Rad229 – MRI Signals and Sequences

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Lecture-9A — Gradient-Echo Sequences

Balanced-SSFP Dynamics

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Learning Objectives

- Explain geometric derivation of bSSFP dynamics
- Describe characteristics of the bSSFP signal vs frequency
- Explain phase cycling and why it is useful

Short-TR Gradient Echo

- Rapid, efficient 2D/3D imaging
- High-resolution with minimal blurring
- Steady states and equilibrium

  Pushing a swing (with friction)

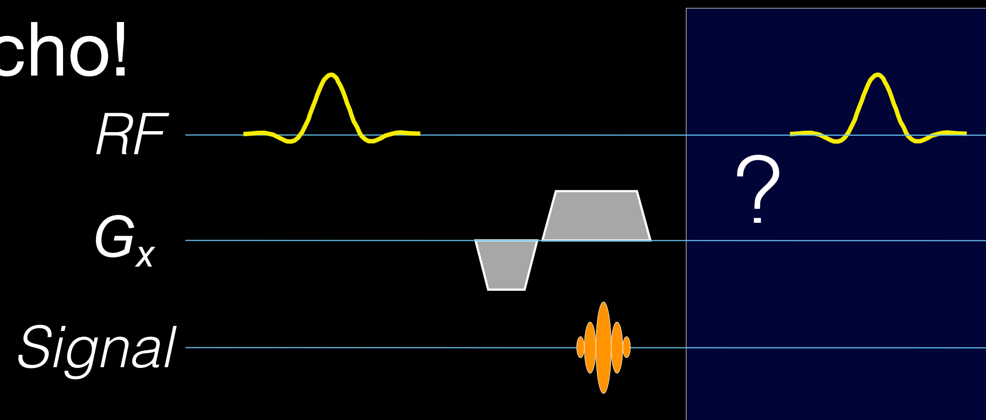
  Heating a room (with a window open)

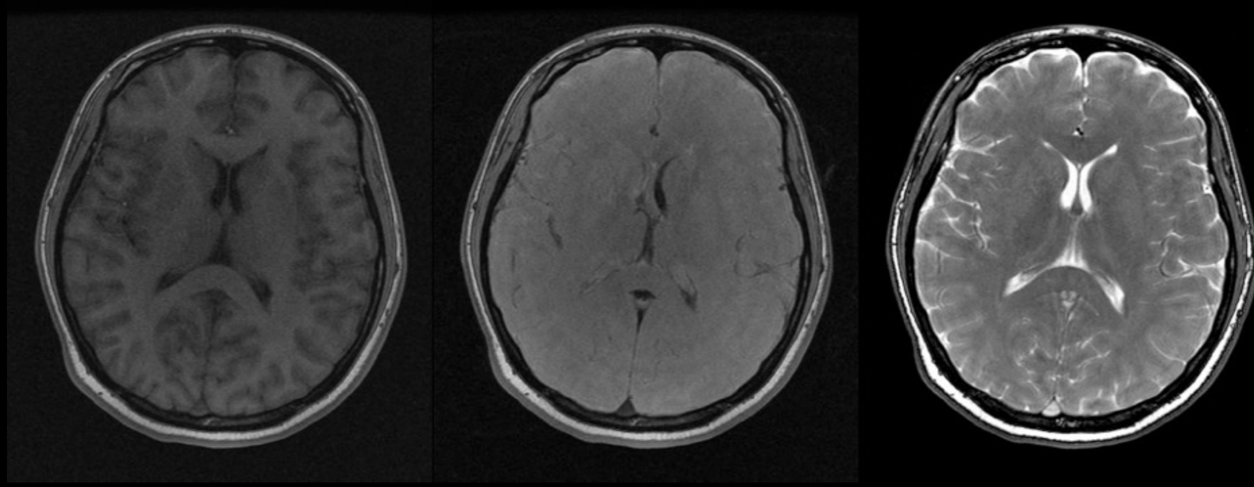
  Exciting magnetization (with relaxation)

