Spin-Echo Sequences

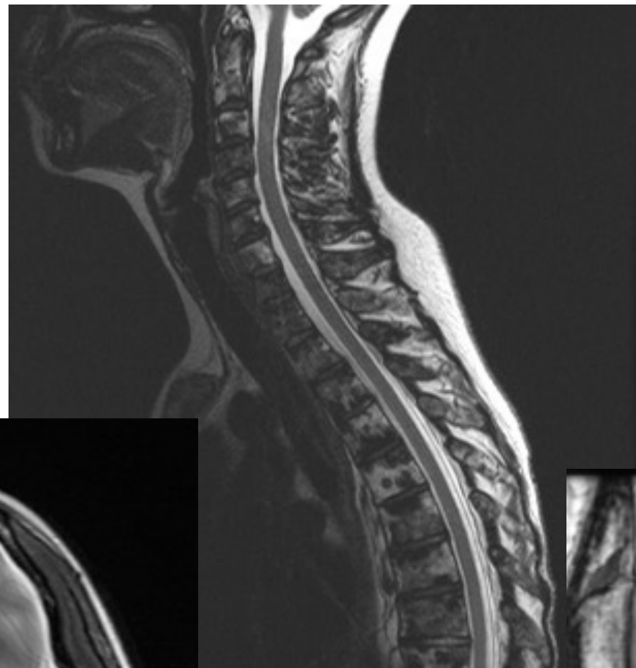
- Spin Echo Review
- Echo Trains
  - Applications: RARE, Single-shot, 3D
  - Signal and SAR considerations
- Hyperechoes

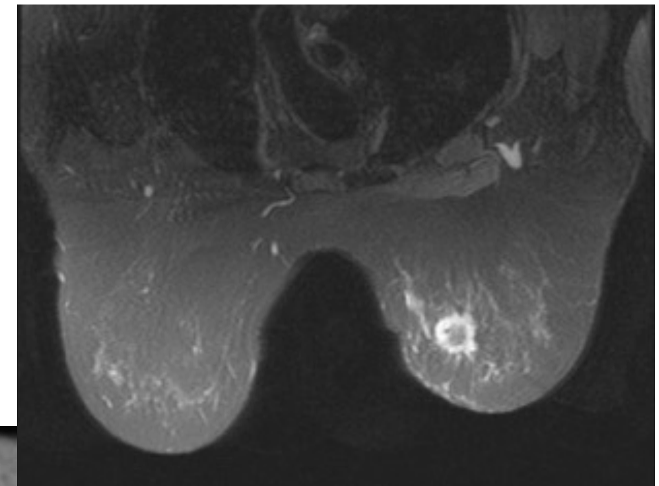
Spin Echo Review

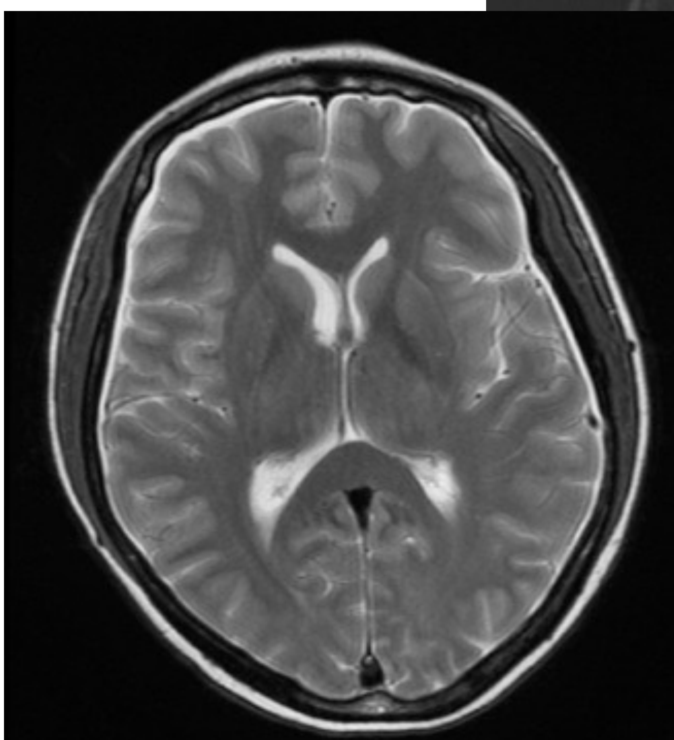
- Static Dephasing: $1/T_2^* = 1/T2 + 1/T2'$
- Spin echo "rephases" magnetization
- Spin echoes can be repeated

