Rad229 – MRI Signals and Sequences

Daniel Ennis & Brian Hargreaves

dbe@stanford.edu –or– bah@stanford.edu

Lecture-8B — Spin-Echo Sequences

Practical Spin-Echo-Train Signals

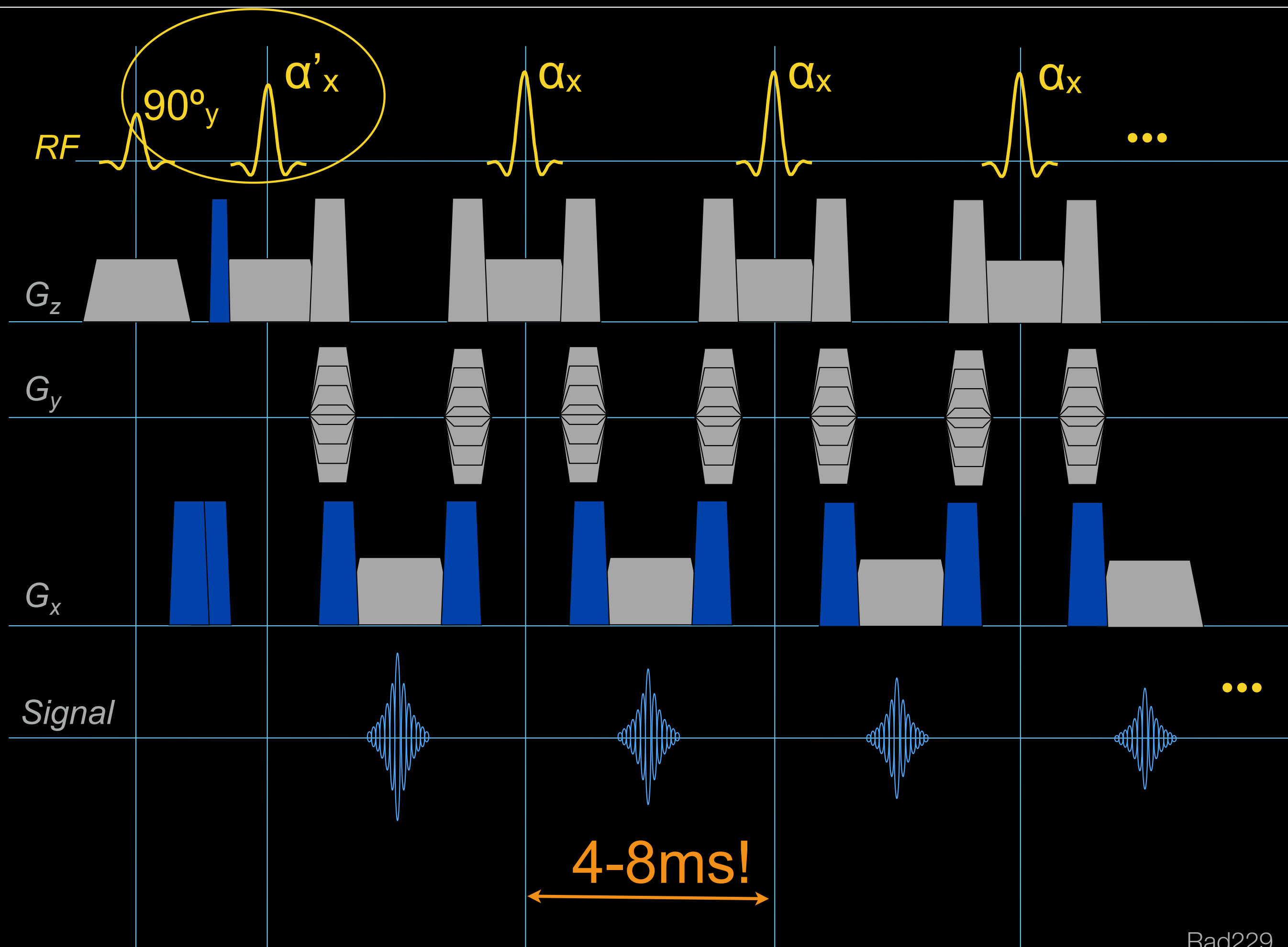
Brian Hargreaves
bah@stanford.edu

Learning Objectives

- Draw waveforms for a practical spin-echo-train sequence
- Explain the function of crusher gradients
- Explain the CPMG condition and why it is important
- Calculate the signal for reduced and variable refocusing angles

Spin-Echo Trains: Practical Concepts

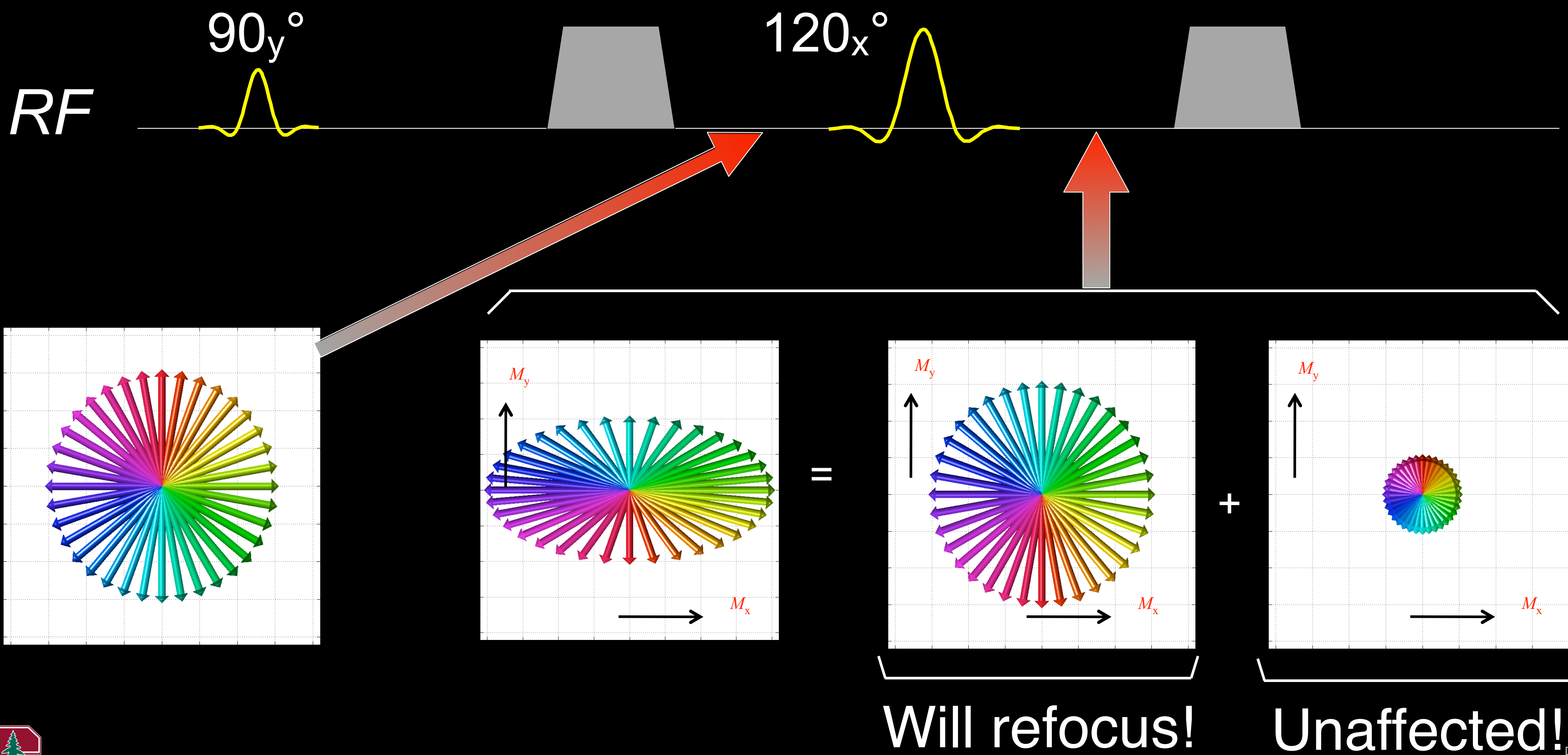
- Reduced Refocusing
- Short Echo Spacings
- Crusher Gradients
- CPMG
- Stabilization
- Eddy-current correction



