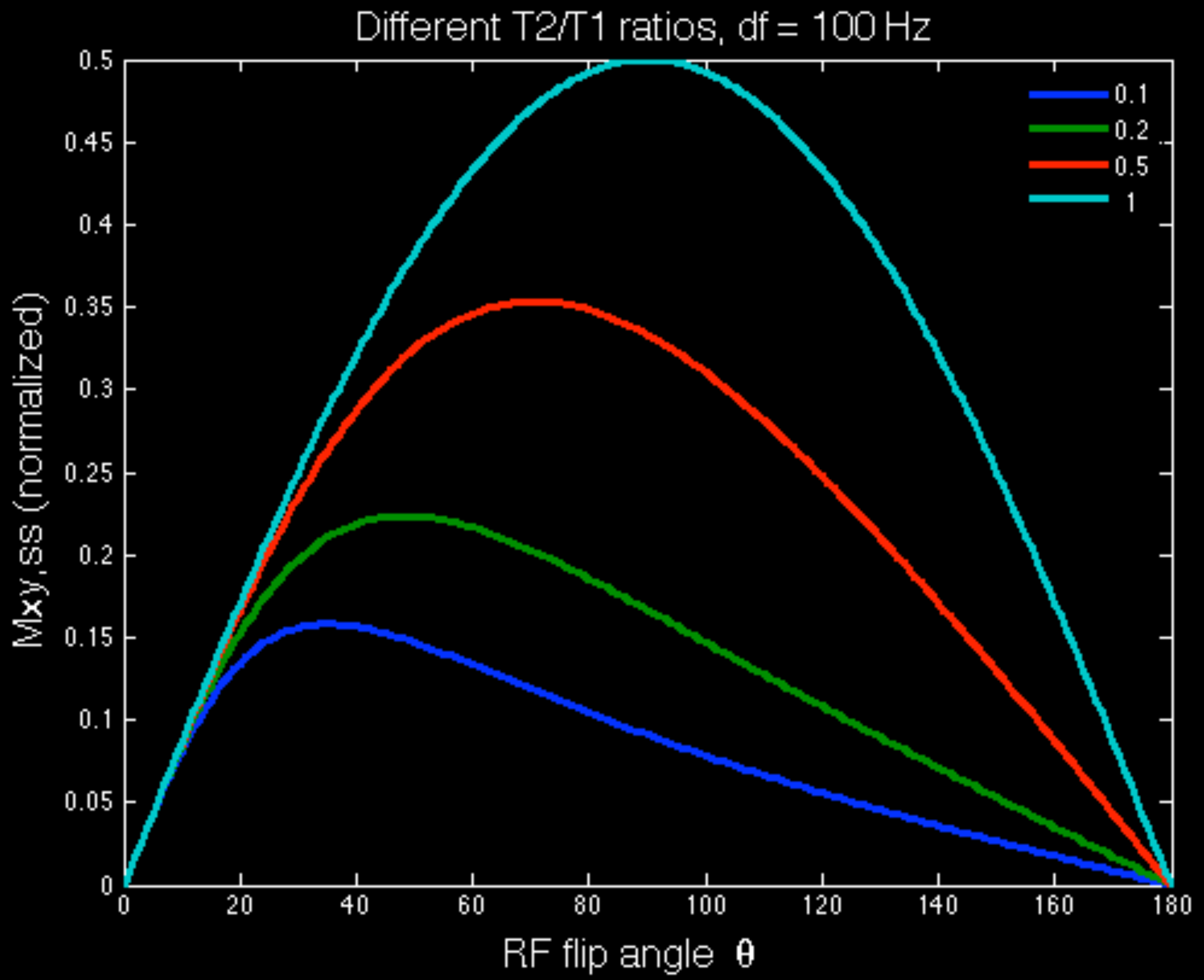
T_1 = 1000 ms, T_2 = 100,200,500,1000 ms