Motivation: Spin Echo Imaging

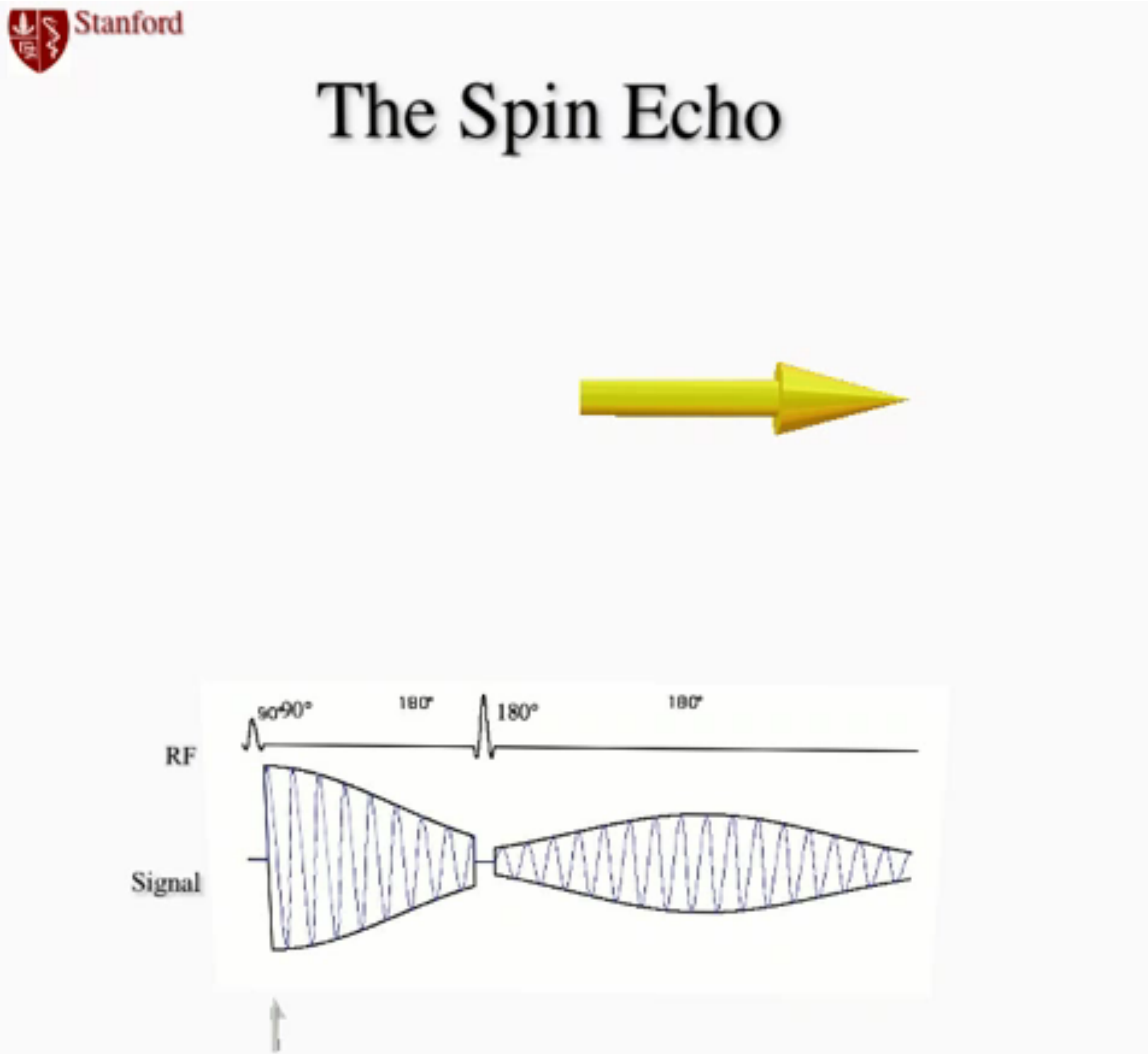
- Probably over 75% of clinical MRI



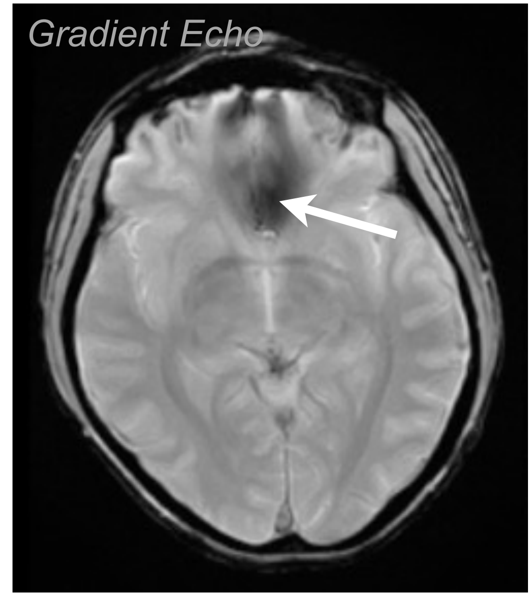


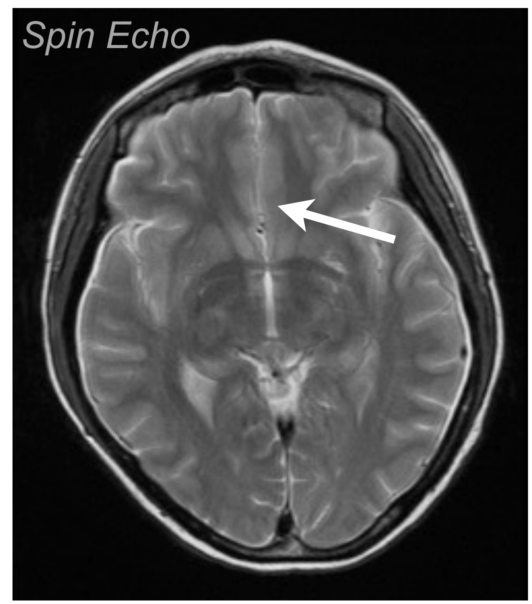


Spin Echo: T_2 and T_2* Decay



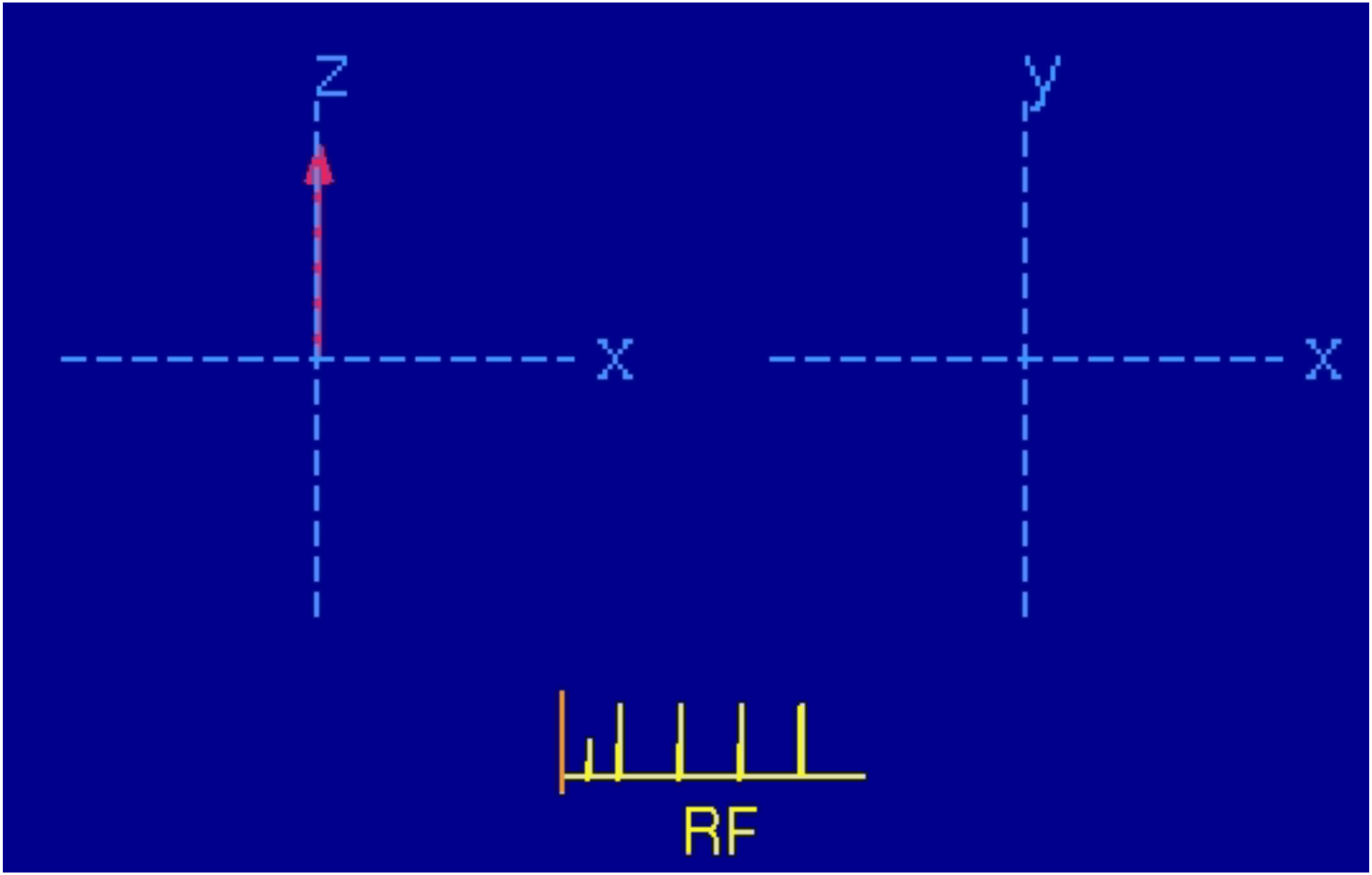
Courtesy of Kim Butts Pauly





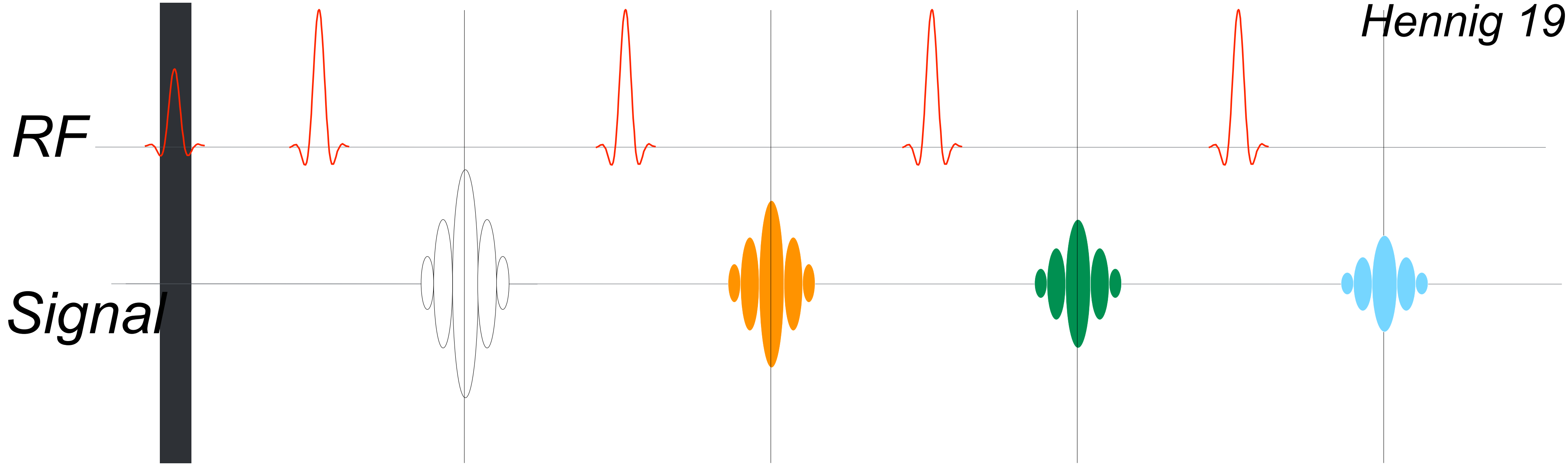
Multi-Echo Trains: RARE, TSE, FSE

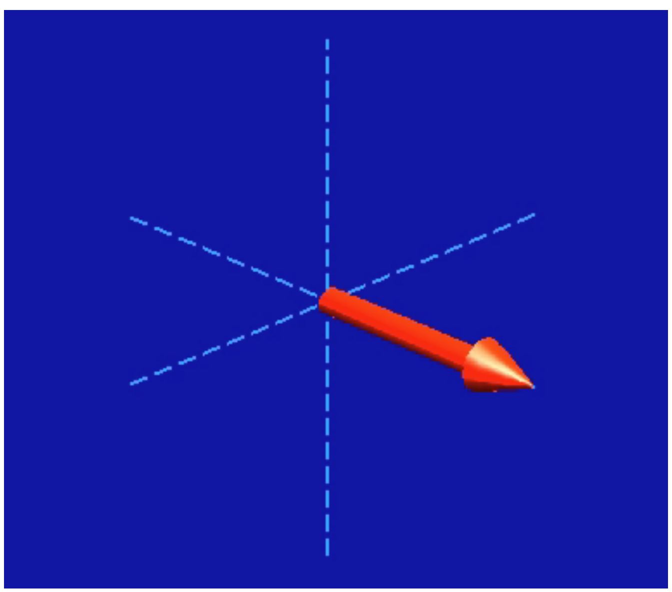
Hennig 1986

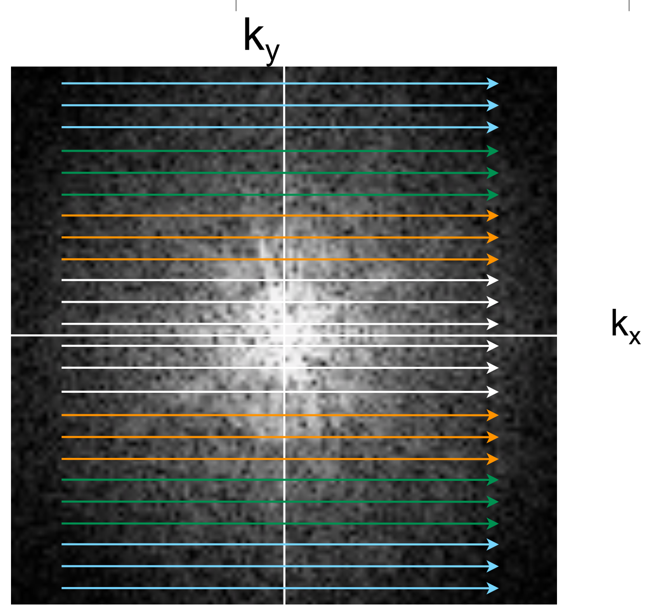


Spin-Echo-Train Imaging

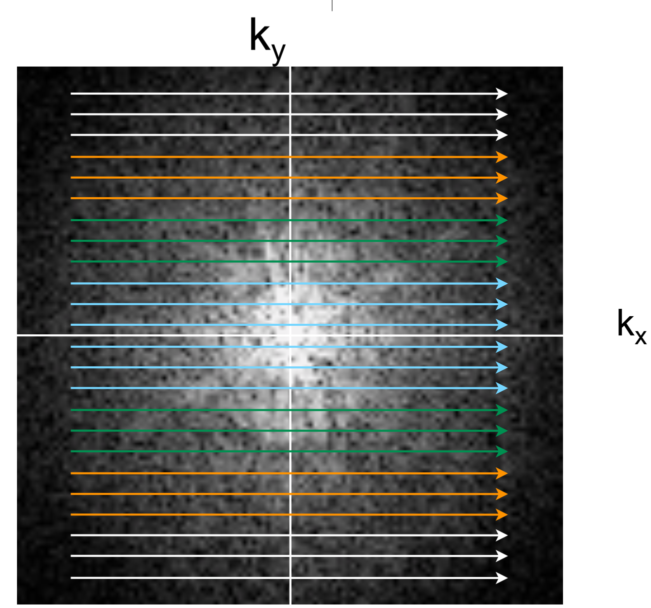
Hennig 1986







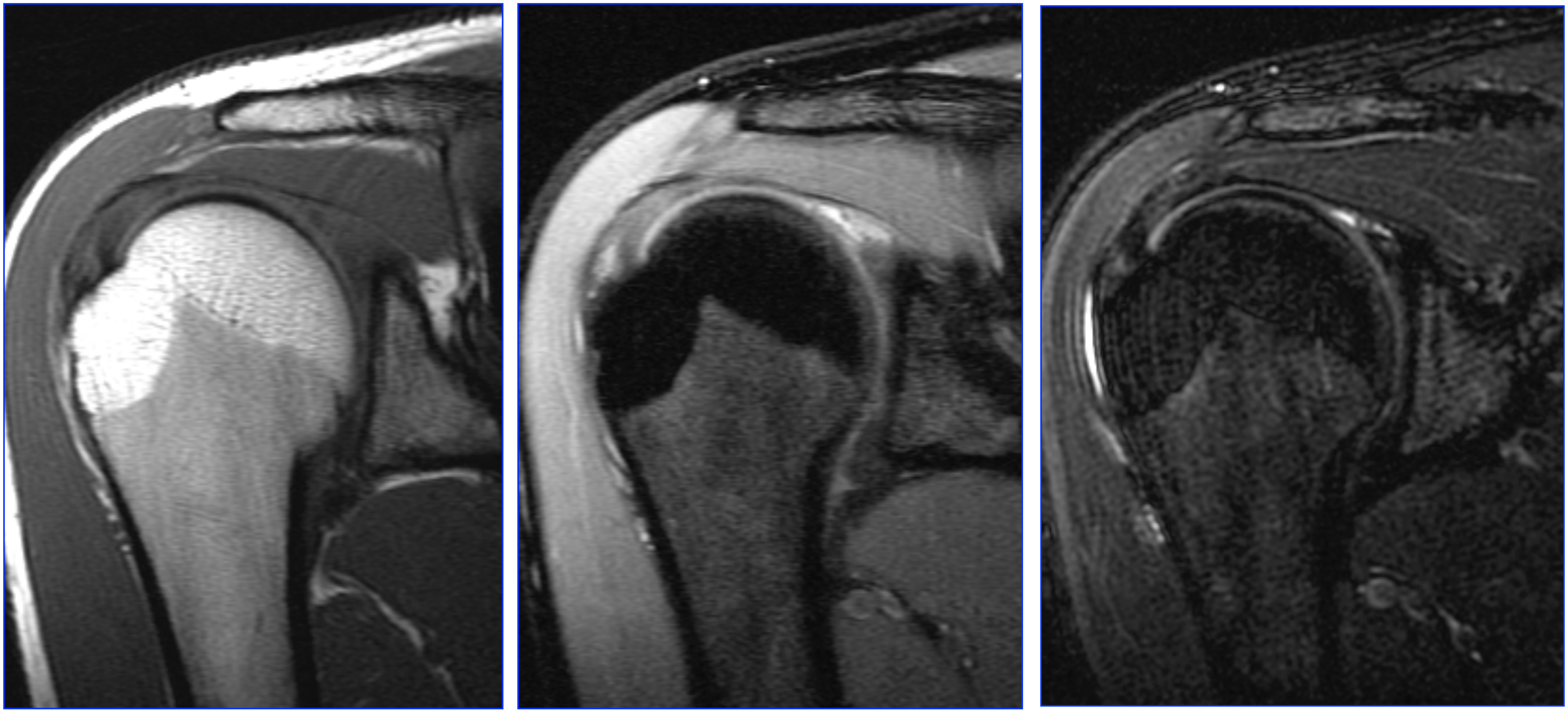
PD-weighted k-space



T_2-weighted k-space

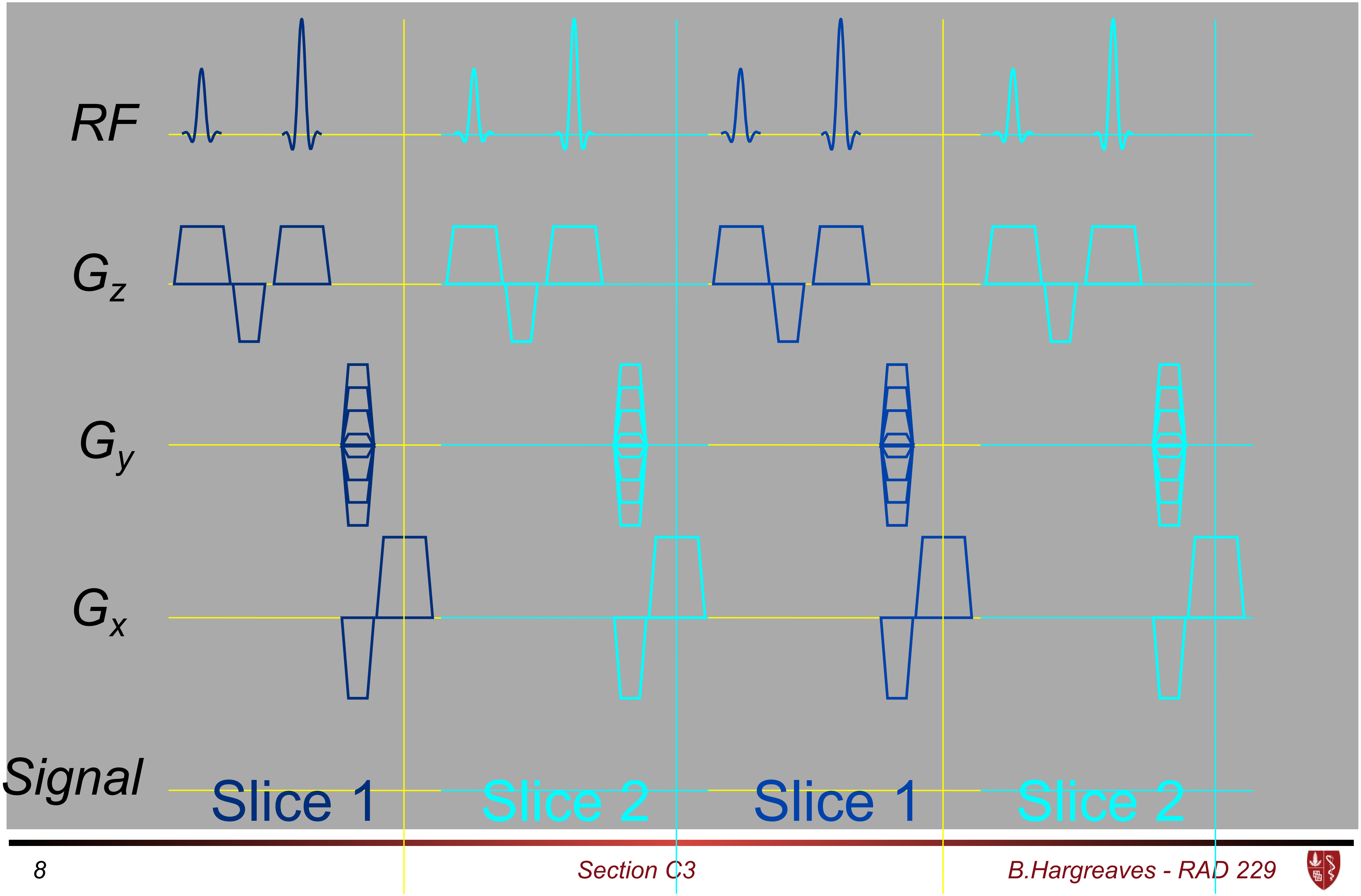
Spin-Echo Contrast Variations

T1-weighted | Proton Density | T2-weighted



(Coronal shoulder images showing rotator cuff tear)

Interleaved T_1-weighted Imaging

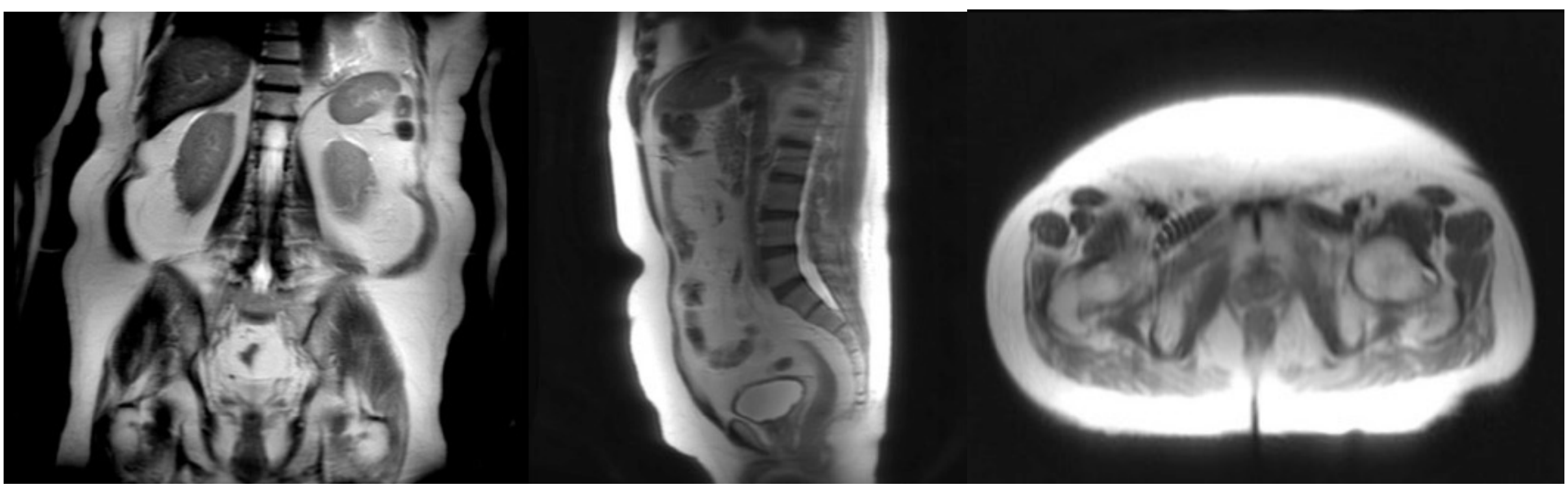


Single-Shot FSE (SSFSE, HASTE)