Practical spin-echo train sequences use reduced refocusing angles and crusher gradients

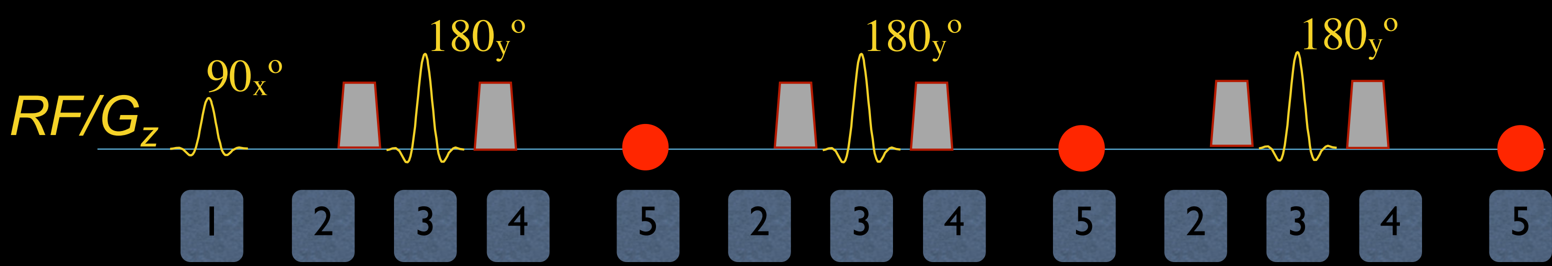
Question 1

Spin Echo Formation: Reduced Refocusing Angle (120°)



A spin-echo will form with almot any refocusing angle - lec8_03.m

Spin Echo Train Simulation: epg_cpmg.m

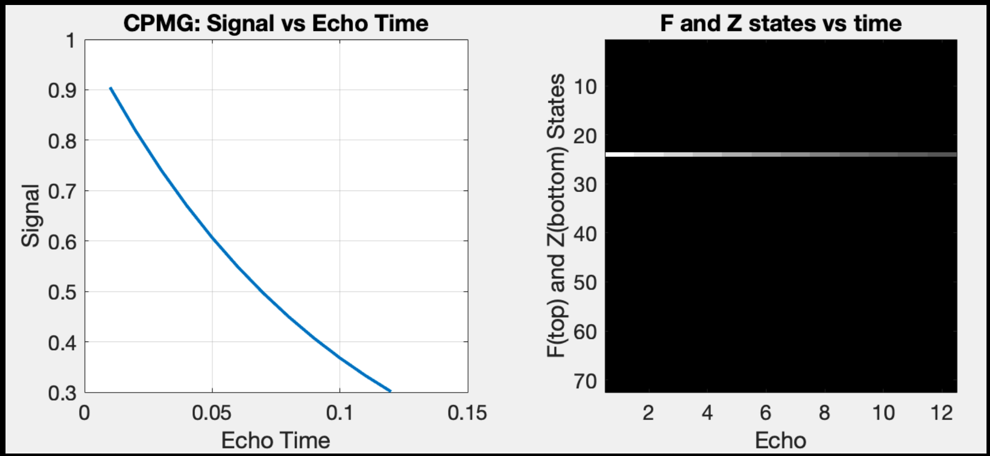


Simulate

1. 90° excitation

Repeat:

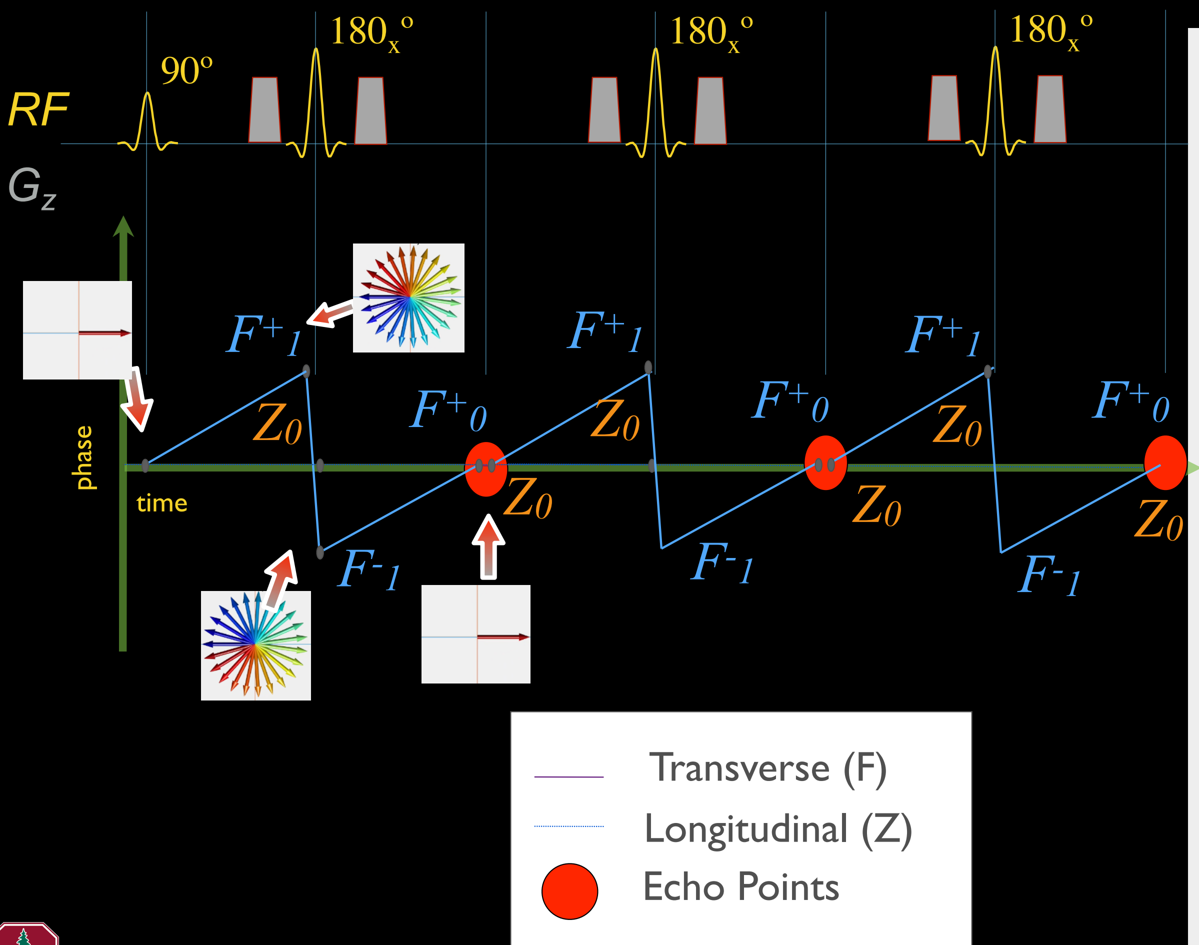
2. Relaxation and crusher gradient
3. Refocusing pulse
4. Relaxation and crusher gradient
5. Signal at spin echo