Gradient-spoiled GRE

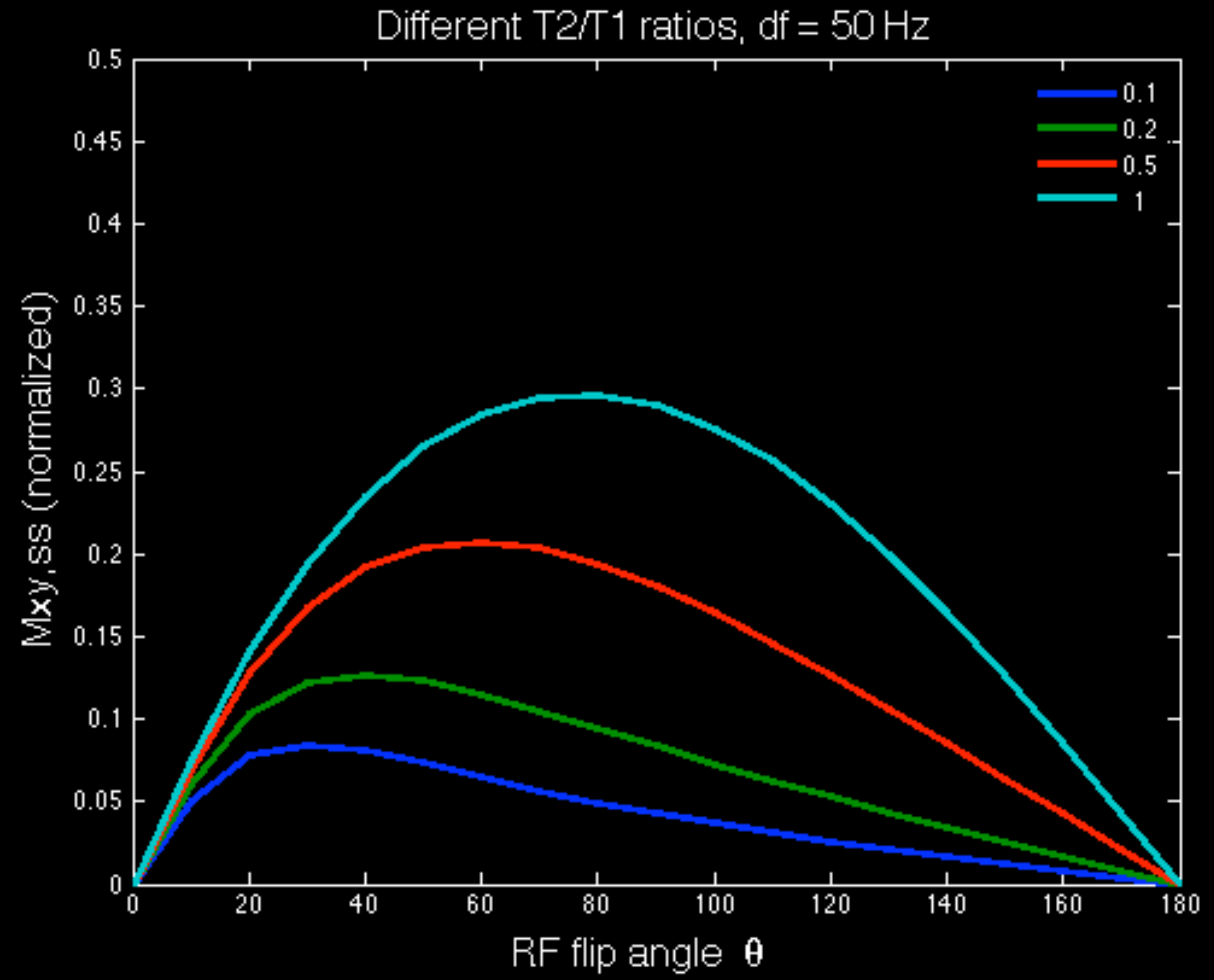
(*reversed*)

SS signal as a function of flip angle:

bSSFP



GRE (SSFP-Echo)