Entire image acquired in single echo train

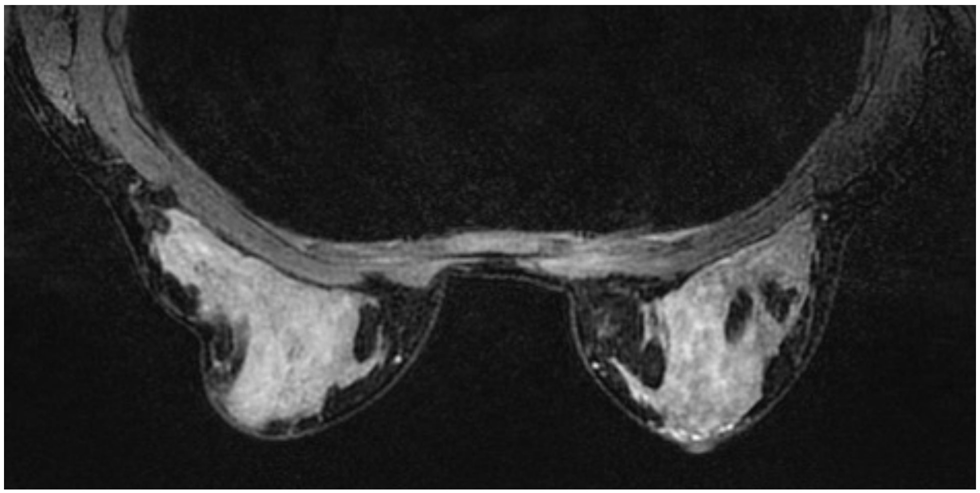
- Lower resolution
- Significant echo-train blurring
- Robust to motion

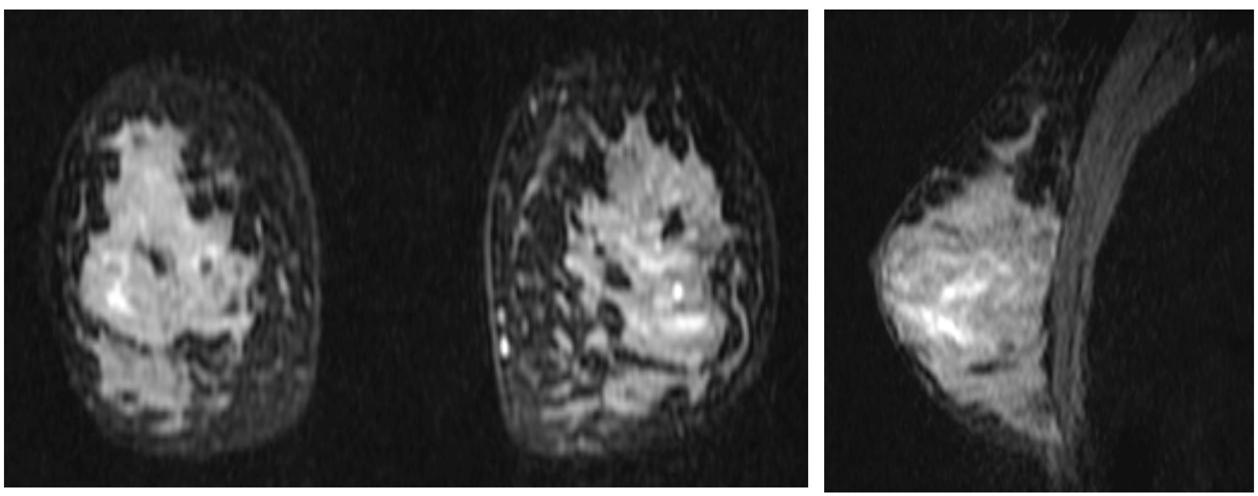
RF



3D Spin Echo Train Methods

- Originally quite long
- Extended echo-trains help
- Phase-encode orders vary k_y and k_z modulation
- No interleaving(!)





Courtesy Ananth Madhuranthakam

Spin Echo Variations - Summary

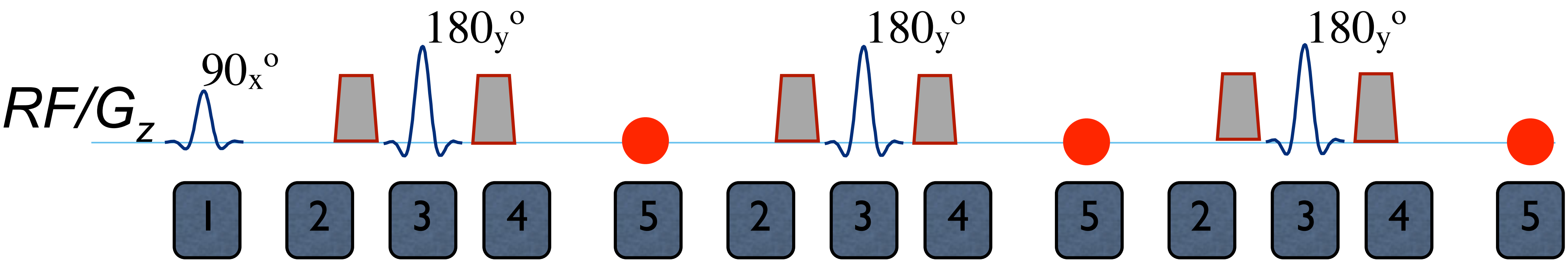
- 2D Interleaved:
  - Single-echo
  - Echo-train PD or T2 (FSE, RARE, TSE)
  - STIR, FLAIR, Fast-recovery options
- Single-shot (SSFSE, HASTE)
- 3D: (Cube, SPACE, VISTA)

Spin-Echo Signals

- Basics: T2 decay models, EPG
- Reduced refocusing angles
  - CPMG
  - Pseudo-steady-states
- Modulated refocusing angles

Spin-Echo Signals - Warmup!

Spin Echo Train Example



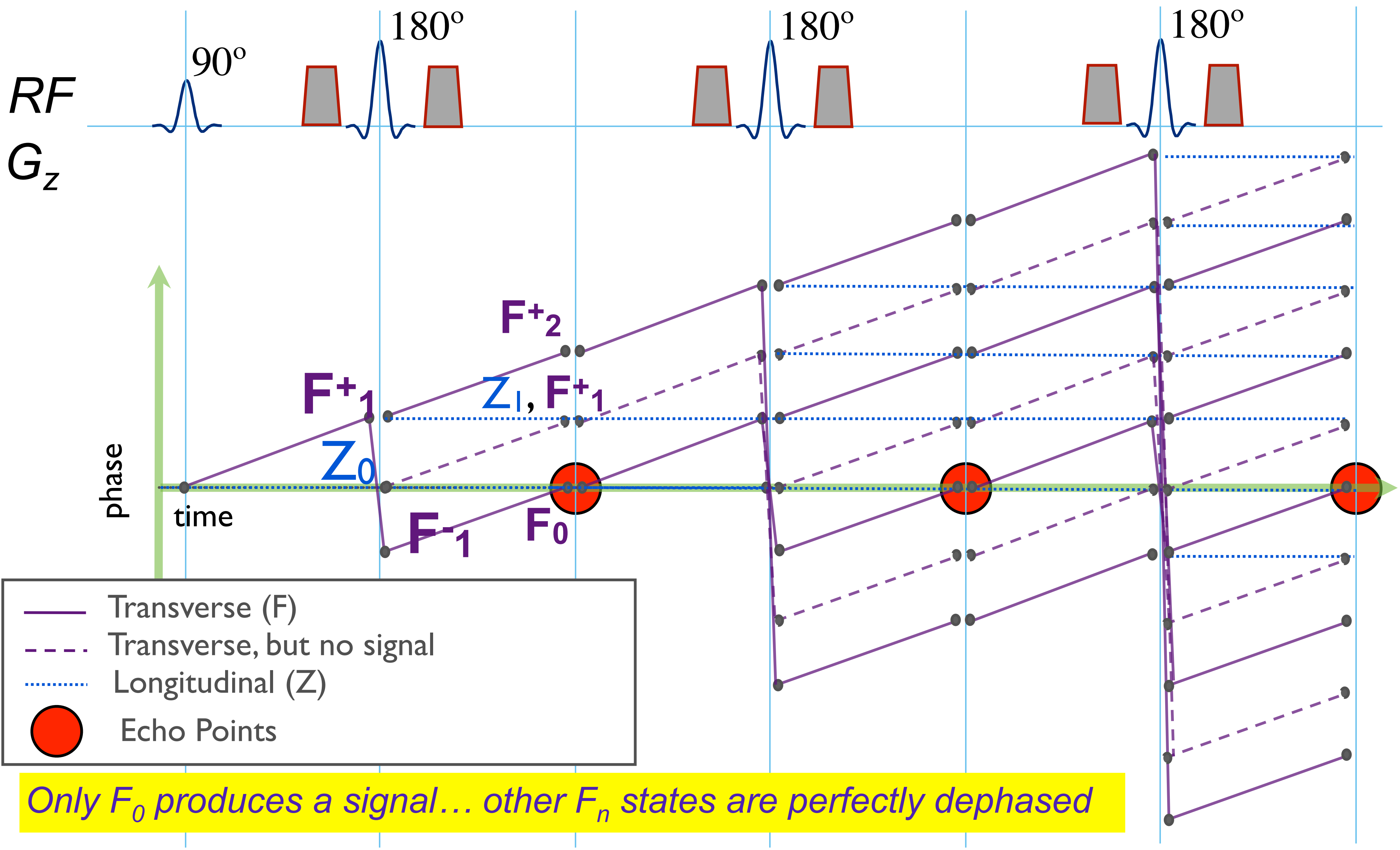
- Simulate
  1. 90^o excitation

  Repeat:

  2. Relaxation and crusher gradient
  3. Refocusing pulse
  4. Relaxation and crusher gradient
  5. Signal at spin echo
- *Vary refocusing angle and/or phase…*

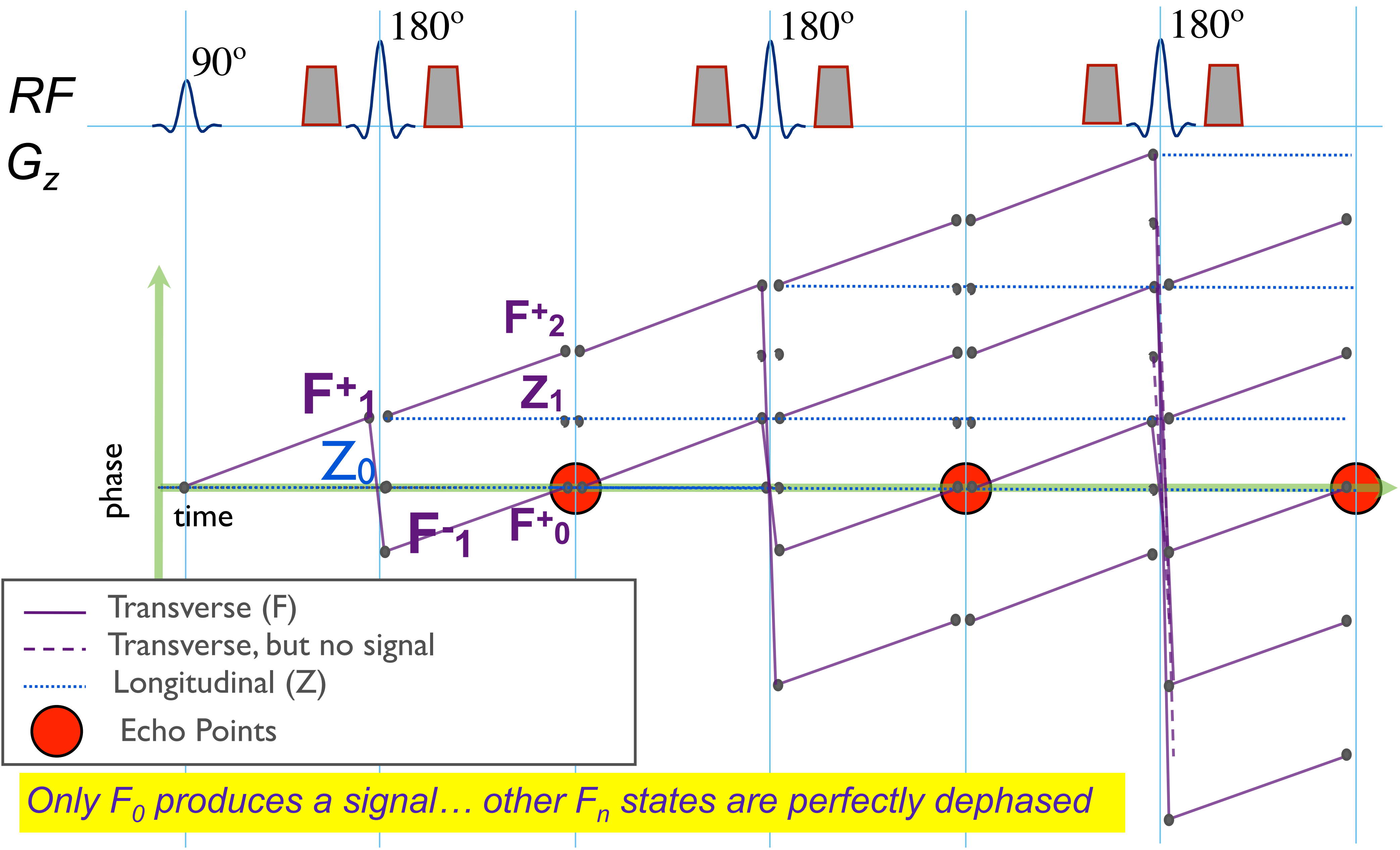
epg_cpmg.m

Review: Spin-Echo Coherence Pathways



Only F_0 produces a signal… other F_n states are perfectly dephased

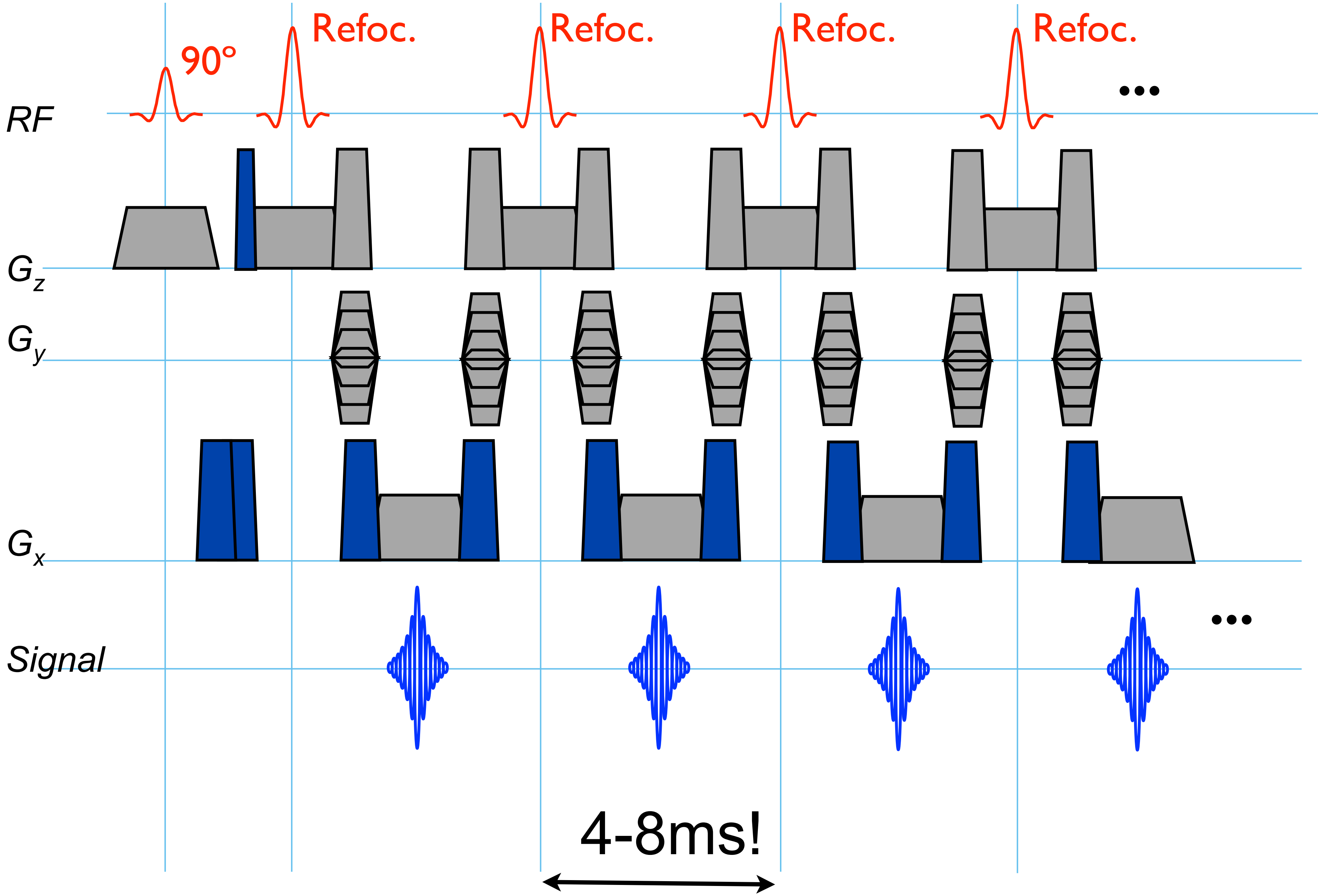
Effect of Crusher Pulses - Eliminate Pathways