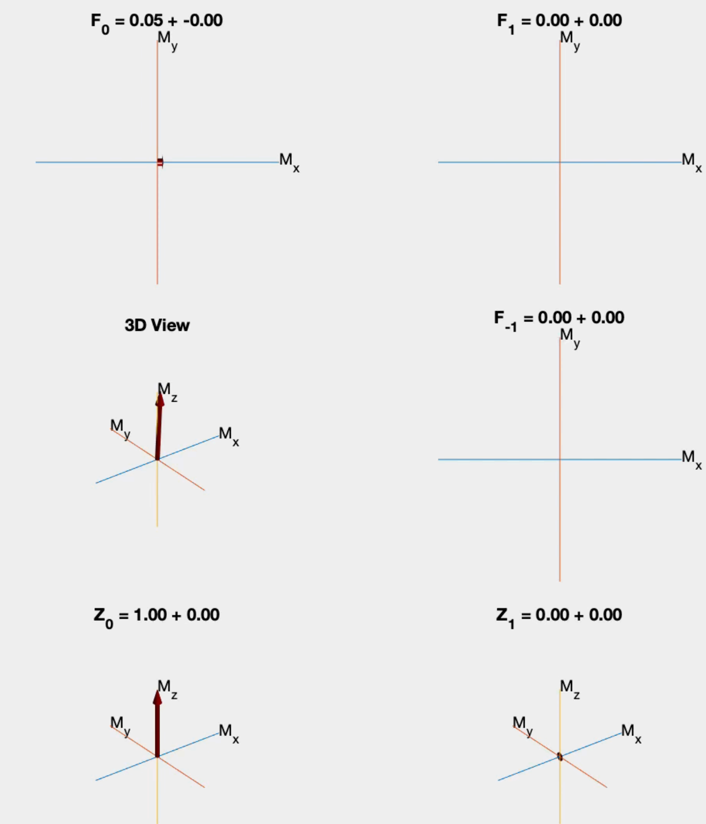


Vary refocusing angle and/or phase…

Using the EPG formalism, simulation of spin-echo trains is relatively easy: epg_cpmg.m

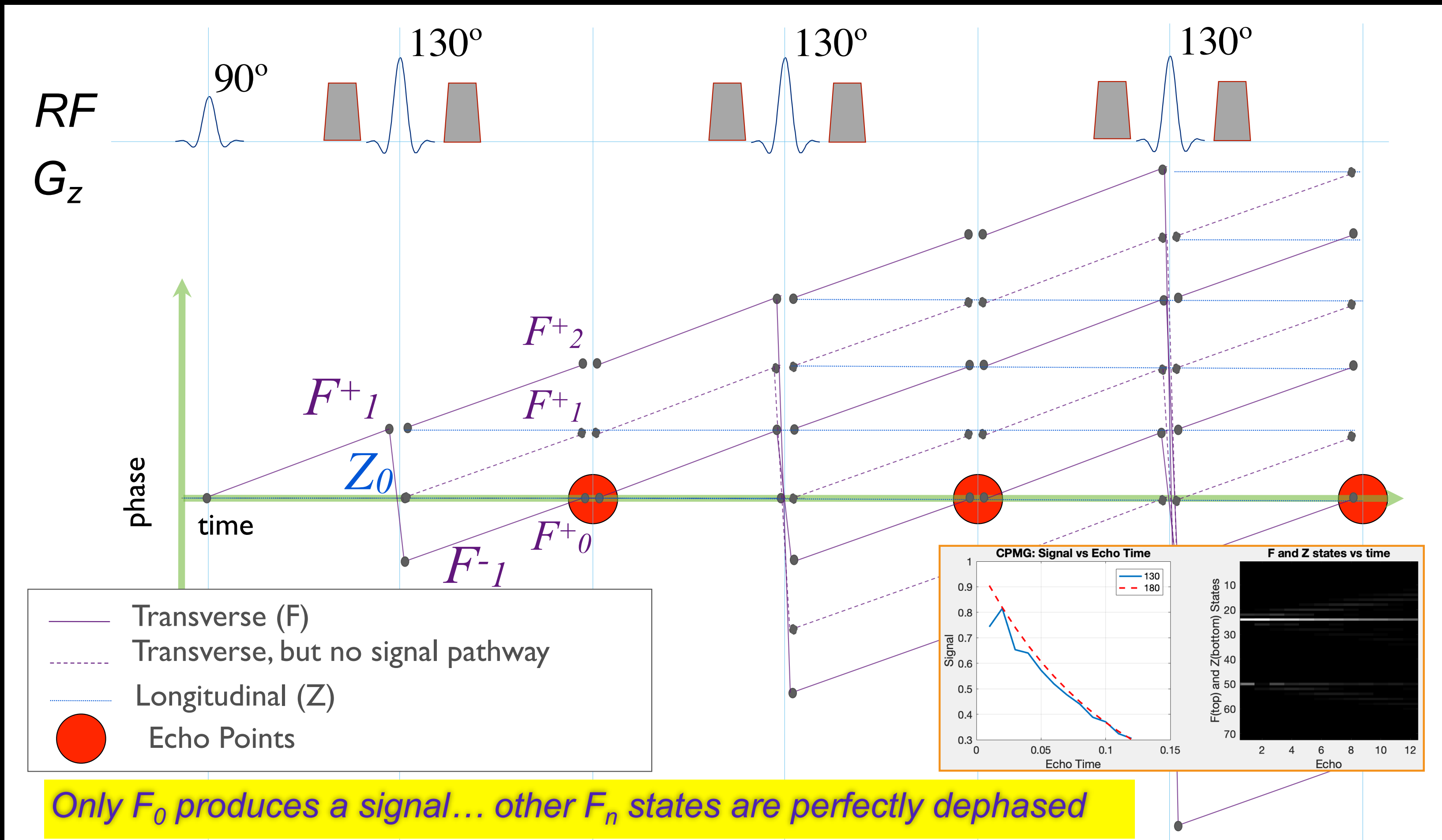
Coherence Pathways: 180° Spin Echo





With perfect 180° pulses, magnetization is fully refocused using low-order EPG states