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

Bloch Simulation

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

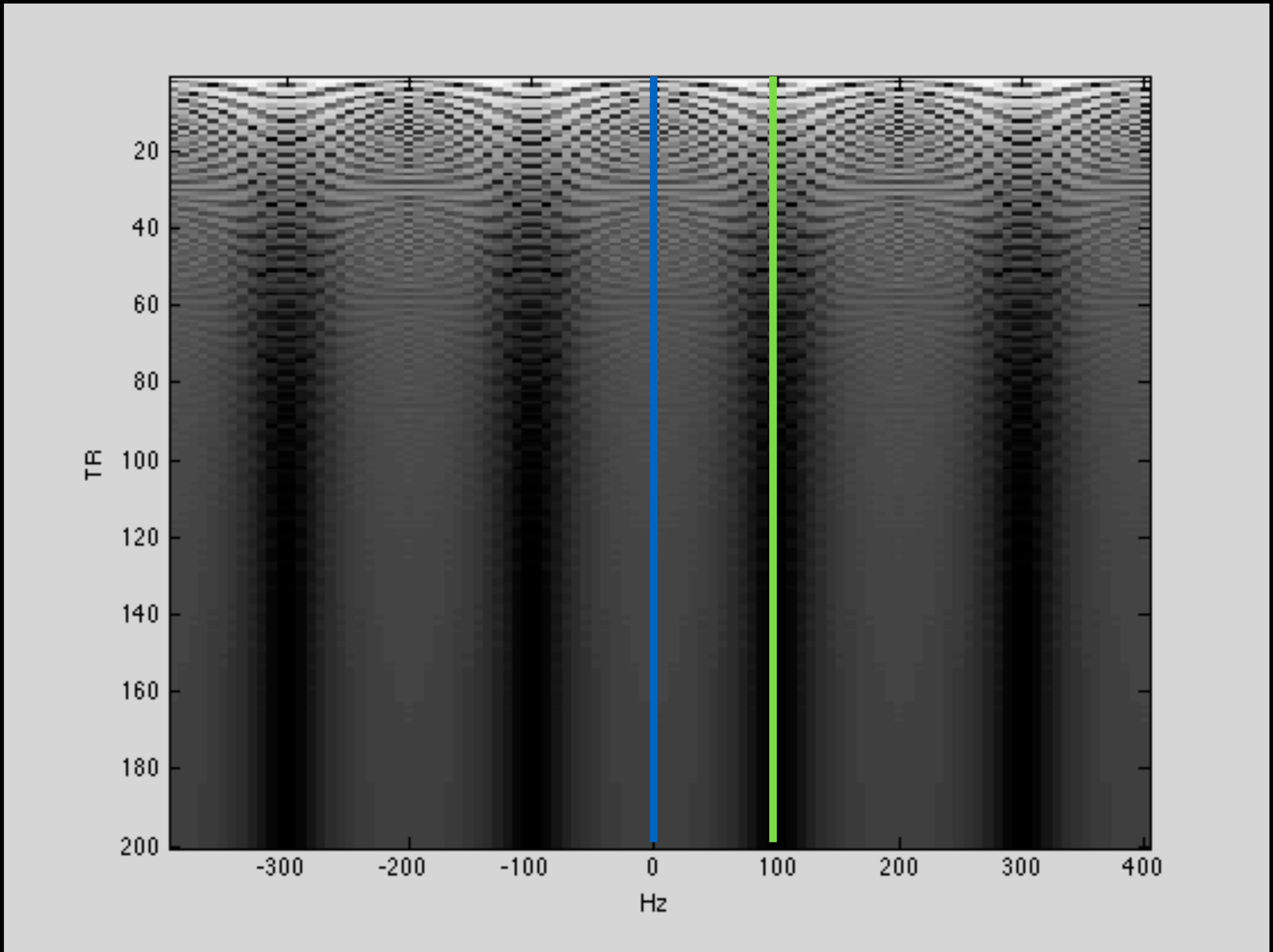
Balanced SSFP

Transition to steady state:

TR = 5 ms

$\Delta\phi = \pi$

$\theta = 60^{o}$



T_1 = 600 ms, T_2 = 100 ms

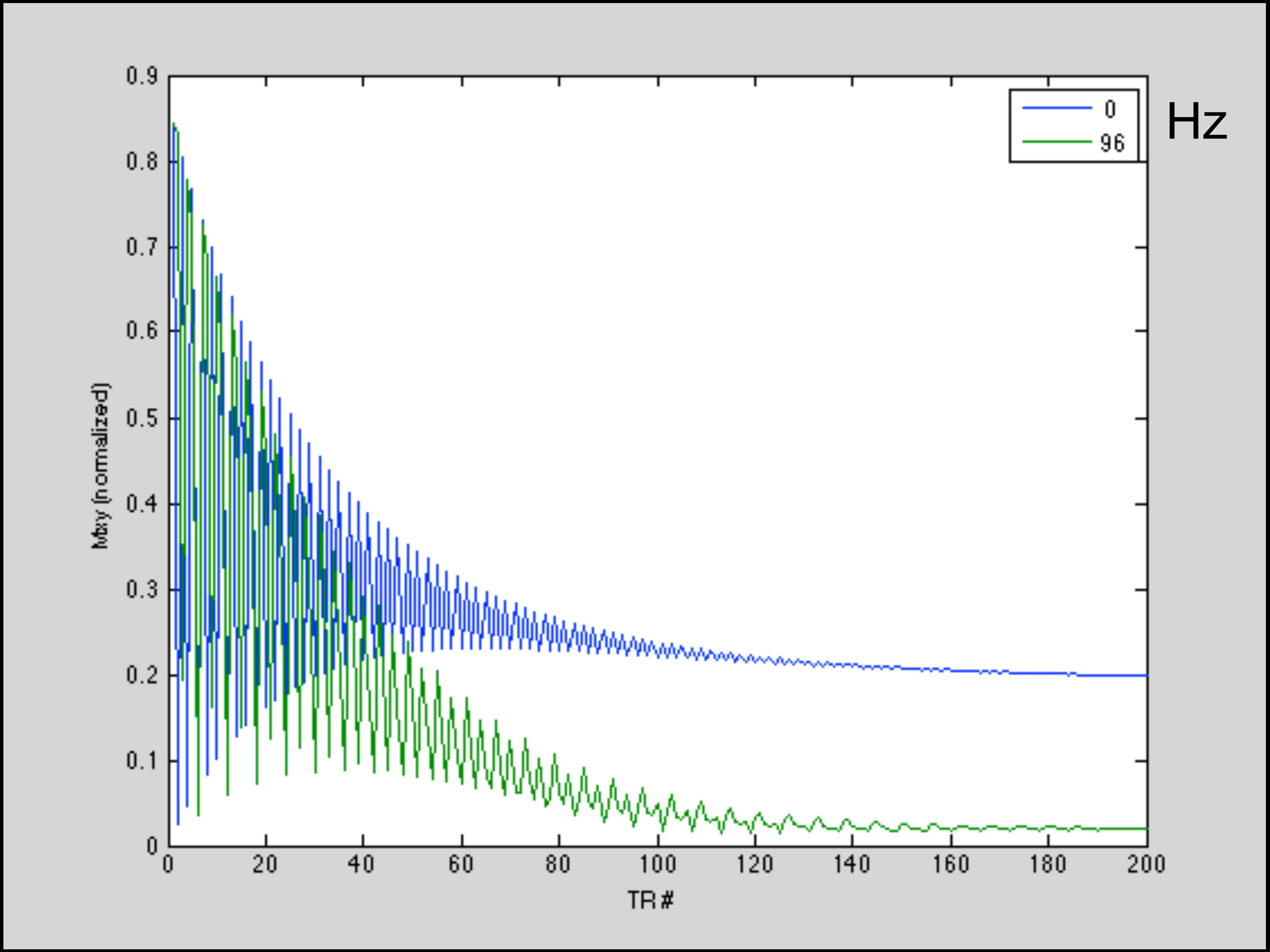
Balanced SSFP

Transition to steady state:

TR = 5 ms

$\Delta\phi = \pi$

$\theta = 60^o$



T_1 = 600 ms, T_2 = 100 ms

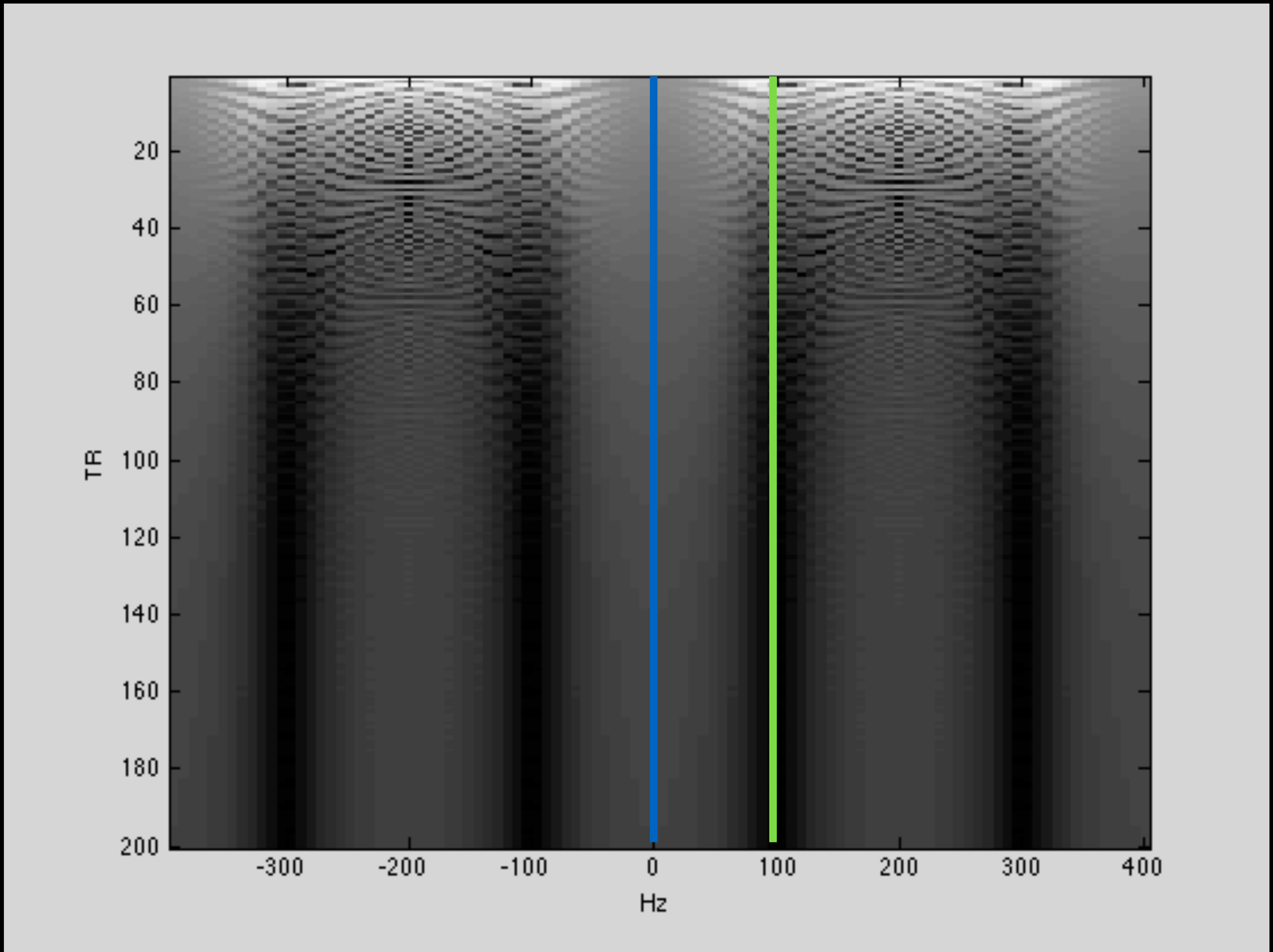
Balanced SSFP

Transition to steady state (θ/2 -TR/2 prep):