Only F_0 produces a signal… other F_n states are perfectly dephased

Crushers Review Question

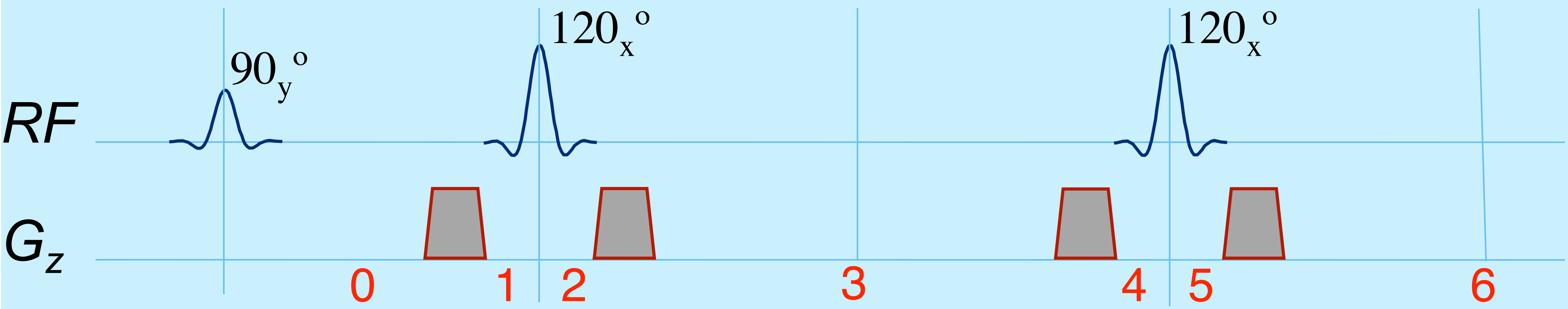
Standard CPMG Sequence… FAST!



CPMG Sequences

- Most spin-echo train sequences use CPMG
- CPMG = Carr Purcell Meiboom Gill
  - 90_x , 180_y , 180_y , 180_y , ...
  - 90_x , -180_x , 180_x , -180_x , ... (alternate ref. frame)
  - \- +90º, +270º, +90º
- Consider the "dephased" disc:
  - If the 180 angle is lower, CPMG "corrects"

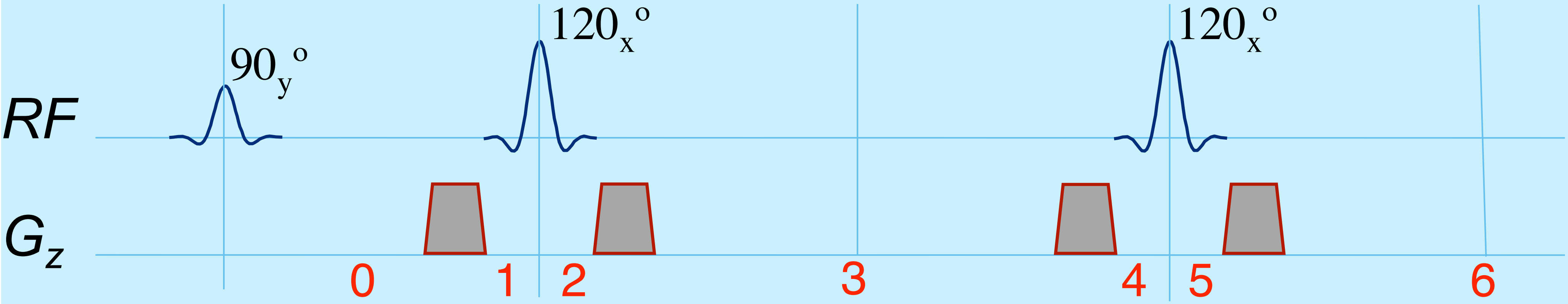
Example: CPMG




```
>> Q0 = [1;1;0];
>> Q1 = epg_grad(Q0)

    0     1
    0     0
    0     0

>> Q2 = RR*Q1

  0.00 + 0.00i   0.25 + 0.00i
  0.00 + 0.00i   0.75 + 0.00i
  0.00 + 0.00i   0.00 - 0.43i

>> Q3 = epg_grad(Q2)

  0.75 + 0.00i   0.00 + 0.00i   0.25 + 0.00i
  0.75 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i   0.00 - 0.43i   0.00 + 0.00i
```

```
>> Q4 = epg_grad(Q3)

  0.00 + 0.00i   0.75 + 0.00i   0.00 + 0.00i   0.25 + 0.00i
  0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i   0.00 - 0.43i   0.00 + 0.00i   0.00 + 0.00i

>> Q5 = RR*Q4

  0.00 + 0.00i  -0.19 + 0.00i   0.00 + 0.00i   0.063 + 0.00i
  0.00 + 0.00i   0.94 + 0.00i   0.00 + 0.00i   0.19 + 0.00i
  0.00 + 0.00i   0.00 - 0.11i   0.00 + 0.00i   0.00 - 0.11i

>> Q6 = epg_grad(Q5)

  0.94 + 0.00i   0.00 + 0.00i  -0.19 + 0.00i   0.00 + 0.00i   0.06 + 0.00i
  0.94 + 0.00i   0.00 + 0.00i   0.19 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i   0.00 - 0.11i   0.00 + 0.00i   0.00 - 0.11i   0.00 + 0.00i
```

Example: Non-CPMG

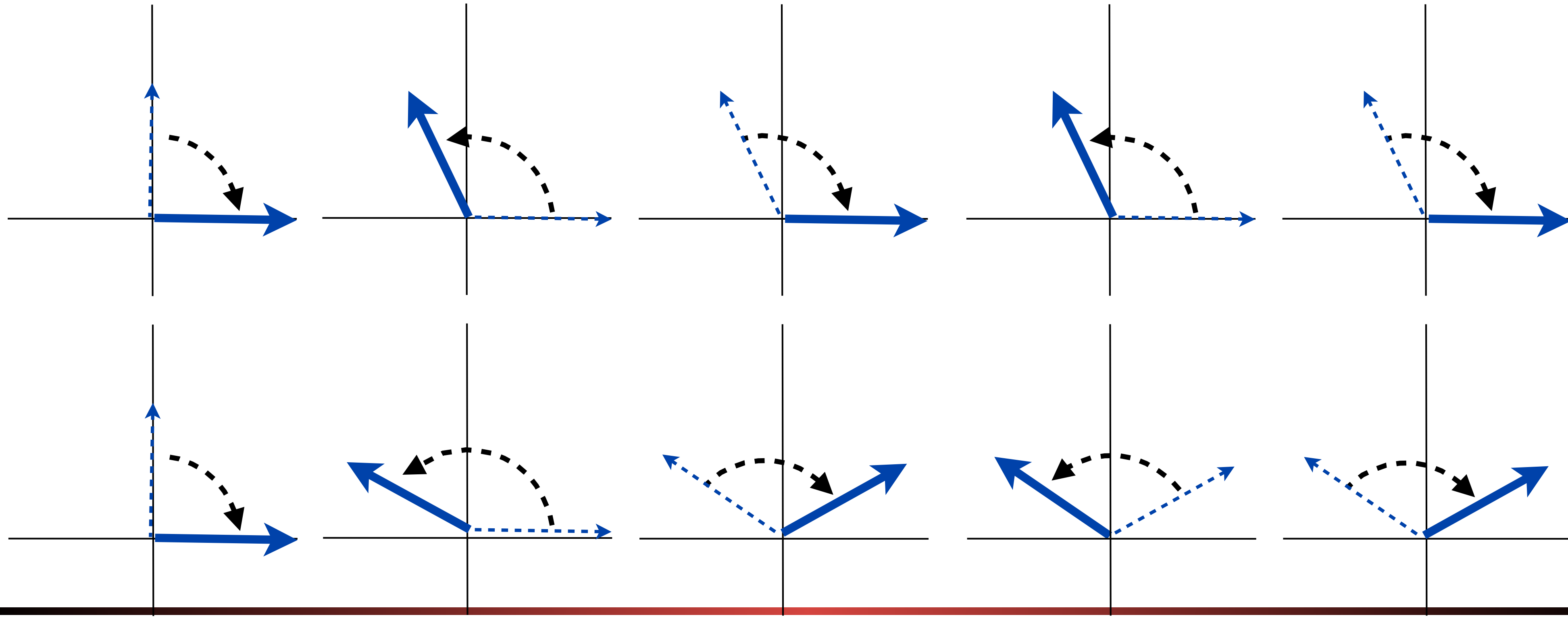



```
>> Q0 = [i;-i;0];
>> Q1 = epg_grad(Q0)

  0.00 + 0.00i   0.00 + 1.00i
  0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i   0.00 + 0.00i

>> Q2 = RR*Q1

  0.00 + 0.00i   0.00 + 0.25i
  0.00 + 0.00i   0.00 + 0.75i
  0.00 + 0.00i   0.43 + 0.00i

>> Q3 = epg_grad(Q2)

  0.00 - 0.75i   0.00 + 0.00i   0.00 + 0.25i
  0.00 + 0.75i   0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i   0.43 + 0.00i   0.00 + 0.00i
```

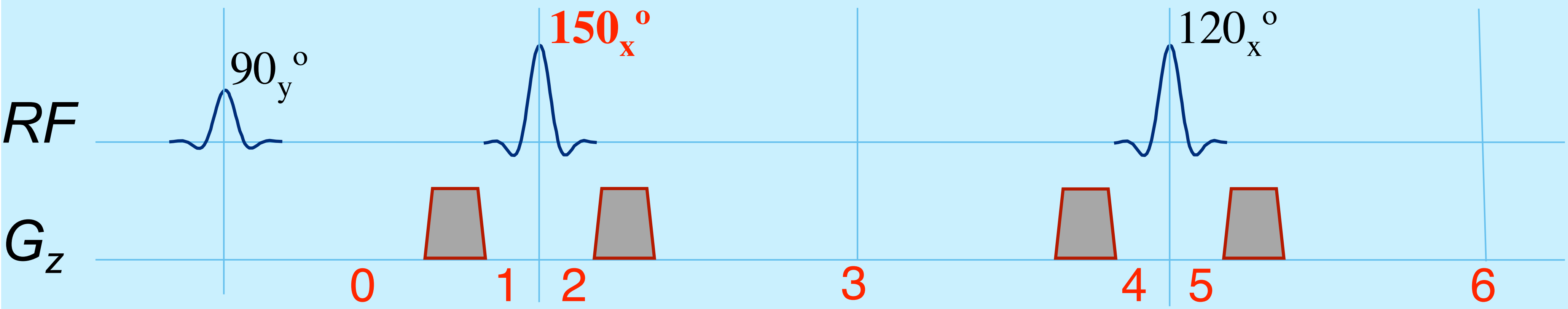
```
>> Q4 = epg_grad(Q3)

  0.00 + 0.00i   0.00 - 0.75i   0.00 + 0.00i   0.00 + 0.25i
  0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i   0.43 + 0.00i   0.00 + 0.00i   0.00 + 0.00i

>> Q5 = RR*Q4

  0.00 + 0.00i   0.00 - 0.56i   0.00 + 0.00i   0.00 + 0.06i
  0.00 + 0.00i   0.00 - 0.19i   0.00 + 0.00i   0.00 + 0.19i
  0.00 + 0.00i  -0.54 + 0.00i   0.00 + 0.00i   0.11 + 0.00i

>> Q6 = epg_grad(Q5)

  0.00 + 0.19i   0.00 + 0.00i   0.00 - 0.56i   0.00 + 0.00i   0.00 + 0.06i
  0.00 - 0.19i   0.00 + 0.00i   0.00 + 0.19i   0.00 + 0.00i   0.00 + 0.00i
  0.00 + 0.00i  -0.54 + 0.00i   0.00 + 0.00i   0.11 + 0.00i   0.00 + 0.00i
```

Intuition: Stabilization Pulse

- Often use reduced refocusing angles (Hennig 2000)
  - 90_x , -120_x , 120_x , -120_x , ...
- Consider the “on-resonant” spins
  - 90x , -150_x , 120_x , -120_x , ...