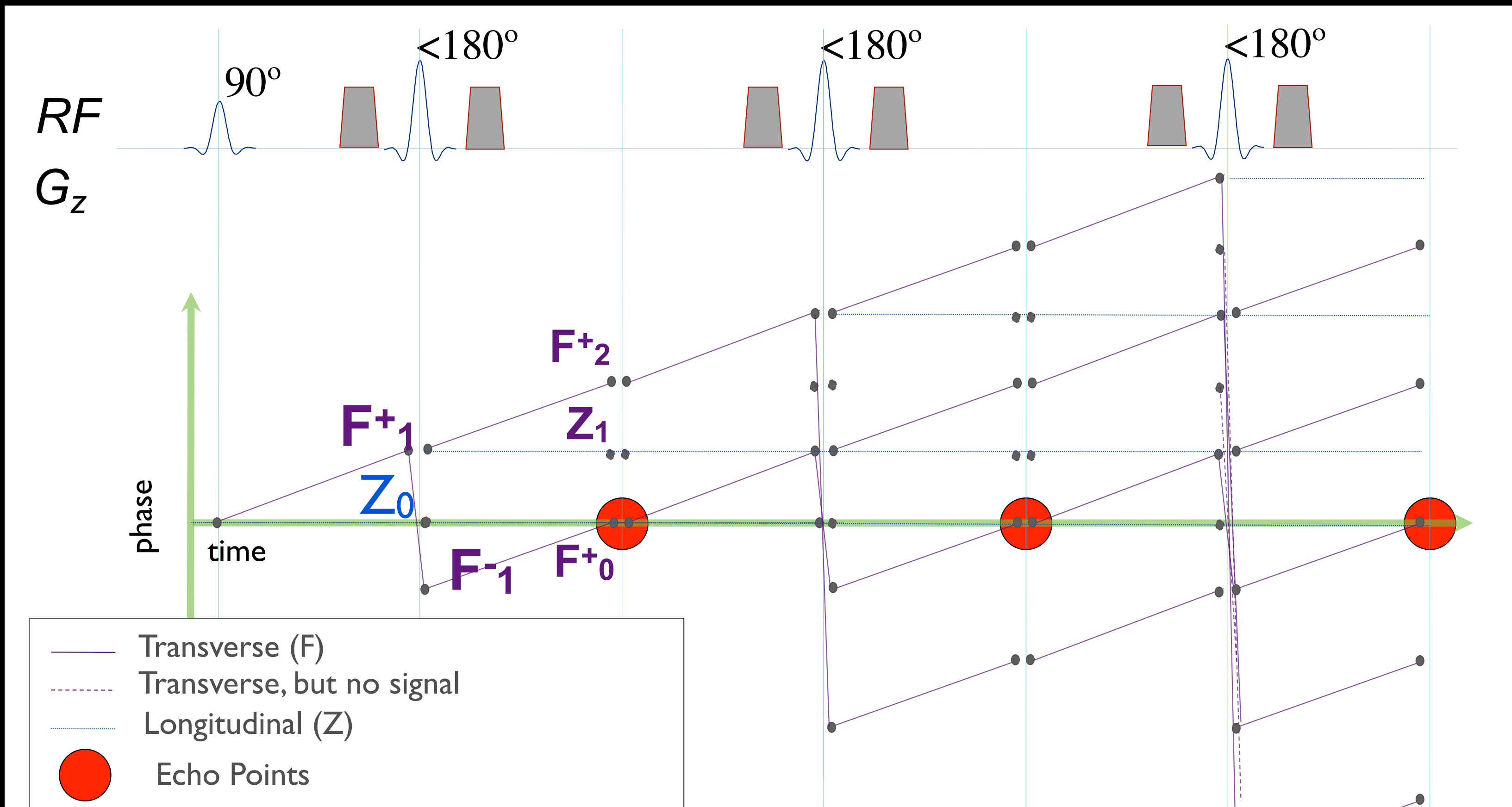
Coherences: Non-180° Spin Echo



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

When the refocusing pulse angle is reduced, higher-order EPG states and many coherence pathways exist

Effect of Crusher Pulses - Eliminate Pathways



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

Crusher pulses limit which coherence pathways produce a signal at the echo

Question 2

CPMG Sequences

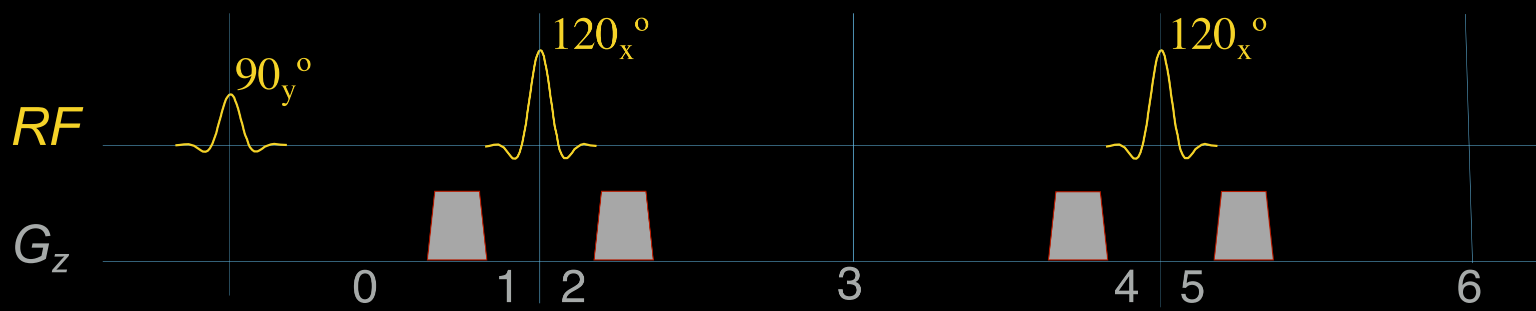
- Most spin-echo train sequences use CPMG
- CPMG = Carr Purcell Meiboom Gill
  - 90_x , 180_y , 180_y , 180_y , ...
  - 90_x , -180_x , 180_x , -180_x , ... (alternate ref. frame)
  - \- +90°, +270°, +90°
- Consider the "dephased" disc:
  – If the refocusing angle is lower, CPMG "corrects"

CPMG is a standard condition for spin-echo-train refocusing pulse phse angles

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)
```

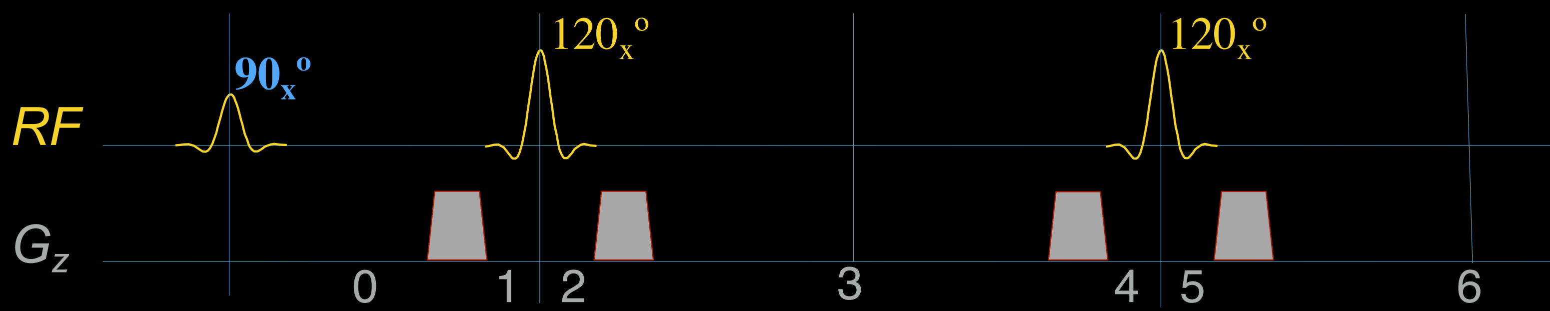
0.94 + 0.00i	0.00 + 0.00i	-0.19 + 0.00i	0.00 + 0.00i	0.06 + 0.00i
0.94 + 0.00i	0.00 + 0.00i	0.19 + 0.00i	0.00 + 0.00i	0.00 + 0.00i
0.00 + 0.00i	0.00 - 0.11i	0.00 + 0.00i	0.00 - 0.11i	0.00 + 0.00i

In CPMG, the F^{+}_{1} and Z_1 states add constructively at the refocusing pulse to F^{-}_{1}

Example: Non-CPMG

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

0	+i
0	0
0	0




```
>> 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
```

Cancellation!

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)
```

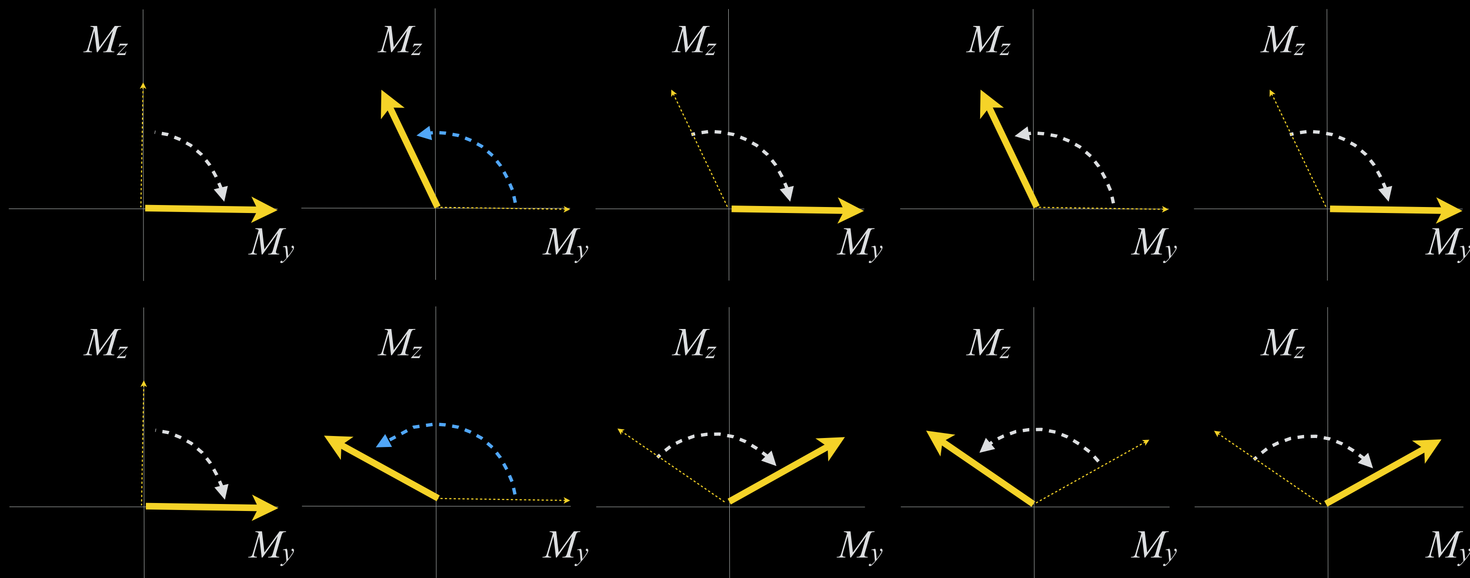
0.00 + 0.19i	0.00 + 0.00i	0.00 - 0.56i	0.00 + 0.00i	0.00 + 0.06i
0.00 - 0.19i	0.00 + 0.00i	0.00 + 0.19i	0.00 + 0.00i	0.00 + 0.00i
0.00 + 0.00i	-0.54 + 0.00i	0.00 + 0.00i	0.11 + 0.00i	0.00 + 0.00i