Short TR sequences require consideration of steady states

Outline: Gradient Echo Sequences

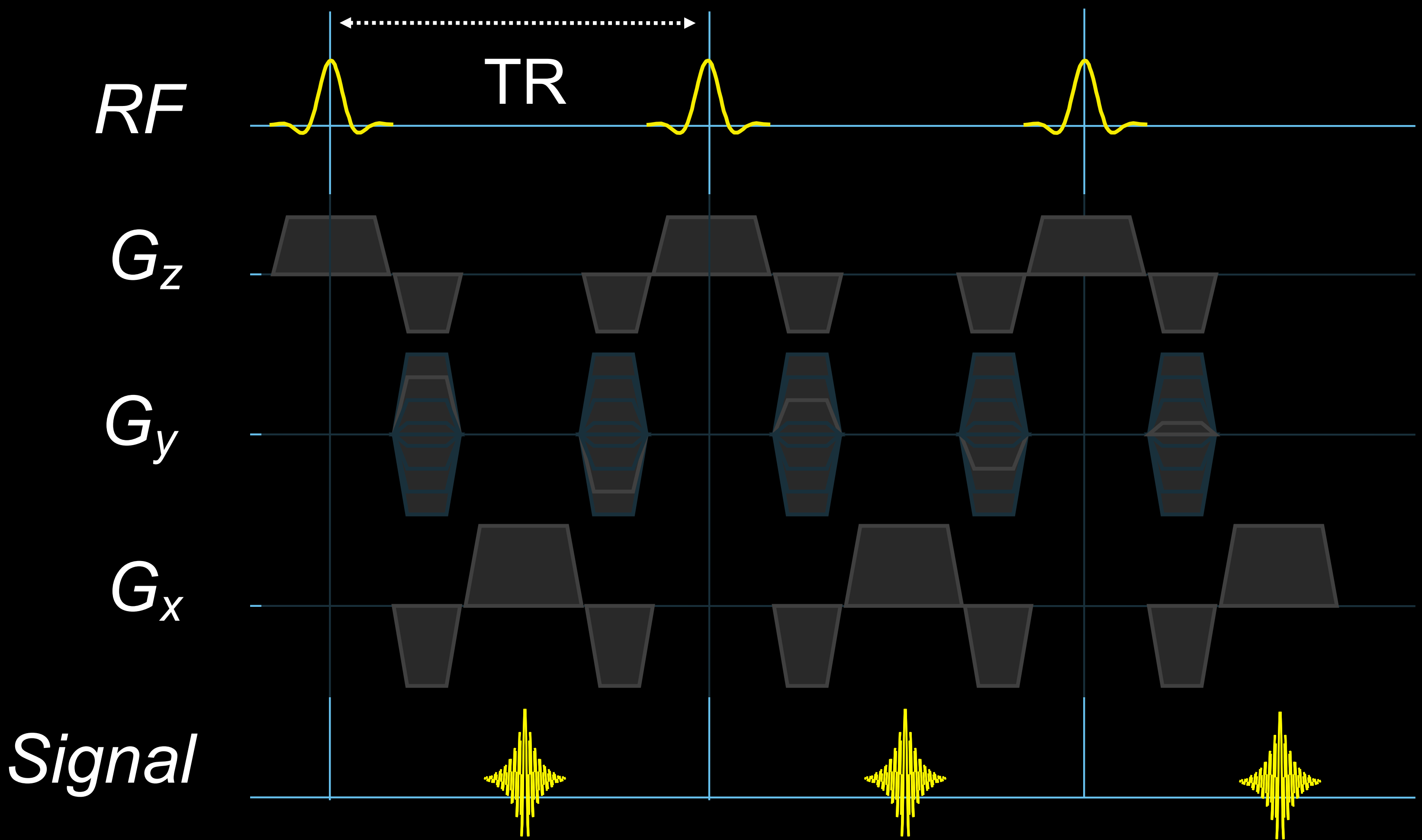
- Gradient Echo = No spin echo!
- Spoiling Types
- Properties