Example: CPMG (prep)



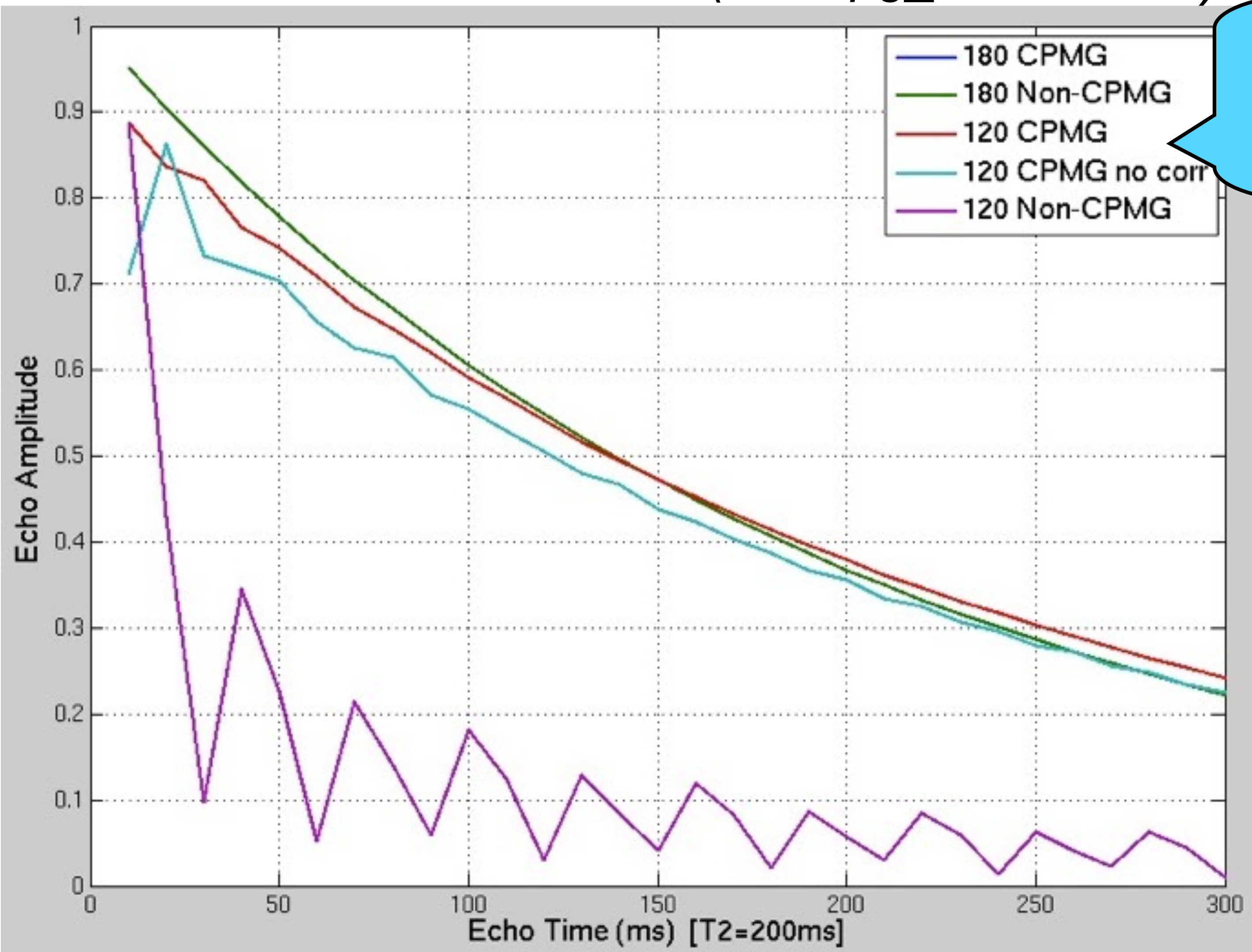

```
>> Q0 = [1;1;0];
>> Q1 = epg_grad(Q0)

     0     1
     0     0
     0     0

>> Q2 = RR1*Q1

   000. + 0.00i   0.07 + 0.00i
   0.00 + 0.00i   0.93 + 0.00i
   0.00 + 0.00i   0.00 - 0.25i

>> Q3 = epg_grad(Q2)

   0.93 + 0.00i   0.00 + 0.00i   0.07 + 0.00i
   0.93 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
   0.00 + 0.00i   0.00 - 0.25i   0.00 + 0.00i
```

```
>> Q4 = epg_grad(Q3)

   0.00 + 0.00i   0.93 + 0.00i   0.00 + 0.00i   0.07 + 0.00i
   0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
   0.00 + 0.00i   0.00 - 0.25i   0.00 + 0.00i   0.00 + 0.00i

>> Q5 = RR*Q4

   0.00 + 0.00i   0.02 + 0.00i   0.00 + 0.00i   0.02 + 0.00i
   0.00 + 0.00i   0.92 + 0.00i   0.00 + 0.00i   0.05 + 0.00i
   0.00 + 0.00i   0.00 - 0.28i   0.00 + 0.00i   0.00 - 0.03i

>> Q6 = epg_grad(Q5)

   0.92 + 0.00i   0.00 + 0.00i   0.02 + 0.00i   0.00 + 0.00i   0.02 + 0.00i
   0.92 + 0.00i   0.00 + 0.00i   0.05 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
   0.00 + 0.00i   0.00 - 0.28i   0.00 + 0.00i   0.00 - 0.03i   0.00 + 0.00i
```

Spin Echo Train Results

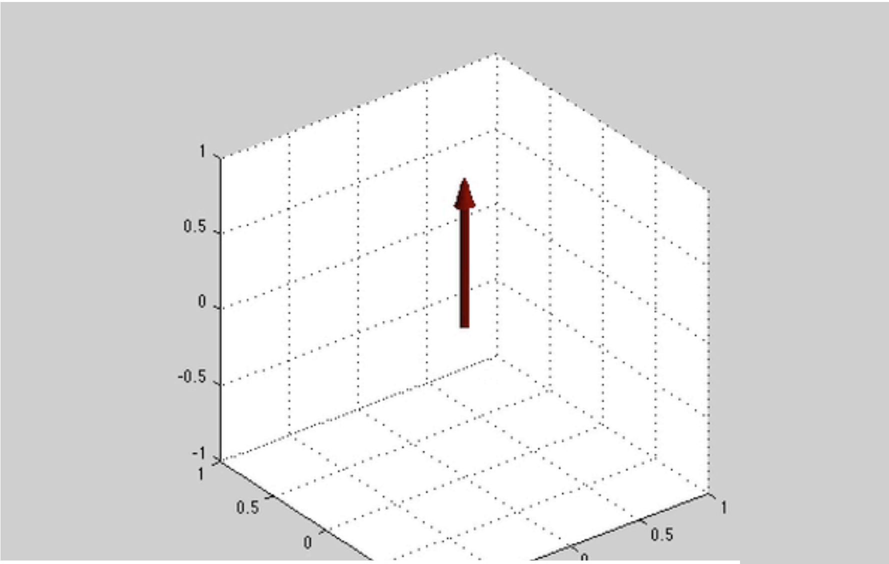
- *Repeated with α_φ refocusing pulses, 10ms echo spacing*

(see epg_echotrain.m)

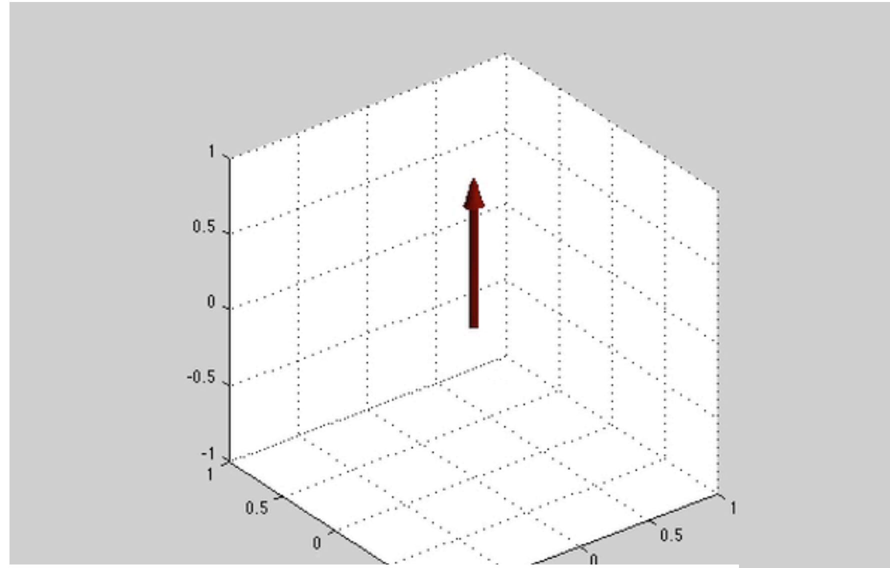


3rd line uses 90-150-120-120
4th line uses 90-120-120-120
(Hennig J et al. 2000; 44: 938)

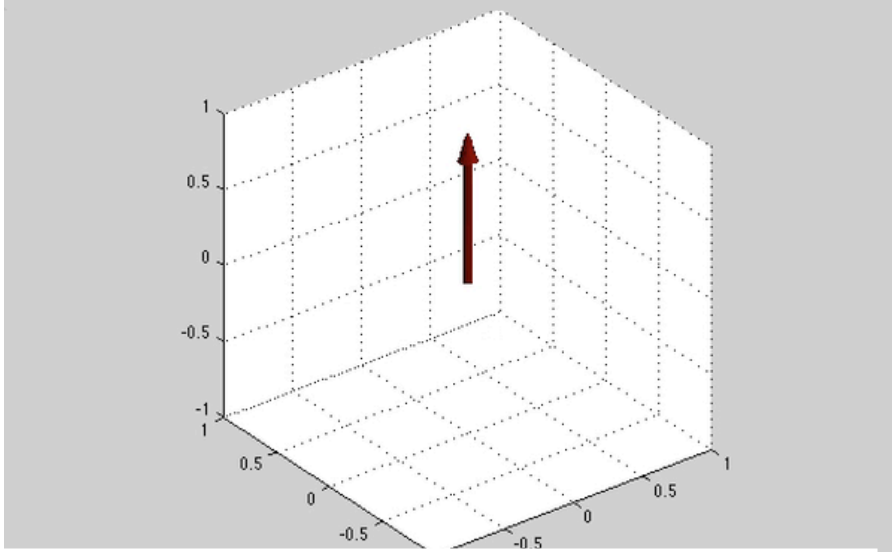
CPMG Cases: Examples



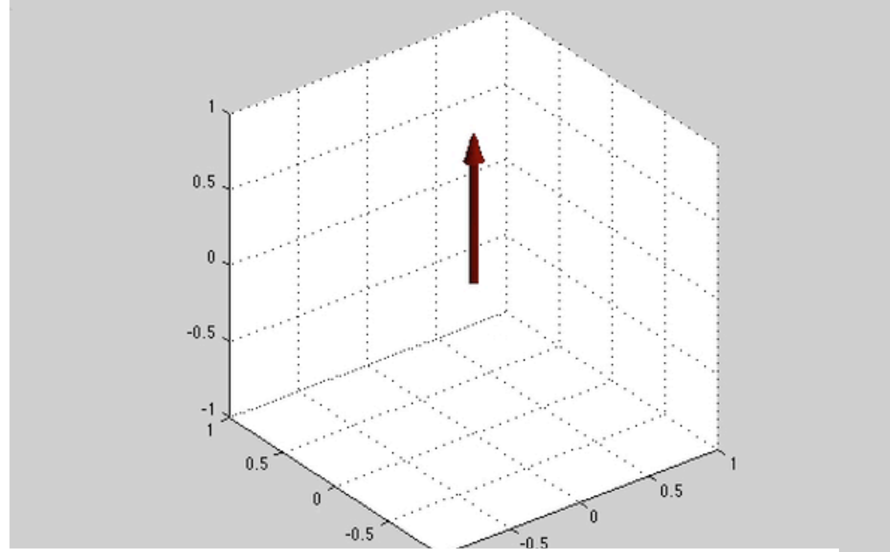
CPMG (90_{-y}, 120_x, 120_x, 120_x, …)



CPMG (90_{-y}, 150_x, 120_x, 120_x, …)



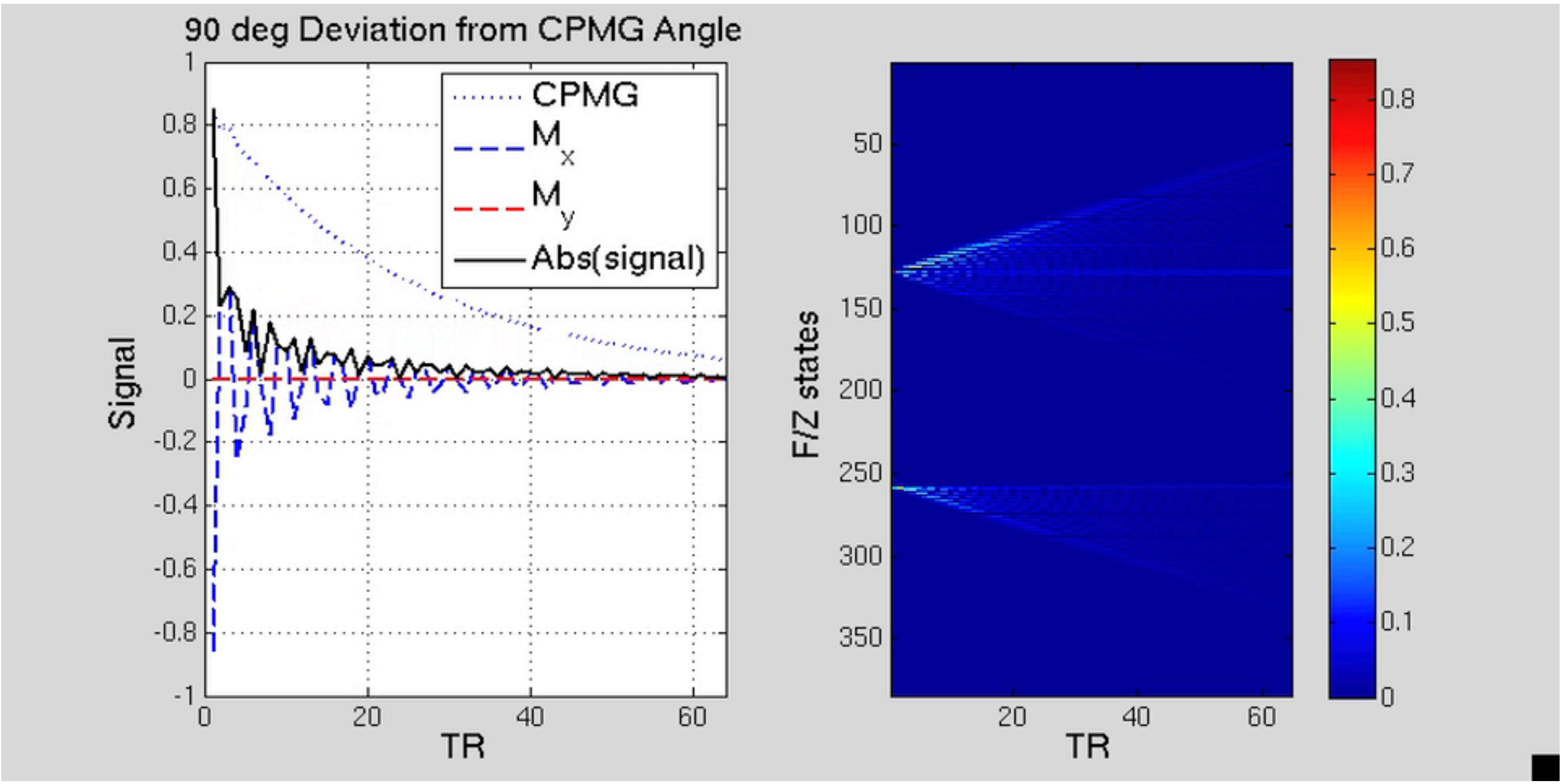
Non-CPMG (90_{-y}, 150_{-y}, 120_{-y}, 120_{-y}, …)



CPMG (90_{-y}, -150_{-y}, $+120_{-y}$, -120_{-y}, …)