In non-CPMG, the F_{+1} and Z_1 states add destructively at the refocusing pulse to F_{-1}

Intuition: Stabilization Pulse

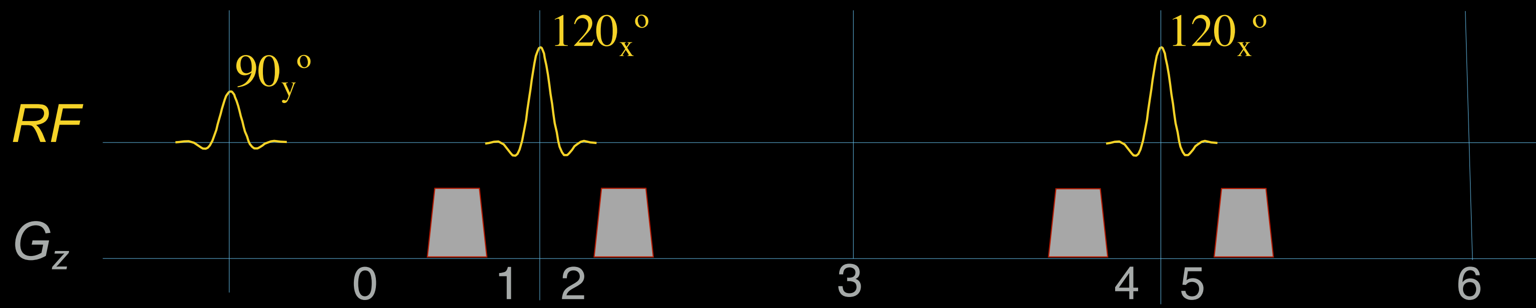
- Usually use reduced refocusing angles
  - 90_x , -120_x , 120_x , -120_x , ...
- Consider the “on-resonant” spins
  - 90_x , -150_x , 120_x , -120_x , ...

$$|\alpha_1| = 90^\circ + \frac{|\alpha_n|}{2}$$



The stabilization pulse makes the odd and even echoes more consistent (Hennig, 2000)

Example: CPMG (Same as before!)



>> 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

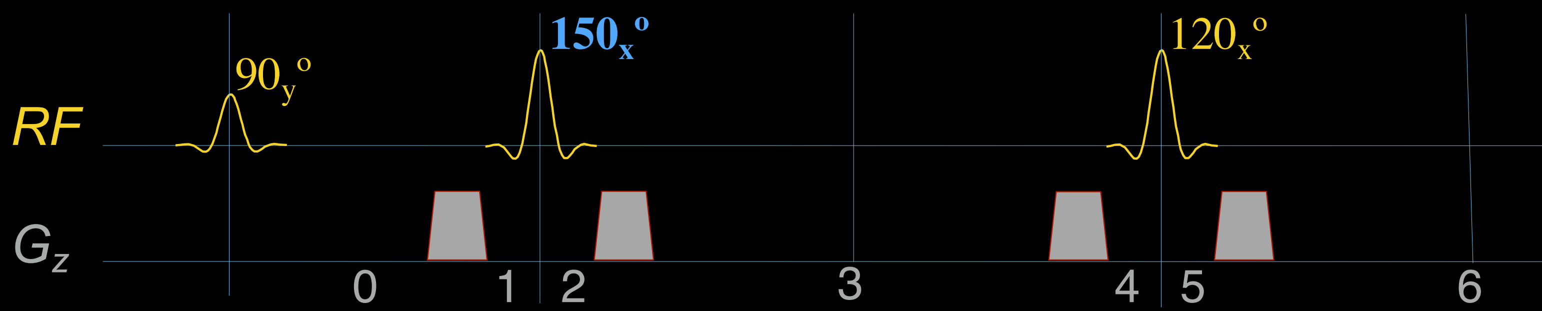
0.00 + 0.00i	-0.19 + 0.00i	0.00 + 0.00i	0.063 + 0.00i
0.00 + 0.00i	0.94 + 0.00i	0.00 + 0.00i	0.19 + 0.00i
0.00 + 0.00i	0.00 - 0.11i	0.00 + 0.00i	0.00 - 0.11i

>> 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

In CPMG, the F^{+}_{1} and Z_1 states add constructively at the refocusing pulse to F^{-}_{1}