TR = 5 ms

$\Delta\phi = \pi$

$\theta = 60^o$



T_1 = 600 ms, T_2 = 100 ms

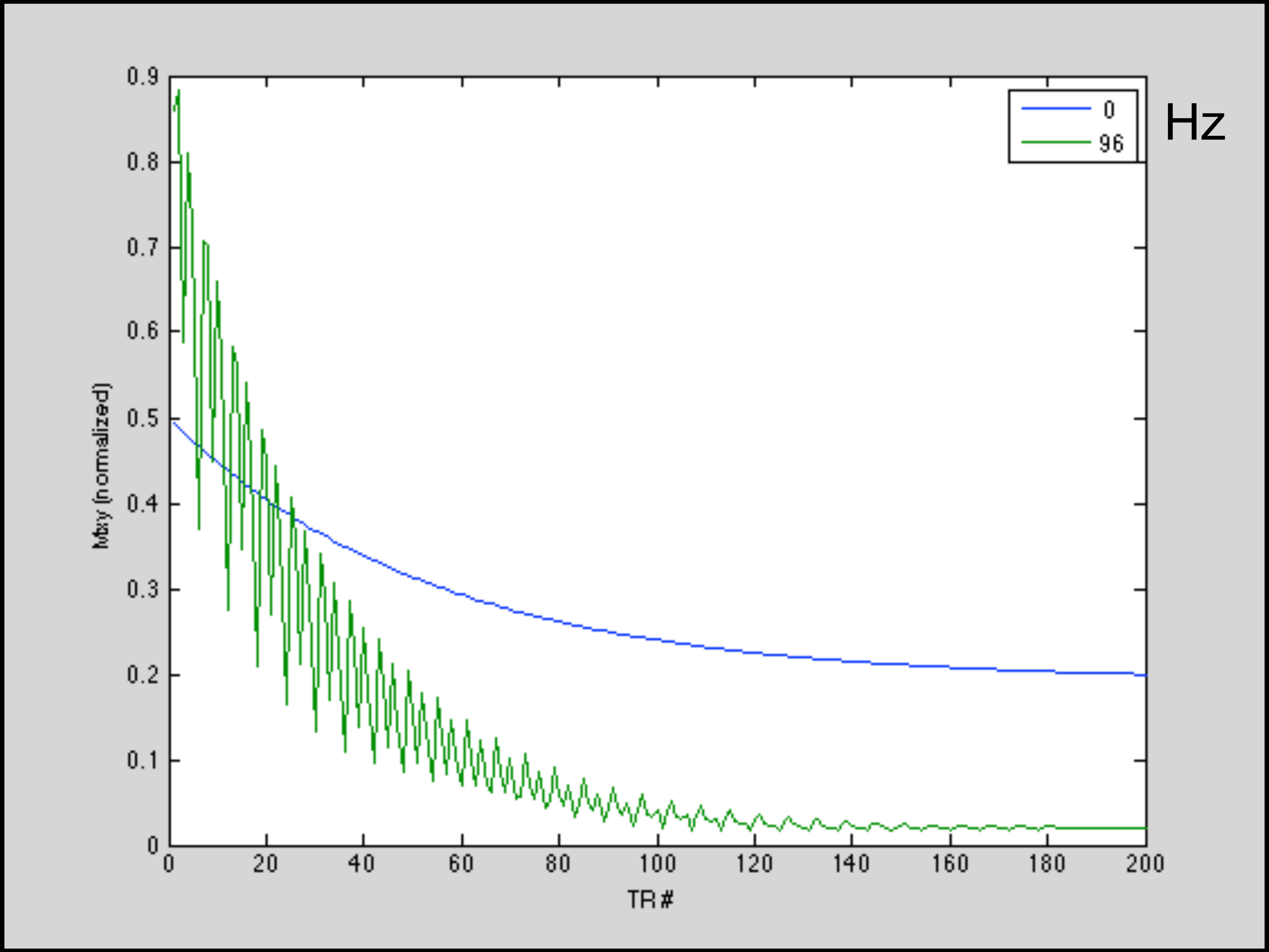
Balanced SSFP

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

TR = 5 ms

$\Delta\phi = \pi$

$\theta = 60^o$



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*:
    $\theta = 60^o$, N = 5
    ramp up pulses $\theta_{lin} = [12^o, 24^o, 36^o, 48^o, 60^o]$

Homework 1

- Pulse Sequence Simulations
  - 1. Bloch: Steady state comparison, bSSFP transient state and catalyzation
  - 2. EPG: SSFP-FID, RF-spoiled GRE
- Due 5 pm, 4/28 Fri 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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  - Brian Hargreaves
- Next lecture
  - EPG and MATLAB demo

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