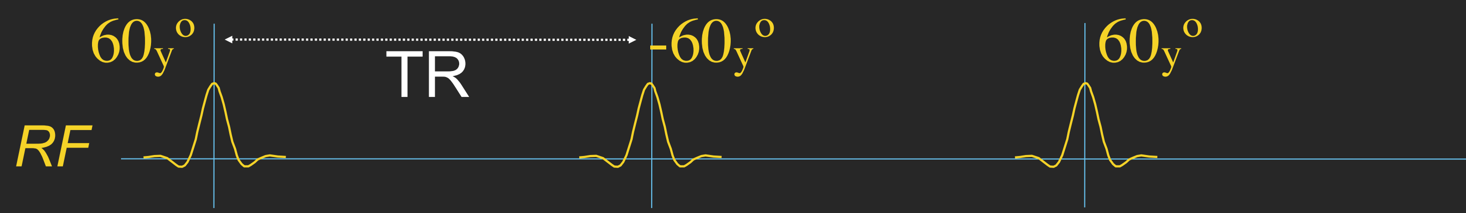
Contrast is based primarily on the end-of-TR action

Balanced Steady-State Free Precession (bSSFP)



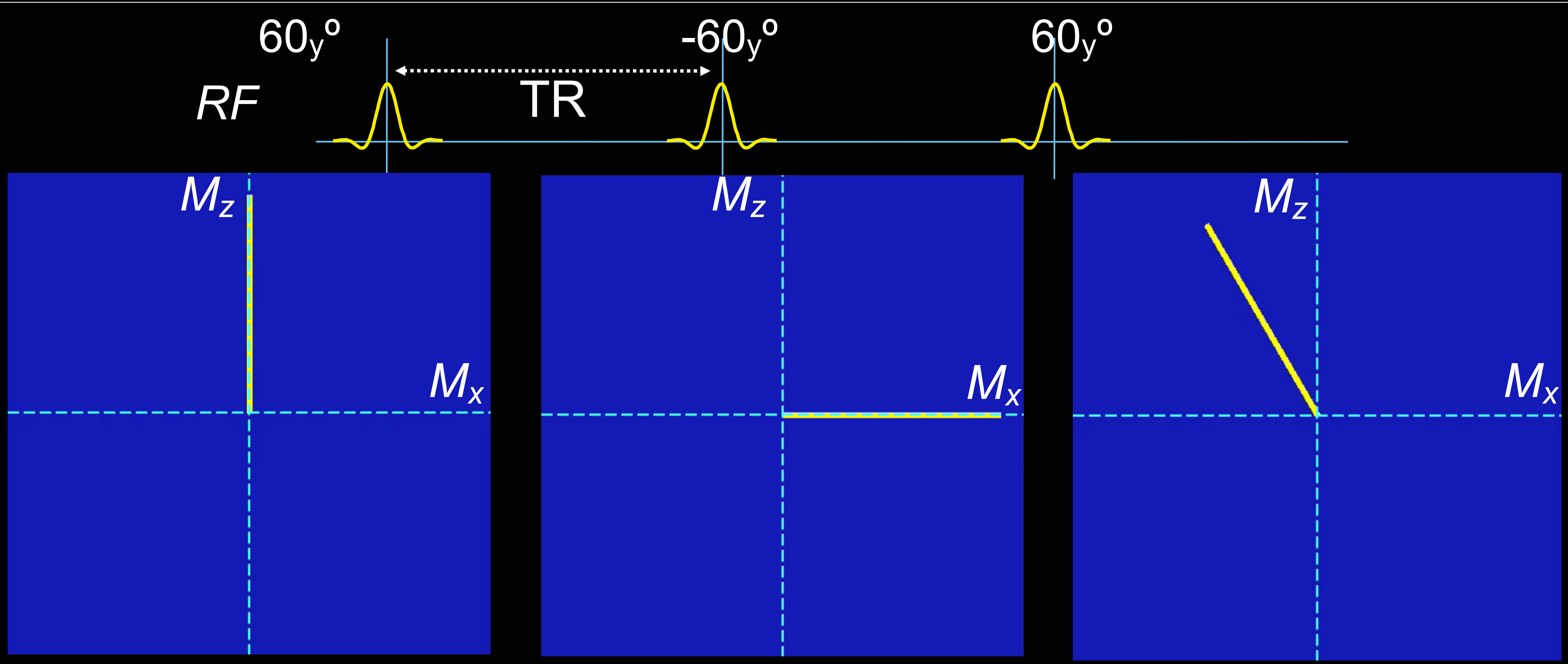
In balanced SSFP, all gradients are designed to have zero area over TR

Question 1: Balanced SSFP



- What do you think happens here?