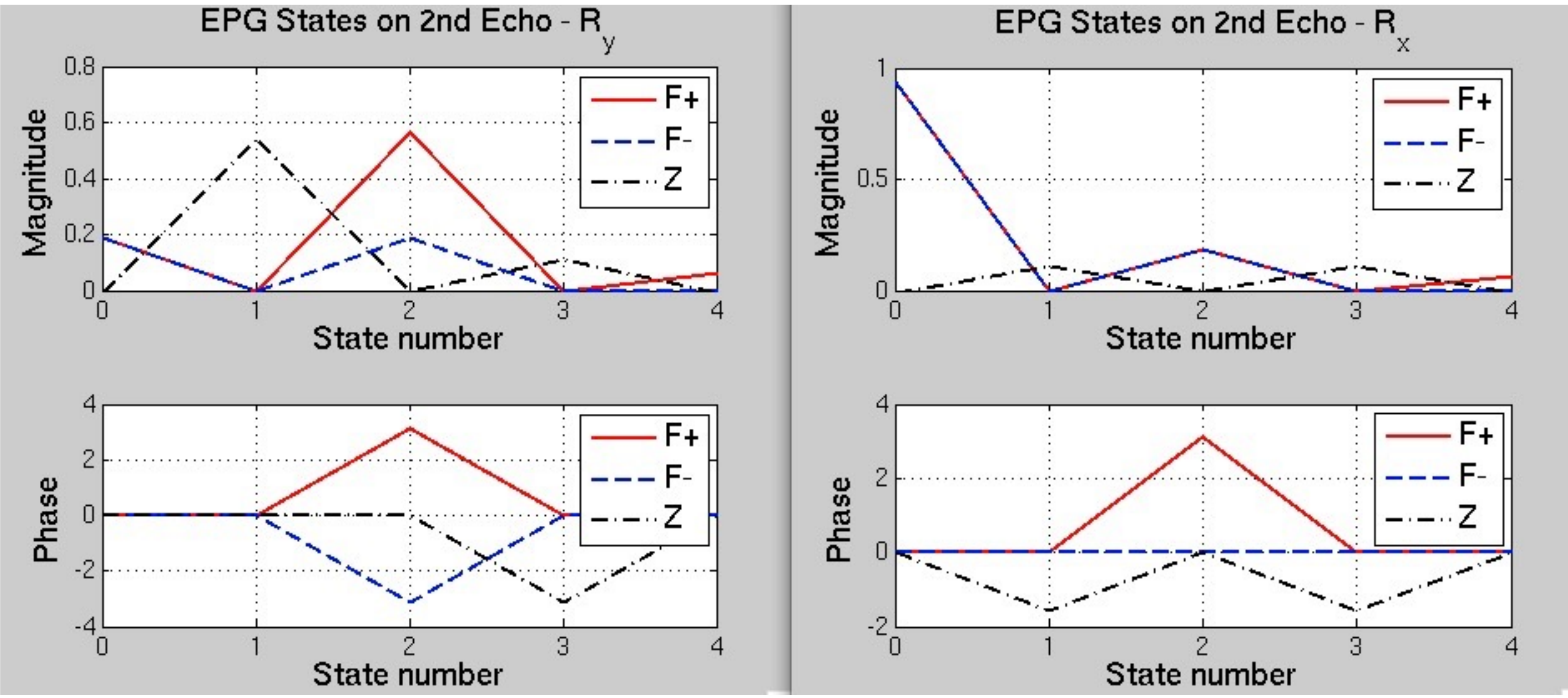
CPMG: Effect of Phase

- Compares $90^o_{-\pi/2}$ - α_φ for $\varphi=[0,\pi]$ and $\alpha=105^o$
- CPMG ($\varphi=0$) shown for reference



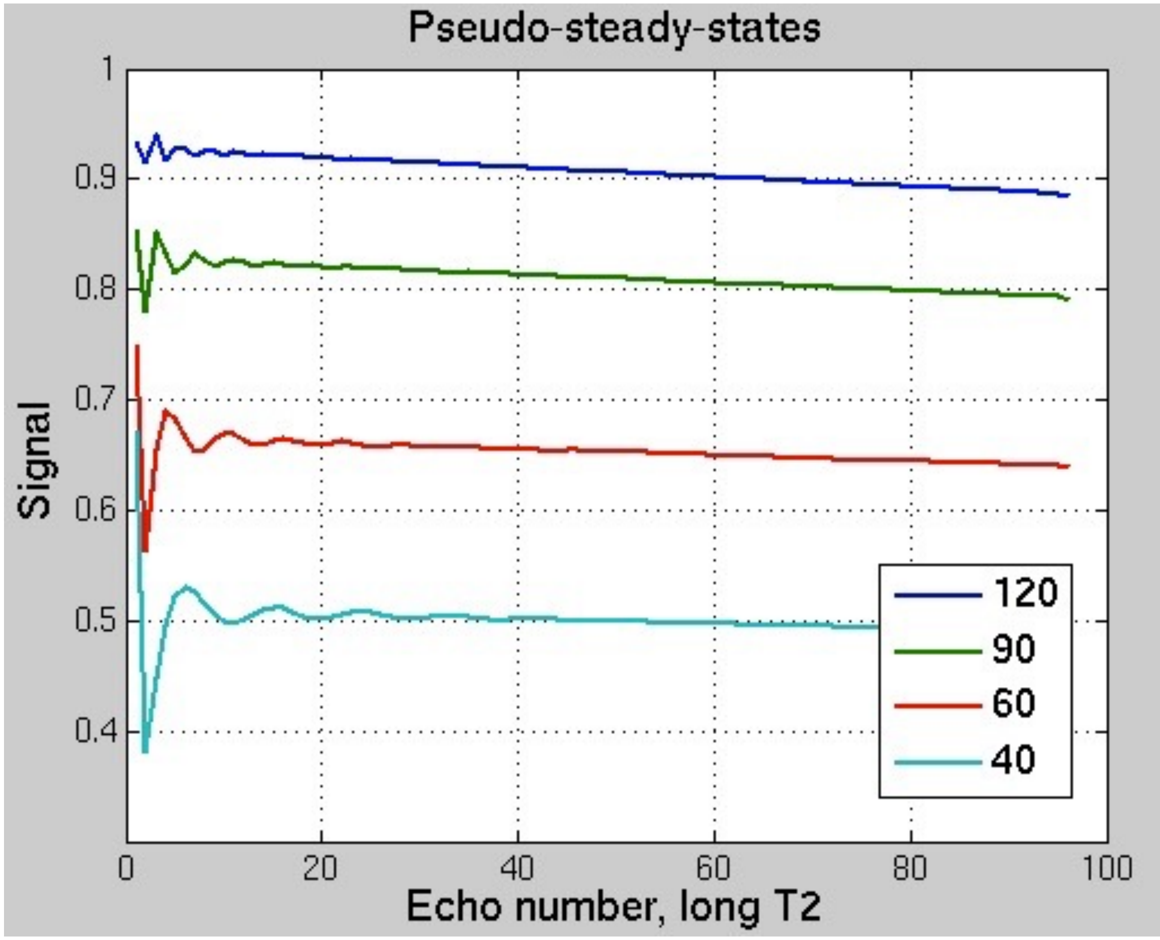
CPMG: EPG States

- Compare 90^o_y - α_y (non-CPMG) to 90^o_y - α_x (CPMG)
- F/Z states on 2nd spin-echo after perfect 90º pulse



Pseudo-Steady States

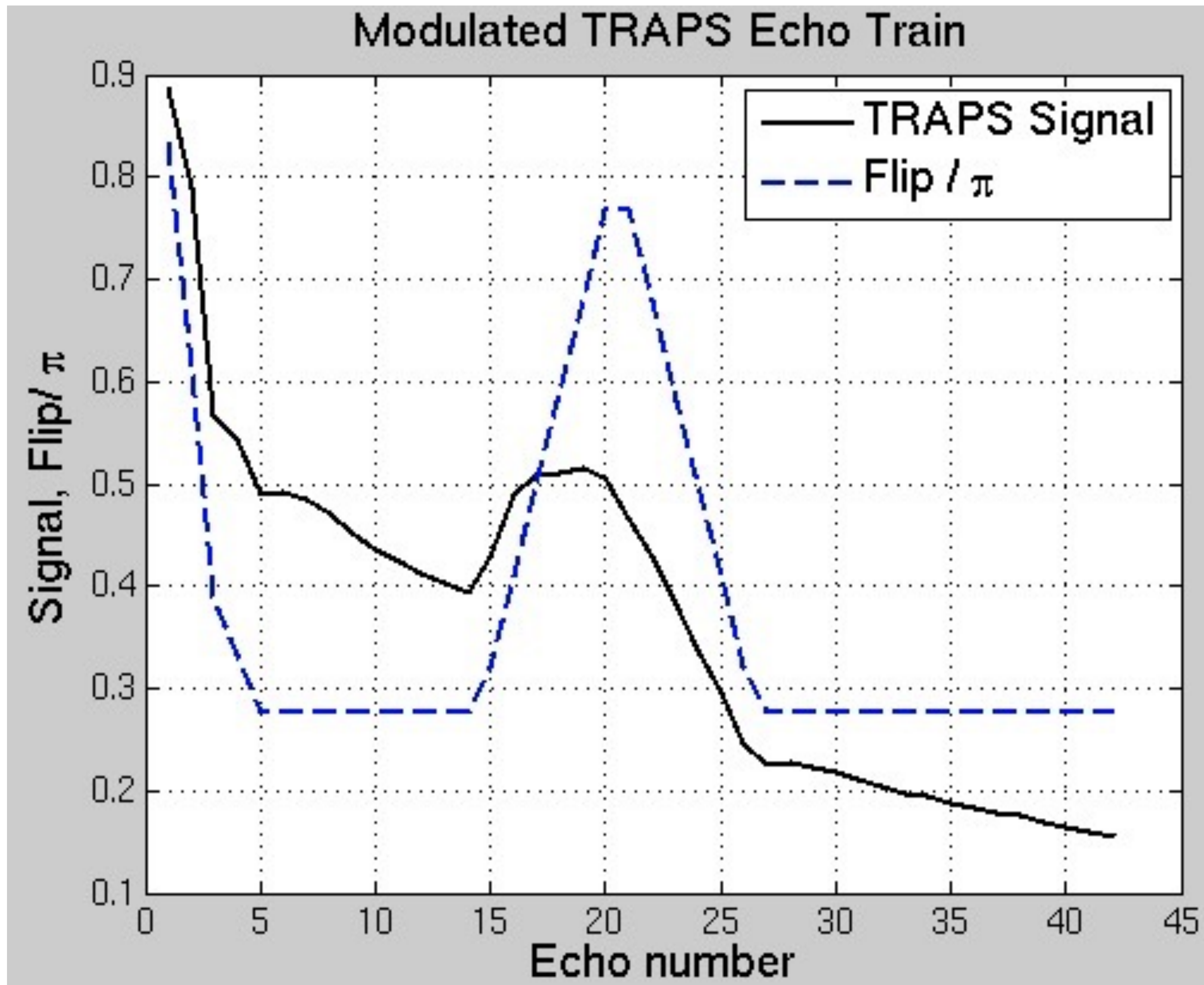
- Reduced flip angles
- “Stabilization” pulse



TRAPS

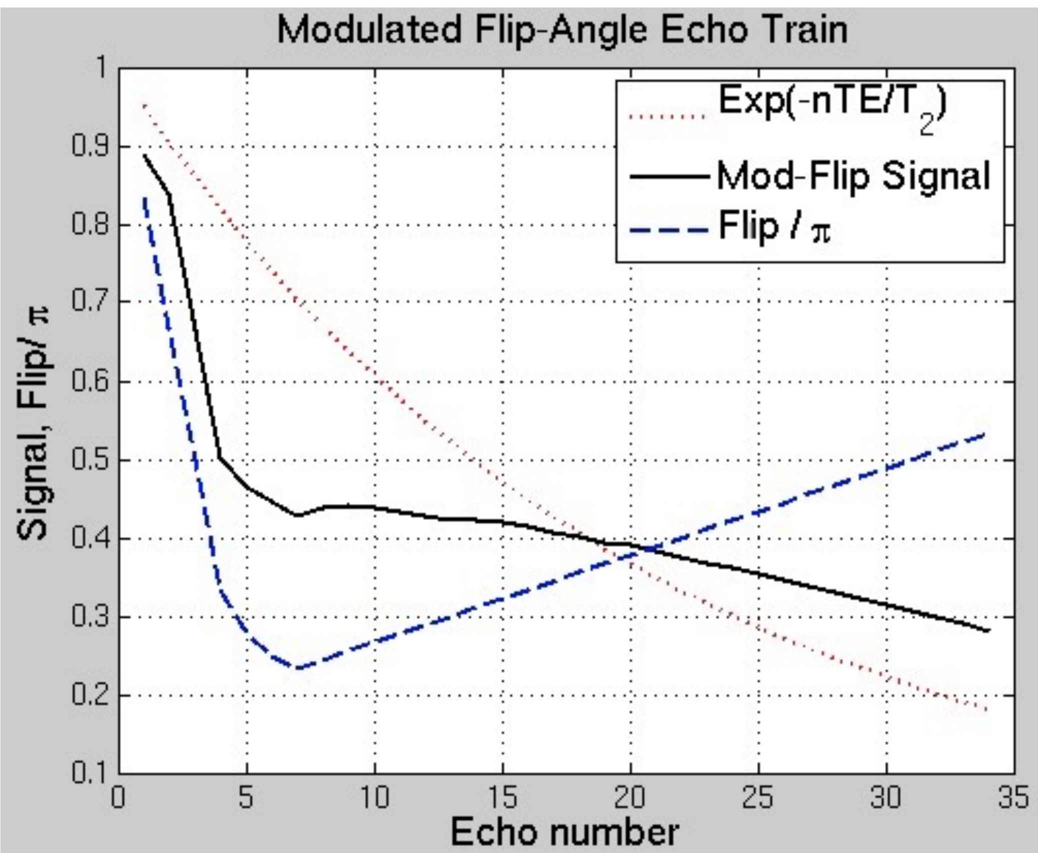
Hennig 2003

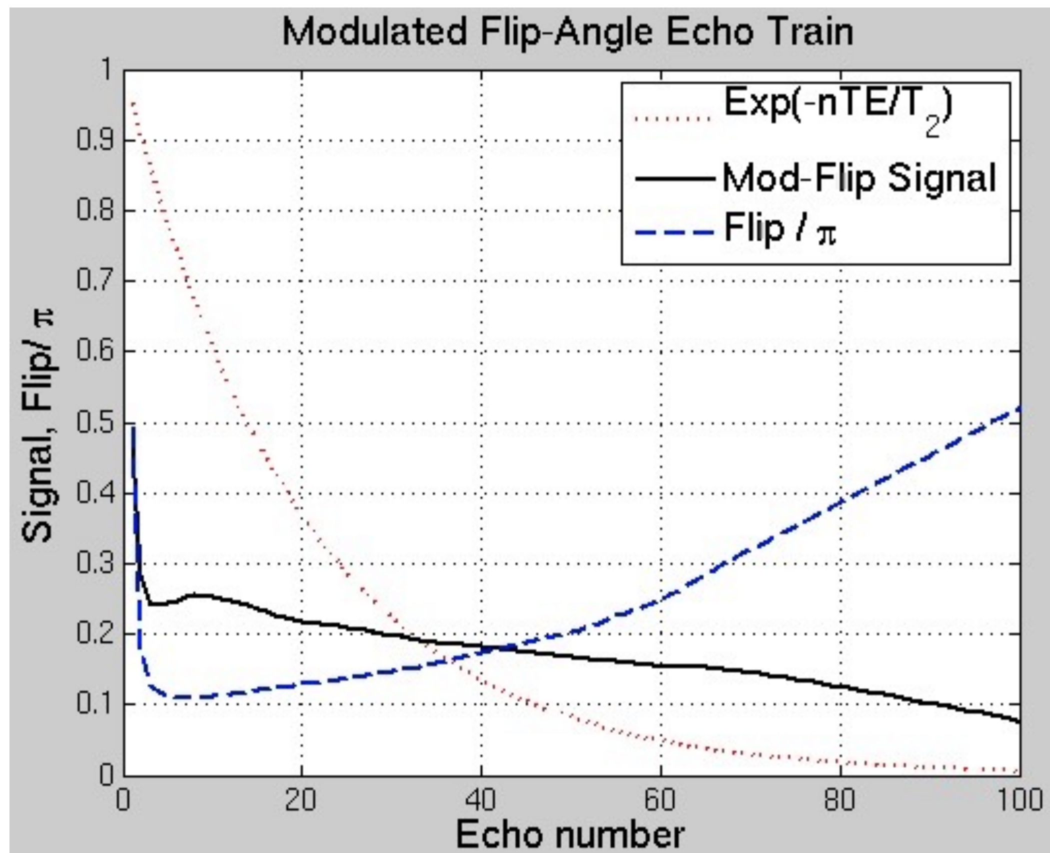
- Transition to Pseudo-steady-states
- Enhance signal at k-space center (sequential k_y)