Example: CPMG (with Stabilization)




```
>> 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

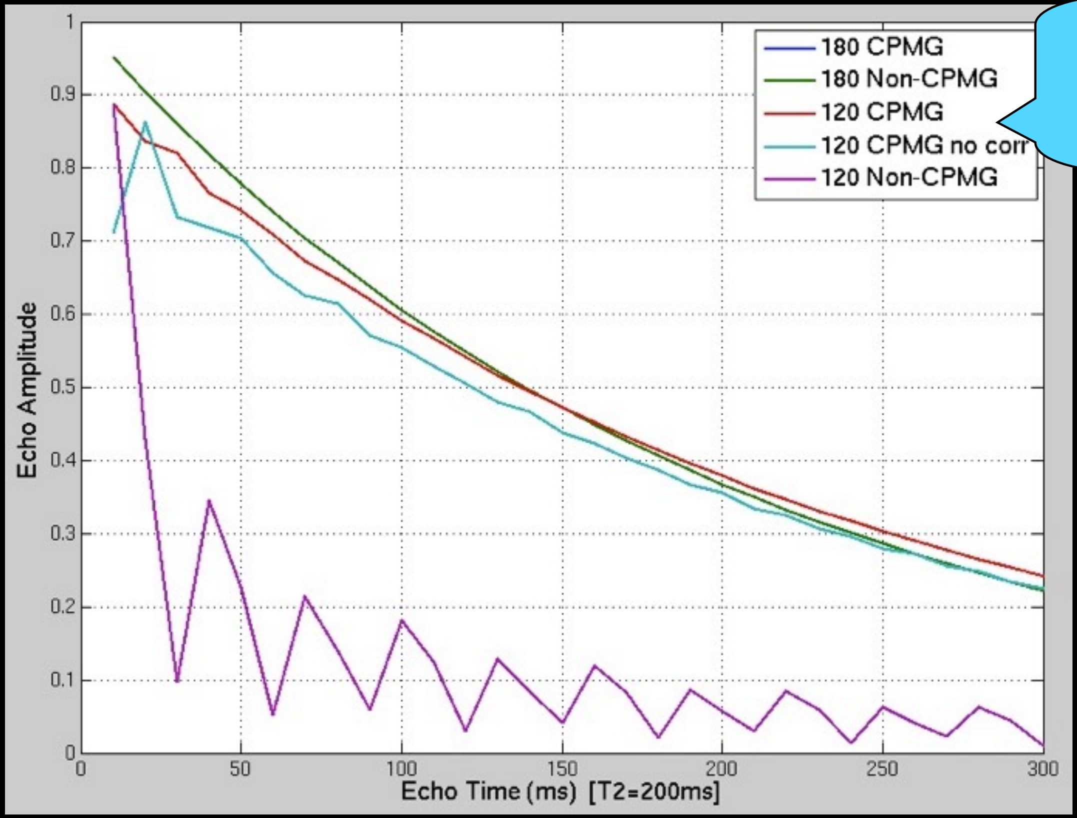
```
>> Q6 = epg_grad(Q5)
```

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

The stabilization pulse brings the odd and even echoes to similar amplitudes, and maintains low-order EPG states

Spin Echo Train Results

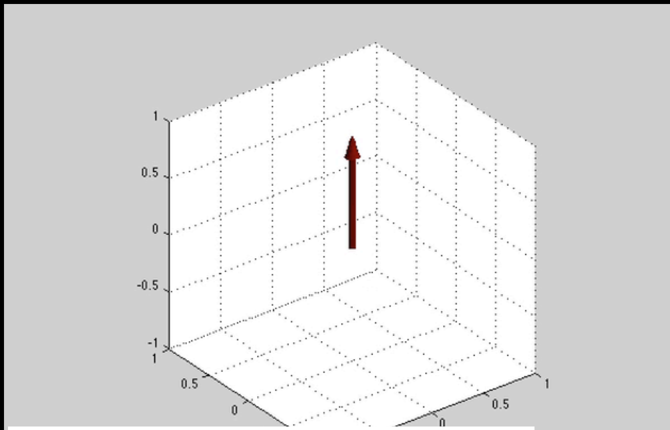
- Varying α_ϕ refocusing pulses, 10ms echo spacing



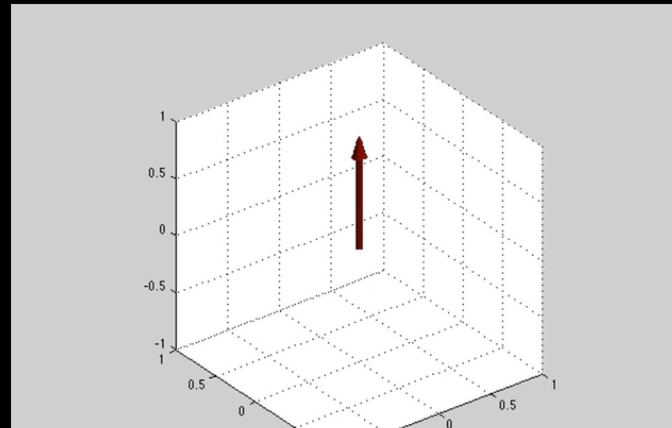
3rd line uses 90-150-120-120
4th line uses 90-120-120-120
(Hennig J et al. 2000; 44: 938)

epg_echotrain.m

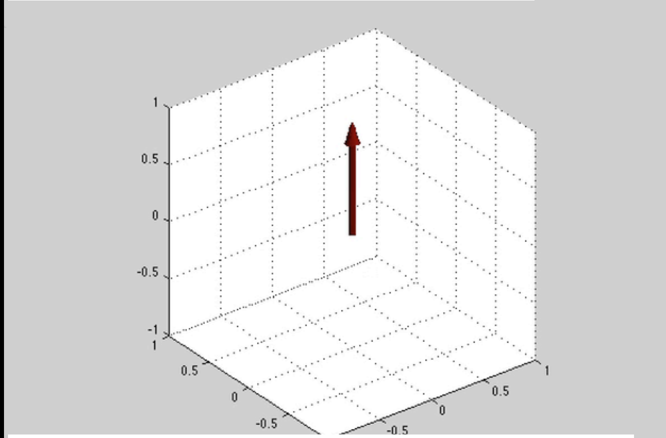
CPMG Cases: Examples



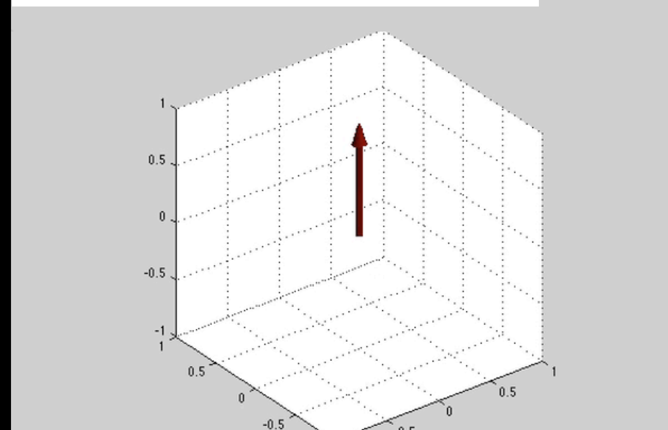
CPMG (90_{-y},120_x, 120_x, 120_x, …)



CPMG (90_{-y},150_x, 120_x, 120_x, …)



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

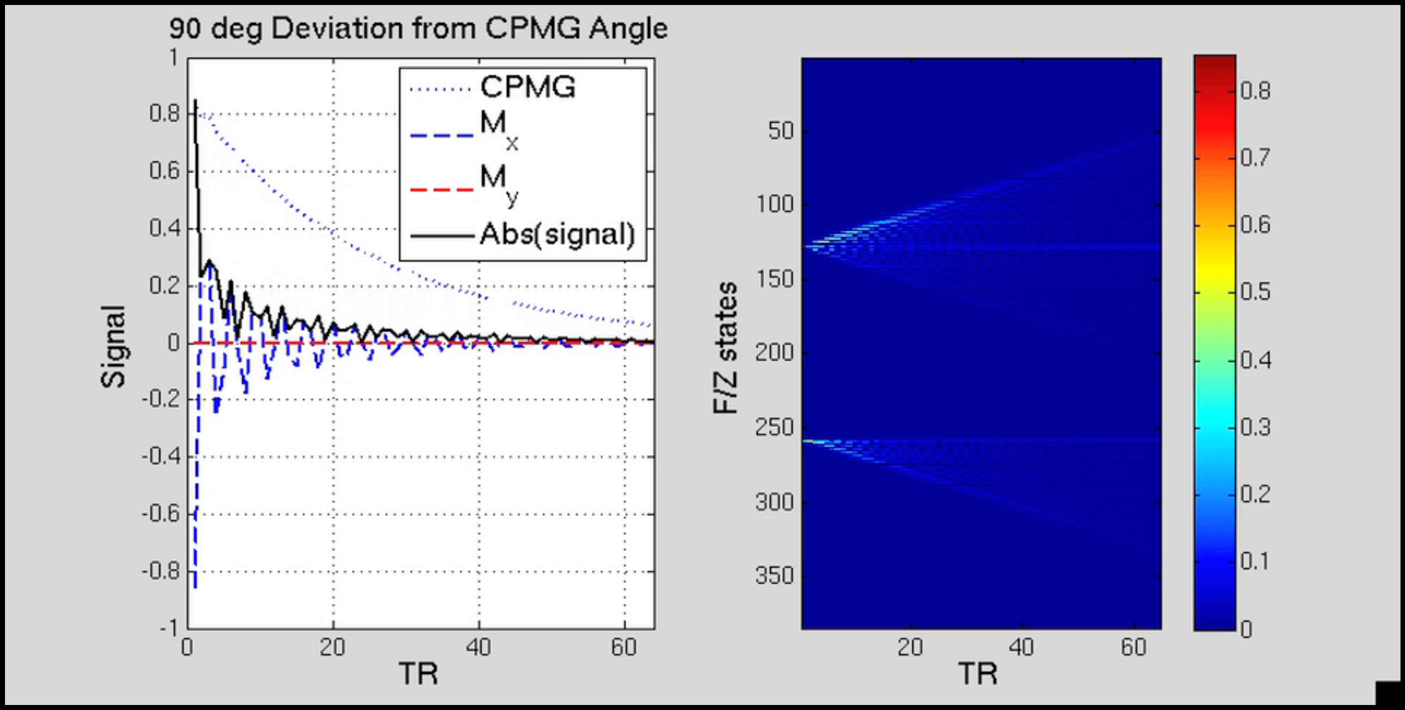


CPMG (90_{-y},-150_{-y}, $+120_{-y}$, -120_{-y}, …)

Examples of CPMG, non-CPMG, and stabilized CPMG in two reference frames

CPMG: Effect of Phase

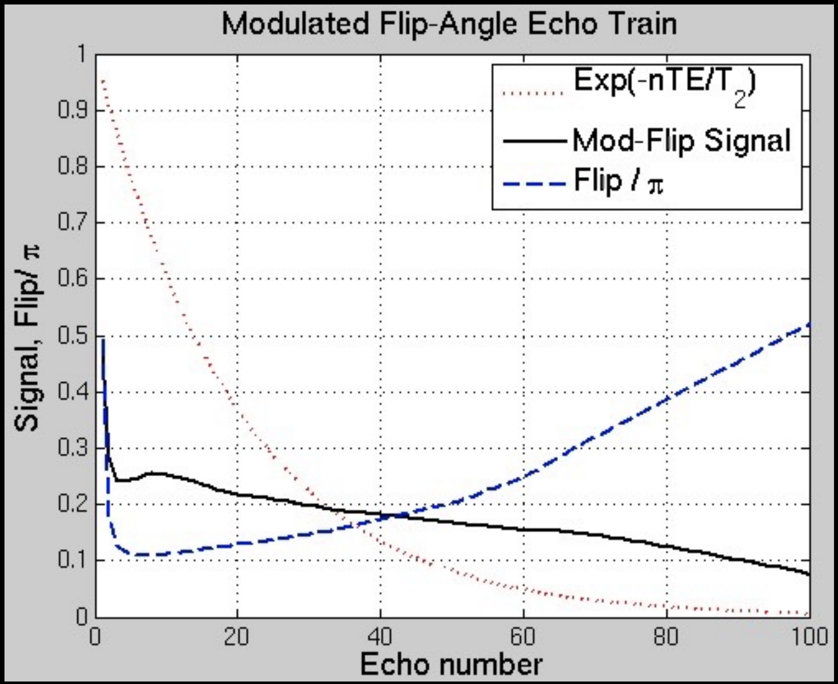