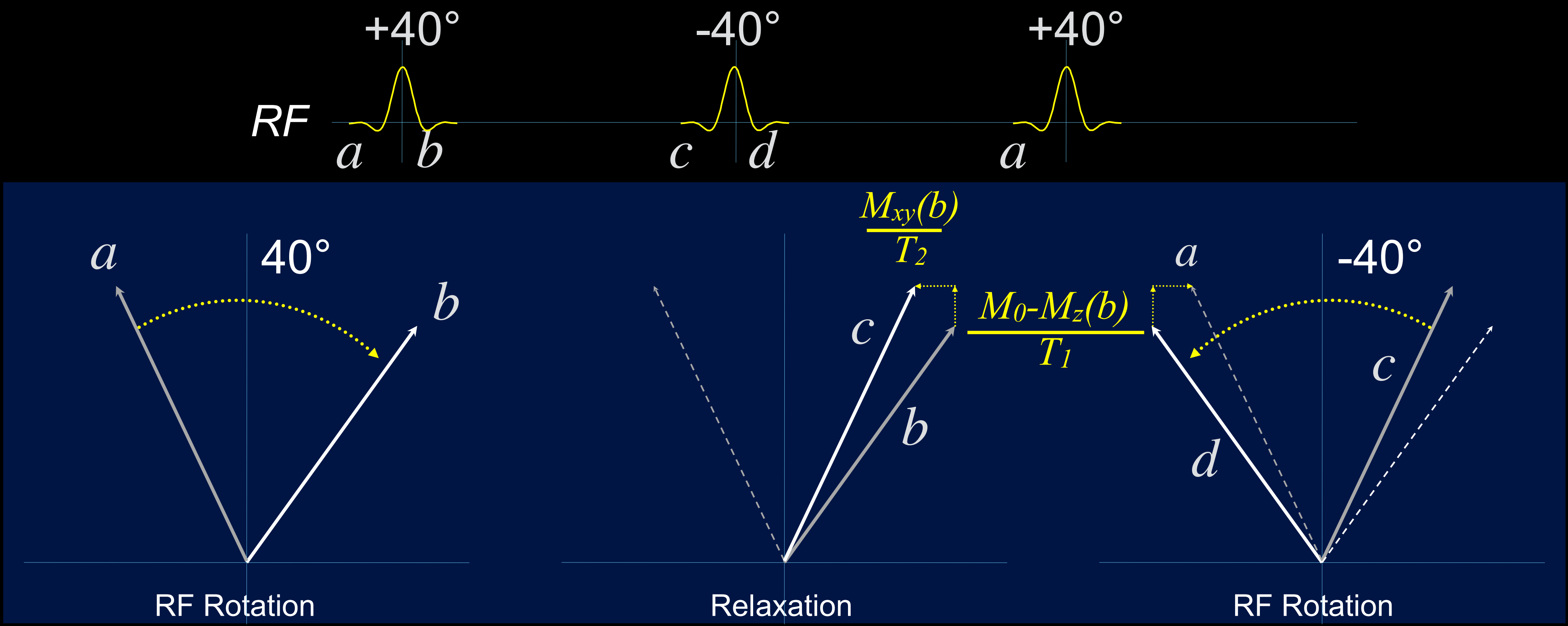
Balanced SSFP: Steady State Formation



- Same unique periodic steady state
- Transient paths differ based on initial state