Modulated Refocusing Angles

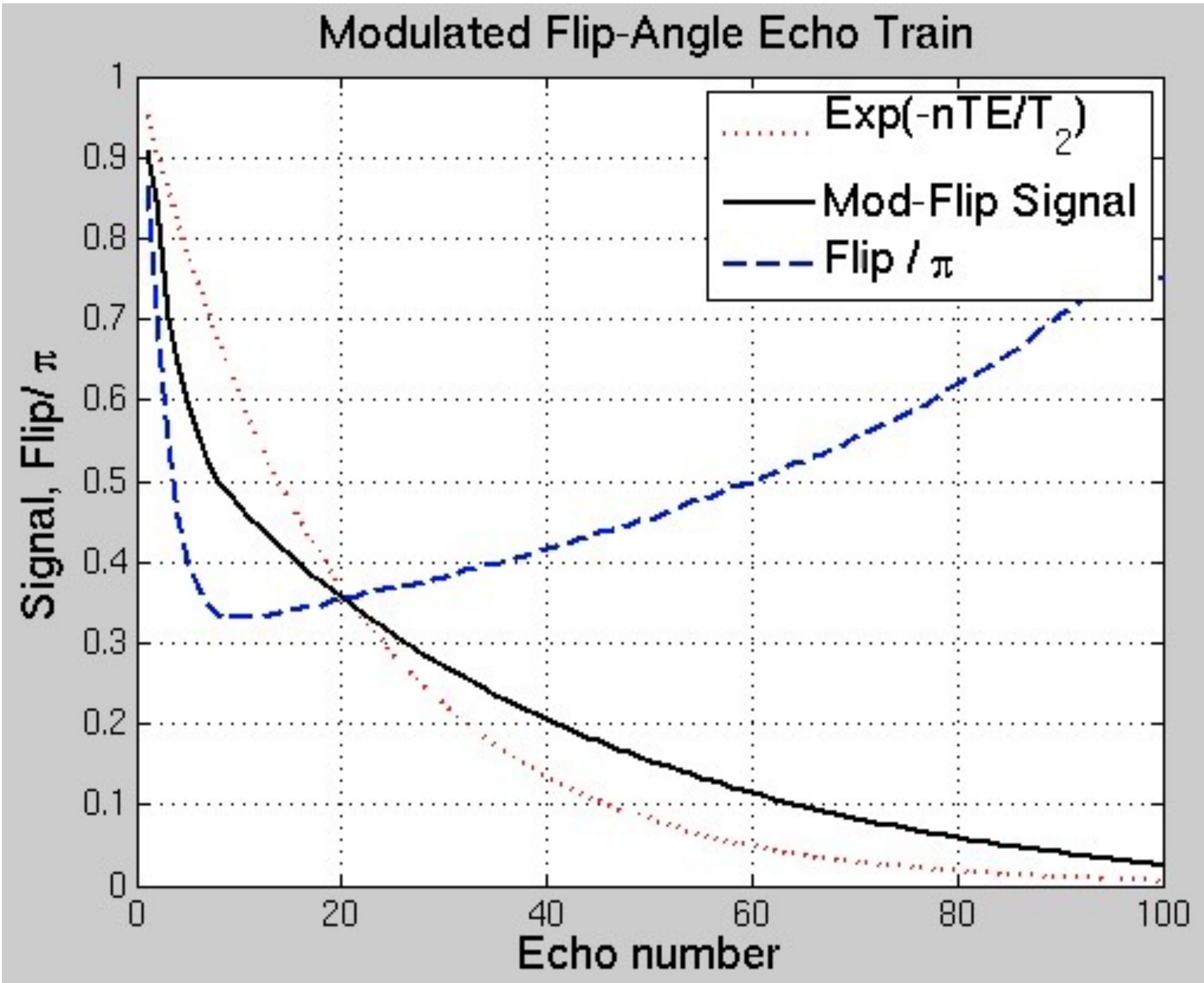
- Variable flip-angles with CPMG
- Different schemes to “optimize” signal over echo train
- “optimize” varies(!)
- AUC vs SAR vs flatness?





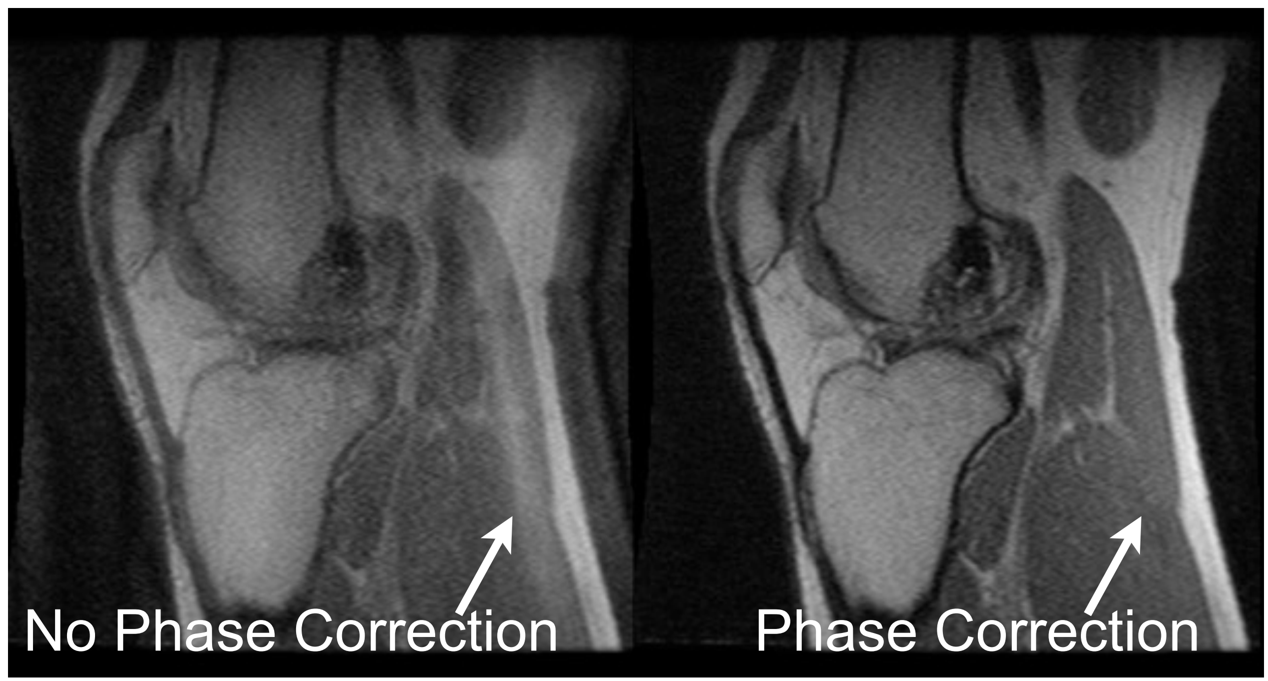
Modulated Refocusing Angles: XETA

- “Extended” exponential -- Busse 2006
- T_2 contrast with extended echo train



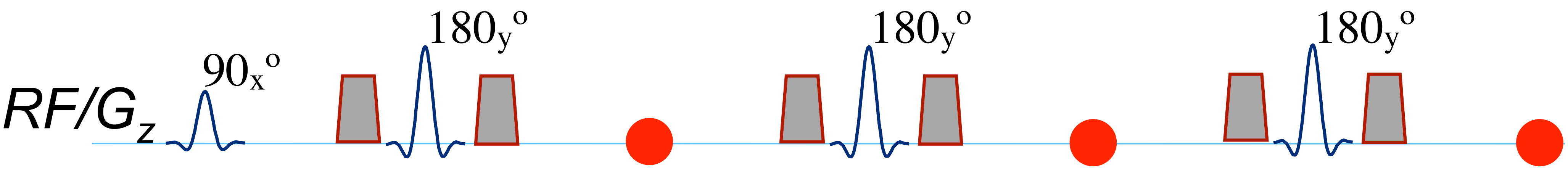
Phase Correction

- Eddy-current variations are a problem
  - Between refocusing pulses eddy currents are the same - so less problematic
  - 90-180 eddy currents differ, causing loss of the 90º phase difference for CPMG
- Linear corrections by modifying G_x and G_z areas



Hinks, 1993

CPMG Summary

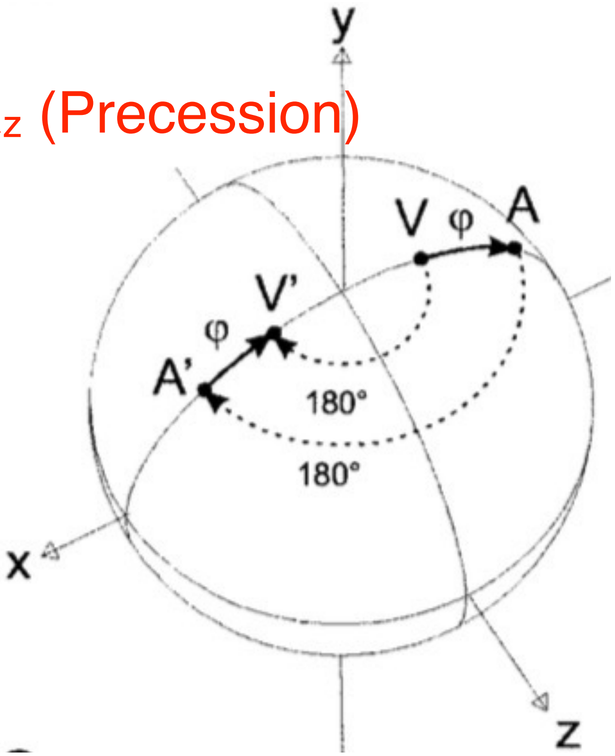


- CPMG: Refocusing pulses "self-correct"
  - $90_x, \alpha_y, \alpha_y, \alpha_y, \ldots$ or $90_x, -\alpha_x, \alpha_x, -\alpha_x, \ldots$
- Prep Pulse: First refocusing pulse balances echoes
- Non-CPMG: Signal oscillates and decays quickly
- CPMG allows reduced, variable refocusing angles
- Eddy-current-induced phase can prevent CPMG

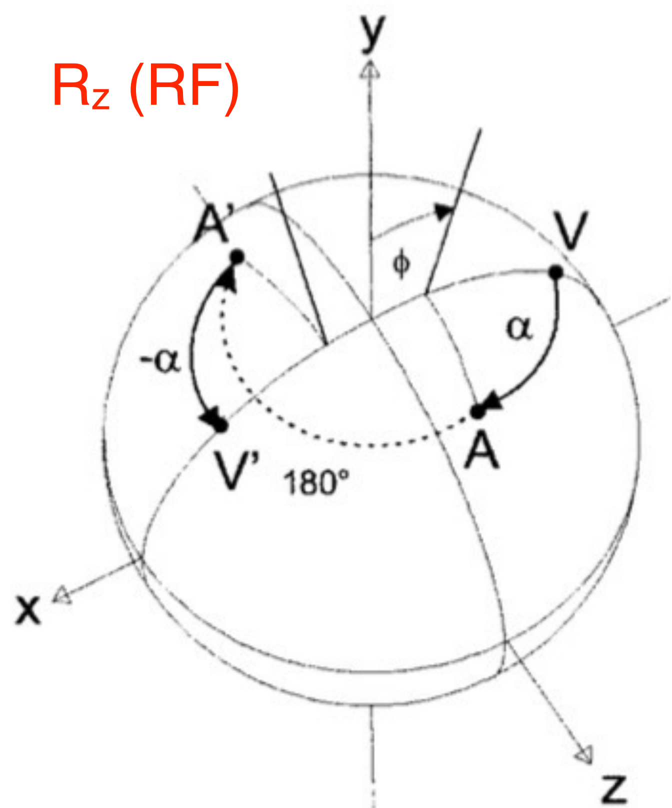
Hyperechoes

Hennig 2001

R_z (Precession)



R_z (RF)

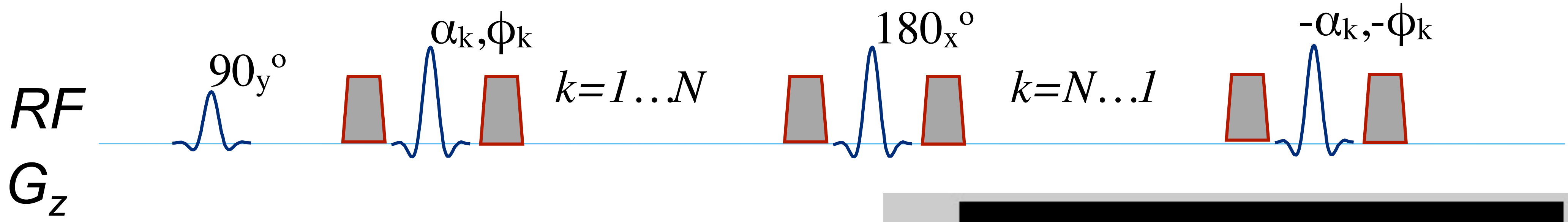


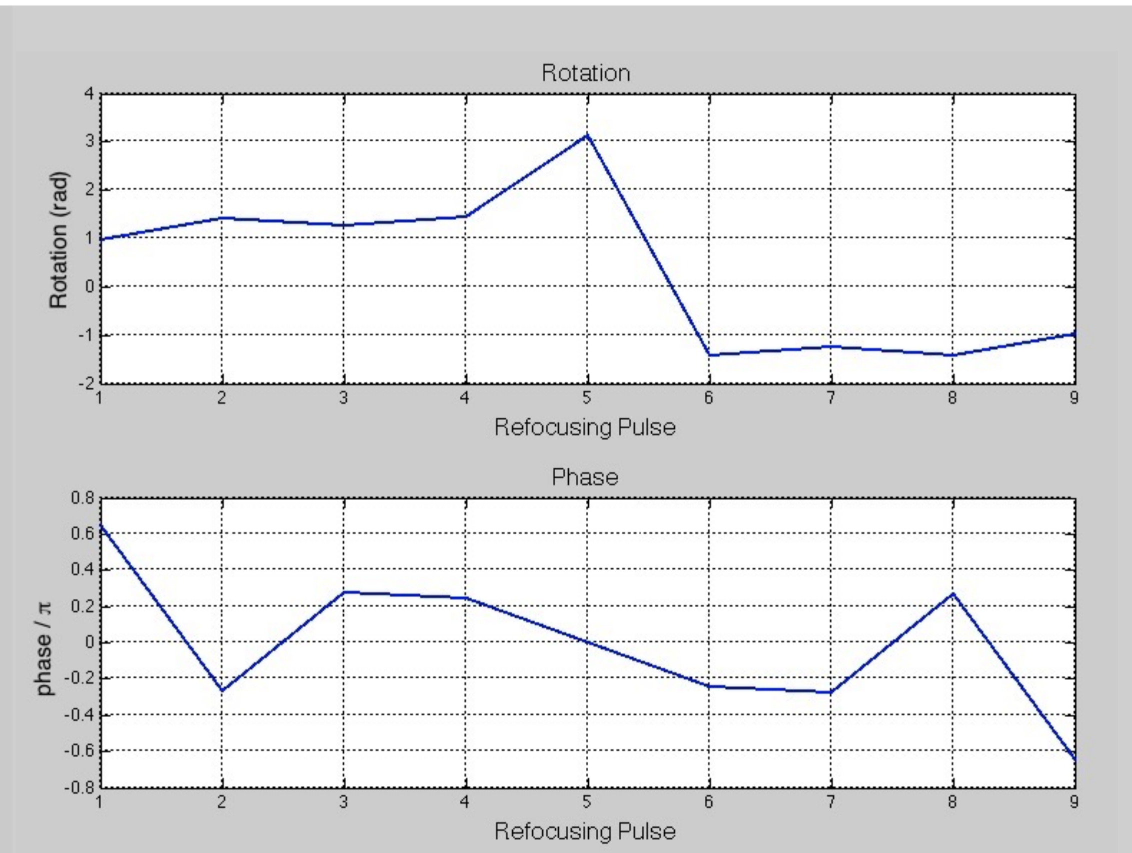
- Symmetry around 180_y^o:
  - $R_z(\beta)\ R_y(180^o)\ R_z(\beta) = R_y(180^o)$
  - $R_\varphi(\alpha)\ R_y(180^o)\ R_{-\varphi}(-\alpha) = R_y(180^o)$
- The following reduces to $R_x(180^o)$, *with φ defined w.r.t x*