- Compares $90^o_{-\pi/2}$ - α_φ for $\varphi=[0,\pi]$ and $\alpha=105^o$
- CPMG ($\varphi=0$) shown for reference

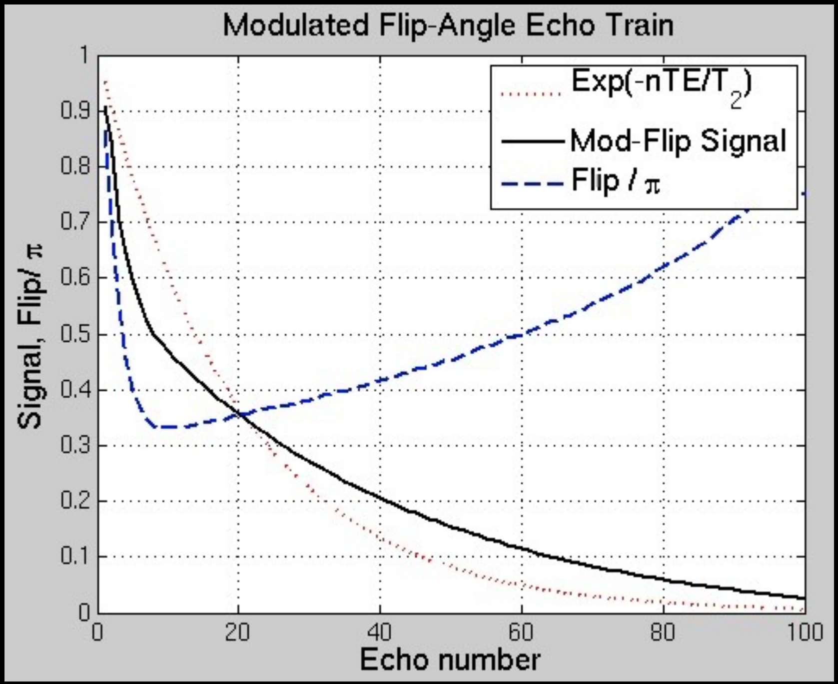


CPMG maintains spins in lower-order EPG states

Modulated Refocusing Angles

- Variable flip-angles with CPMG
- Different schemes to “optimize” signal over echo train
- AUC vs SAR vs flatness vs “extended” exponential



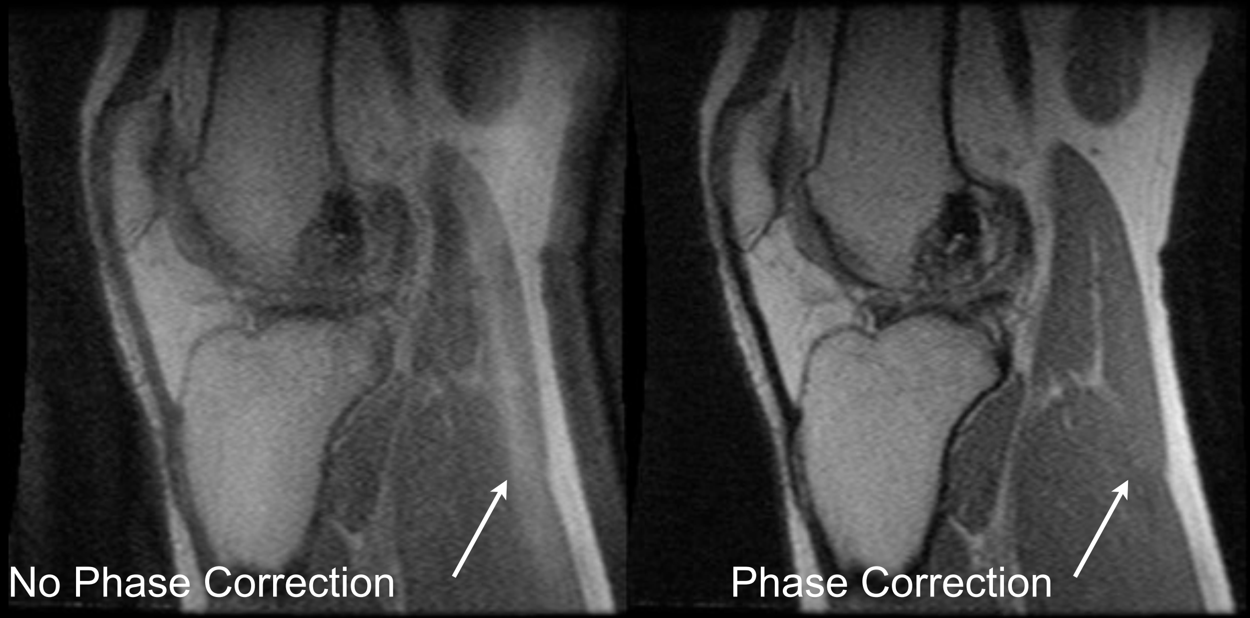


Modulating the reofcusing train will alter the echo-train signal. (Mugler 2000)

Phase Correction

- Eddy-current variations are a problem
  - Between refocusing pulses eddy currents are the same - less problematic
  - 90°-180° eddy currents differ, causing loss of the 90° phase difference for CPMG
  - Oscillation over echo train causes ghosting

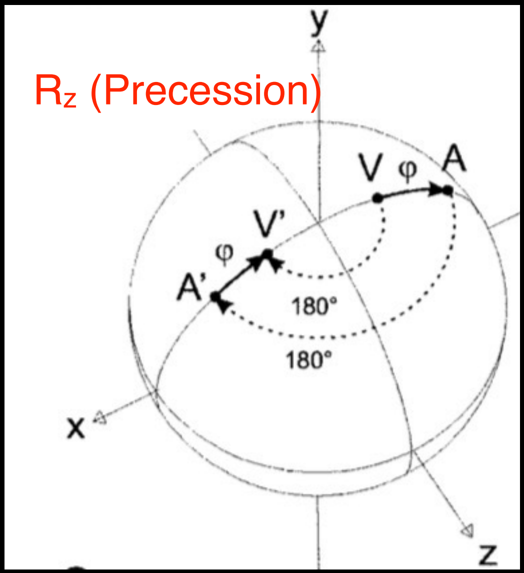
- Linear corrections by modifying G_x and G_z areas

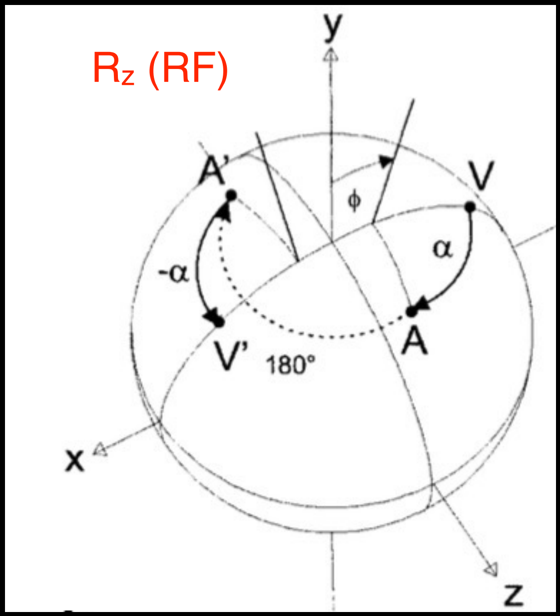


Hinks, 1993

Hyperechoes

Hennig 2001



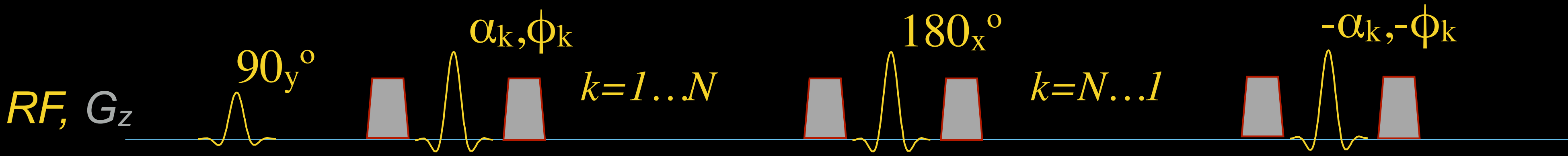


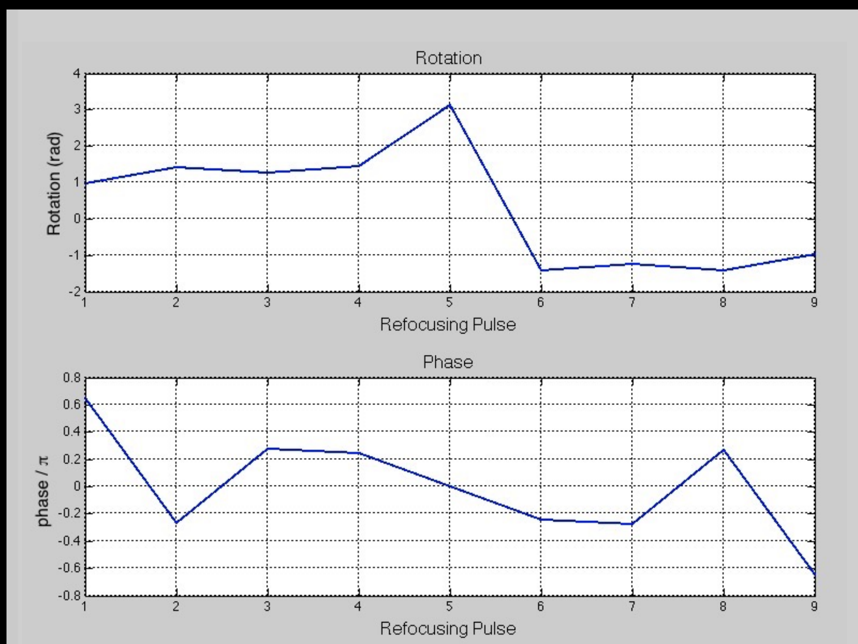
- Symmetry around $180_y°$:
  - $R_z(\beta)\ R_y(180°)\ R_z(\beta) = R_y(180°)$