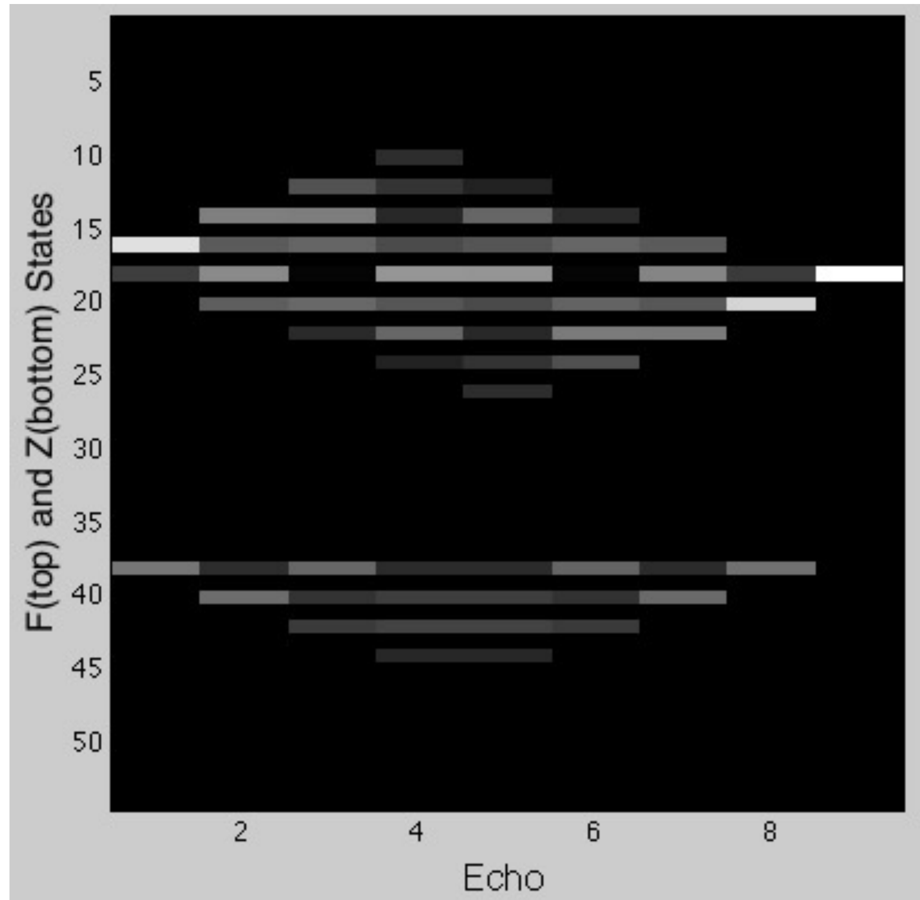
  (α_1,φ_1), (α_2,φ_2), … (α_N,φ_N), $(180^o,0)$, $(-\alpha_N,-\varphi_N)$, …, $(-\alpha_2,-\varphi_2)$,$(-\alpha_1,-\varphi_1)$

Hyperecho Example

Hennig 2001





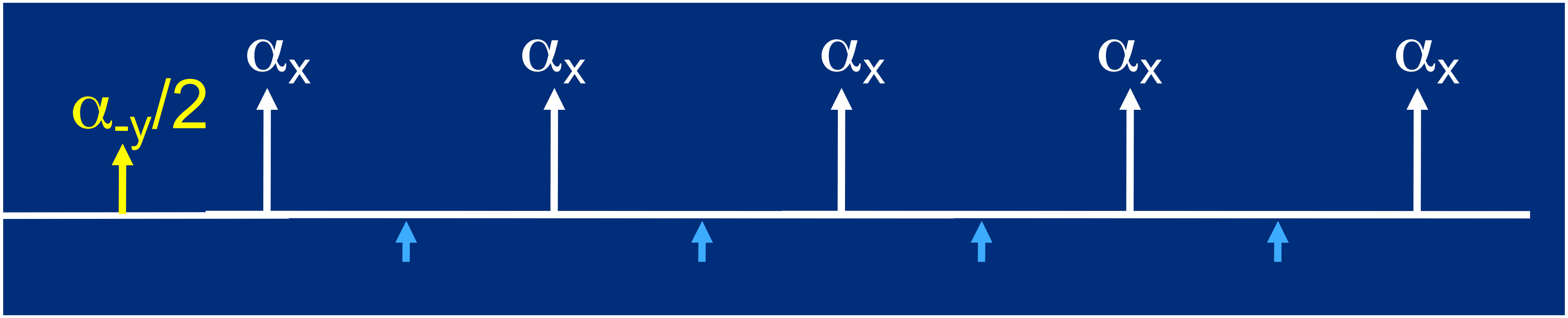


Random α, φ. N=4

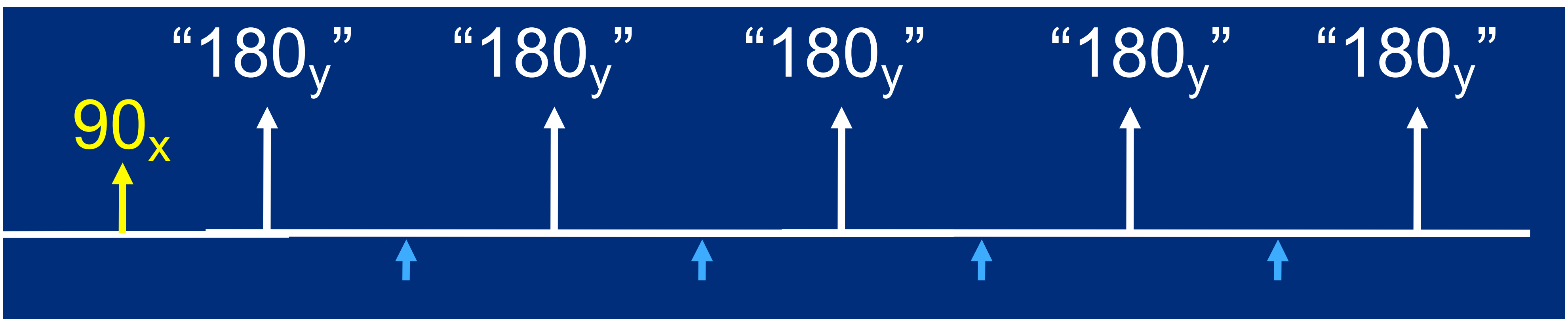
Phase Diagram (epg_cpmg)

SSFP vs Fast Spin Echo

bSSFP



FSE



Spin-Echo vs Balanced SSFP

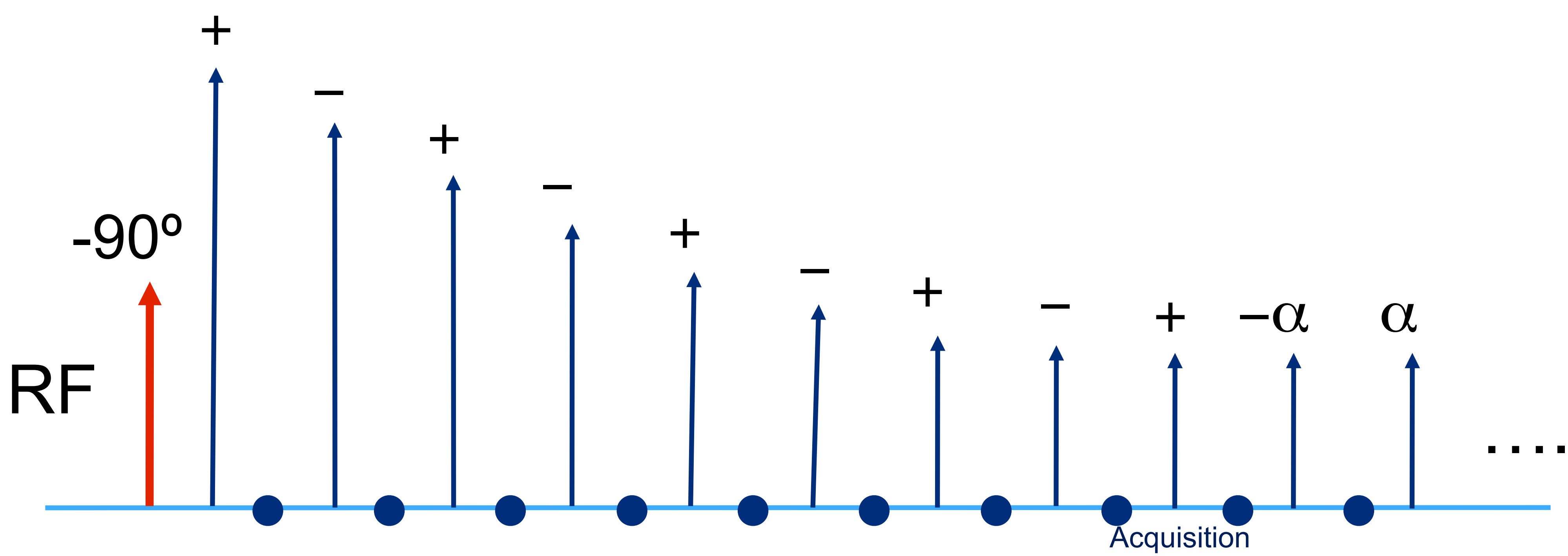
- RARE is bSSFP with high-flip angles and crushers
- 90-TE/2 pulse is like the α/2-TR/2 pulse
    - But steady-state is eliminated by crushers
    - Transient state is imaged

cTIDE:

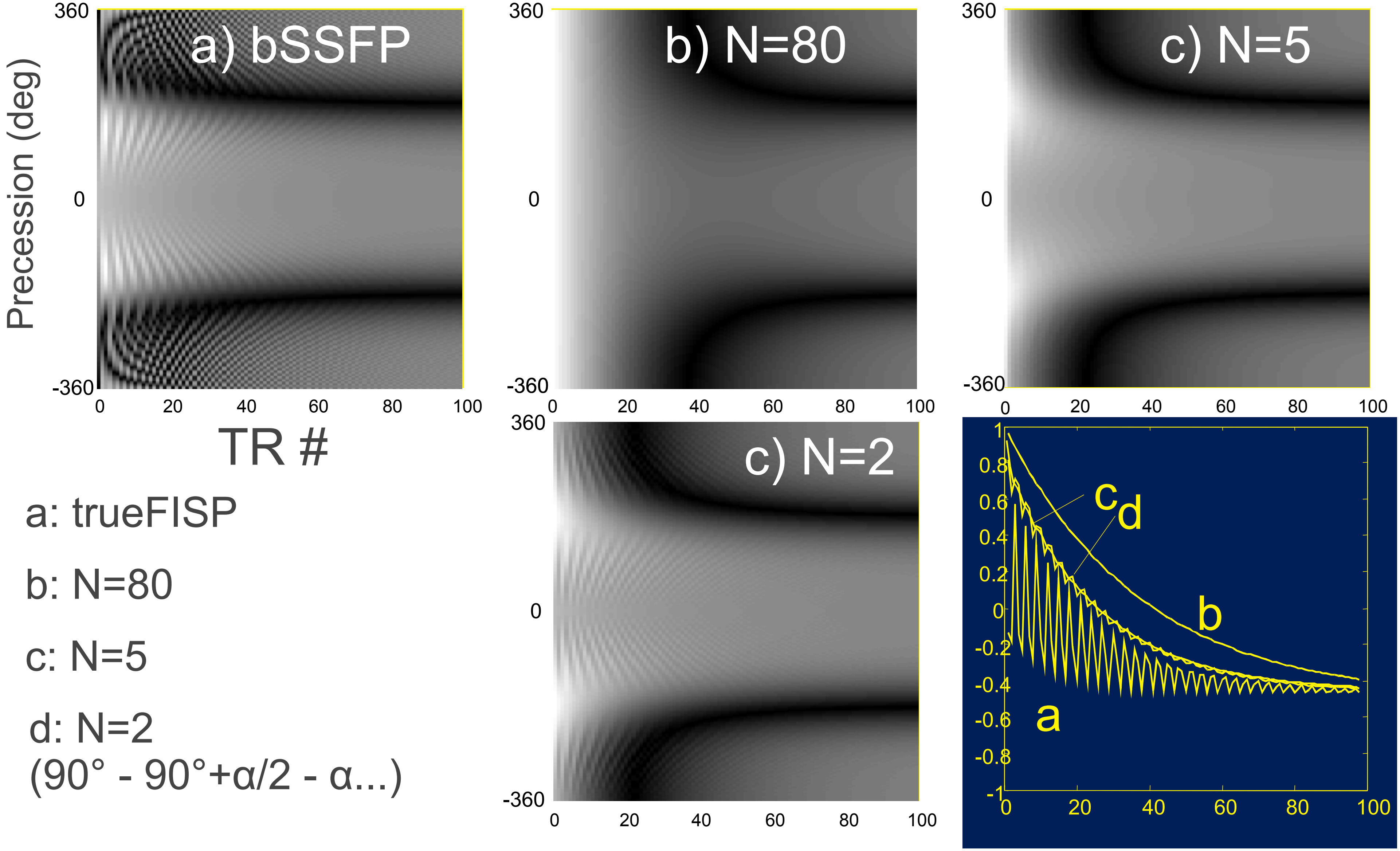
Hennig, et al., 2002

"Continuous Transition into Driven Equilibrium"

- Start with 90º pulse.
- Ramp down from 180º to α
- Looks a lot like modulated spin-echo train
- Usually acquire data during pseudo steady state



Off-resonance Behavior of TIDE



a: trueFISP

b: N=80

c: N=5

d: N=2
(90° - 90°+α/2 - α...)

(Courtesy of Jurgen Hennig, Univ. of Freiburg)

Spin-Echo Trains: Additional Points

- J-coupling: Relaxation mechanism in fat
  - Rapid refocusing decreases relaxation rate, so fat is brighter on FSE/RARE than SE
- MT: Interleaved multislice
  - Slice-selective pulses are off-resonance to others
  - MT saturation effect - suppresses some signals

Summary: Spin-Echo Sequences

- Basic spin echo
- Echo-trains: RARE, FSE, TSE
  - Efficient T2 and PD contrast
  - Extreme cases: SSFSE/HASTE
  - 3D Echo trains
- Signal considerations
  - CPMG / Reduced refocusing angles
  - Modulated echo trains