  - $R_\phi(\alpha)\ R_y(180°)\ R_{-\phi}(-\alpha) = R_y(180°)$
- The following reduces to $R_x(180°)$,
  - *with ϕ defined w.r.t x*

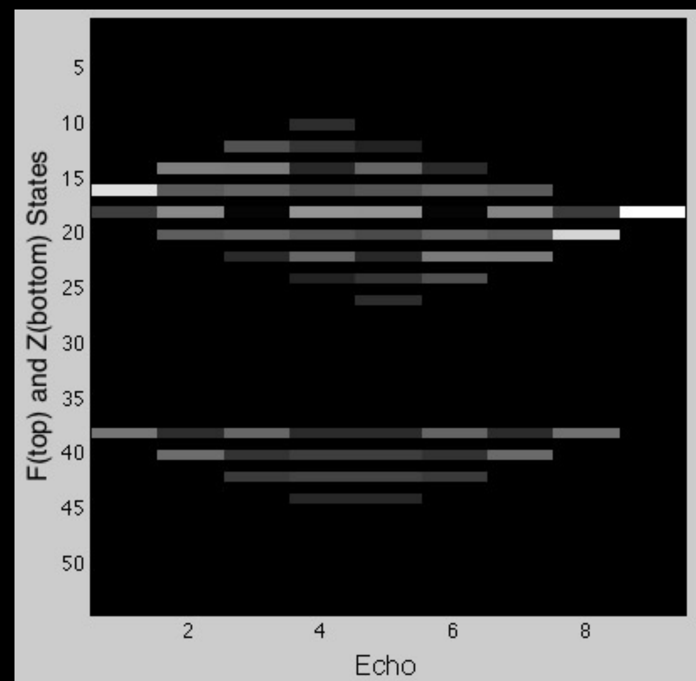
$(\alpha_1,\phi_1), (\alpha_2,\phi_2), \ldots (\alpha_N,\phi_N), (180°,0), (-\alpha_N,-\phi_N), \ldots, (-\alpha_2,-\phi_2),(-\alpha_1,-\phi_1)$

Hennig, 2001

Hyperecho Example





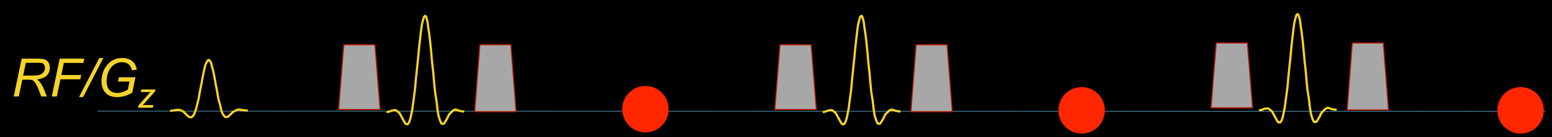


Random α, φ. N=4

Phase Diagram (epg_cpmg)

The time-reversed, conjugate-phase and opposite refocusing angles lead to a hyperecho

Summary



- CPMG: Refocusing pulses "self-correct" $90°_y, \alpha_x, \alpha_x, \alpha_x, \ldots$ or $90°_x, -\alpha_x, \alpha_x, -\alpha_x, \ldots$
- Stabilization Pulse: First refocusing pulse balances echoes
- Non-CPMG: Signal oscillates and decays quickly
- CPMG allows reduced, variable refocusing angles
- Eddy-current-induced phase can disrupt CPMG
- Hyperechoes enable reversal of reduced-refocusing-angle effects

How are spin-echo sequences related to gradient echo sequences?


Rad229 – MRI Signals and Sequences
Daniel Ennis & Brian Hargreaves
dbe@stanford.edu –or– bah@stanford.edu