After many sequence repetitions a steady state forms

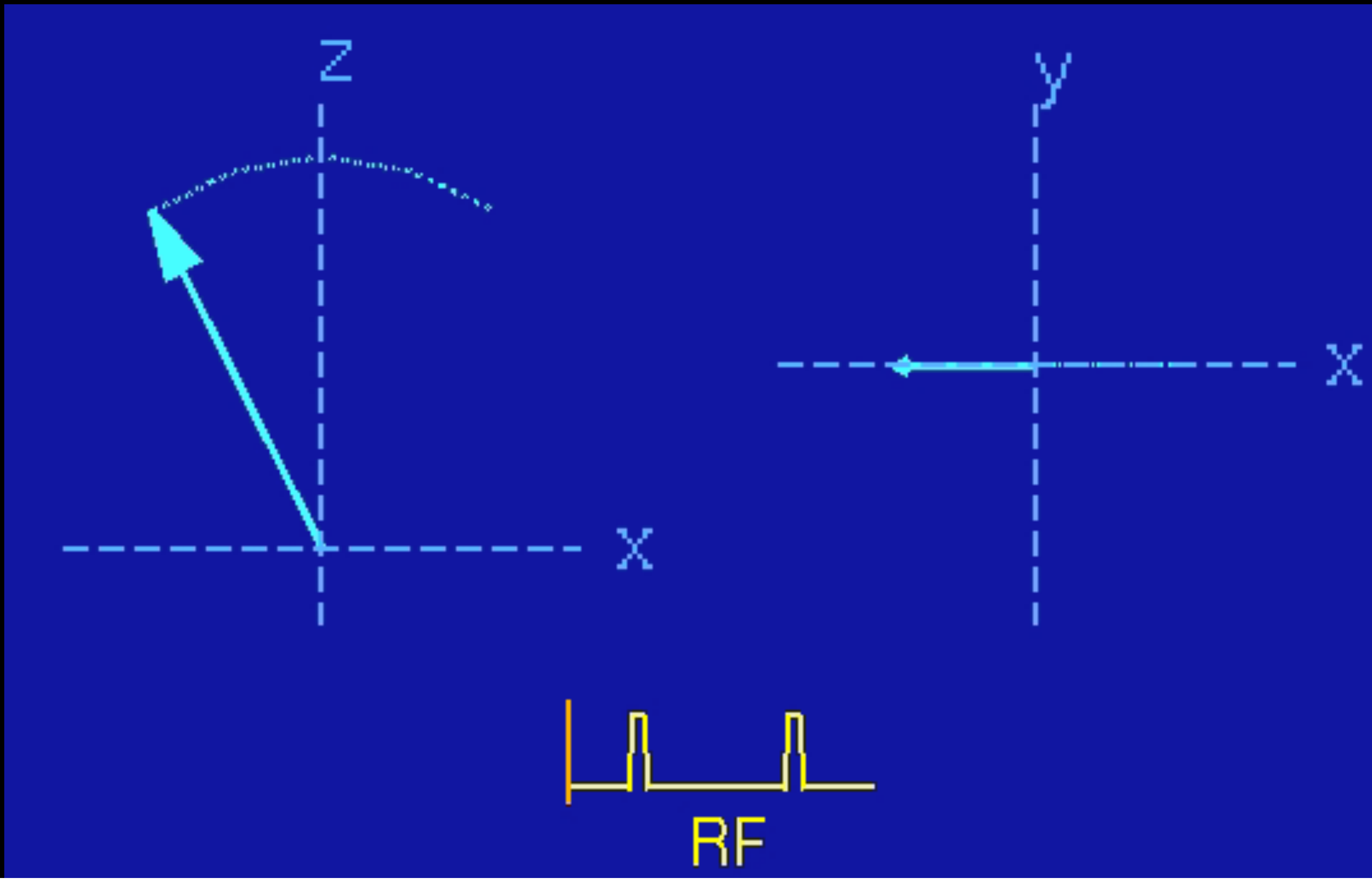
Simple Case: No precession



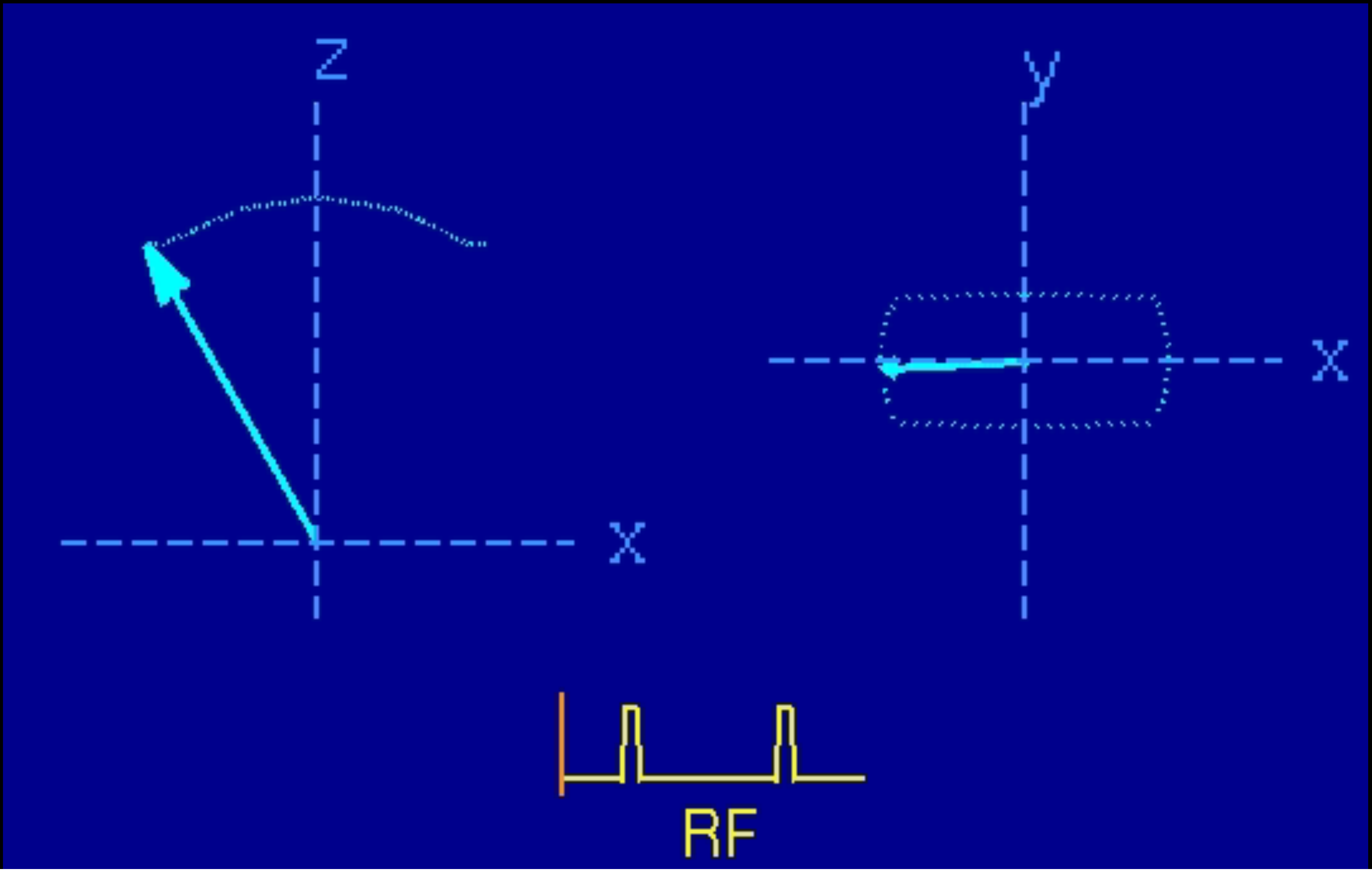
- Intuition: Relaxation does not affect direction much
- RF rotations must balance each other

Basic intuition is that we tip back-and-forth in the steady-state, with small changes based on the Bloch equation

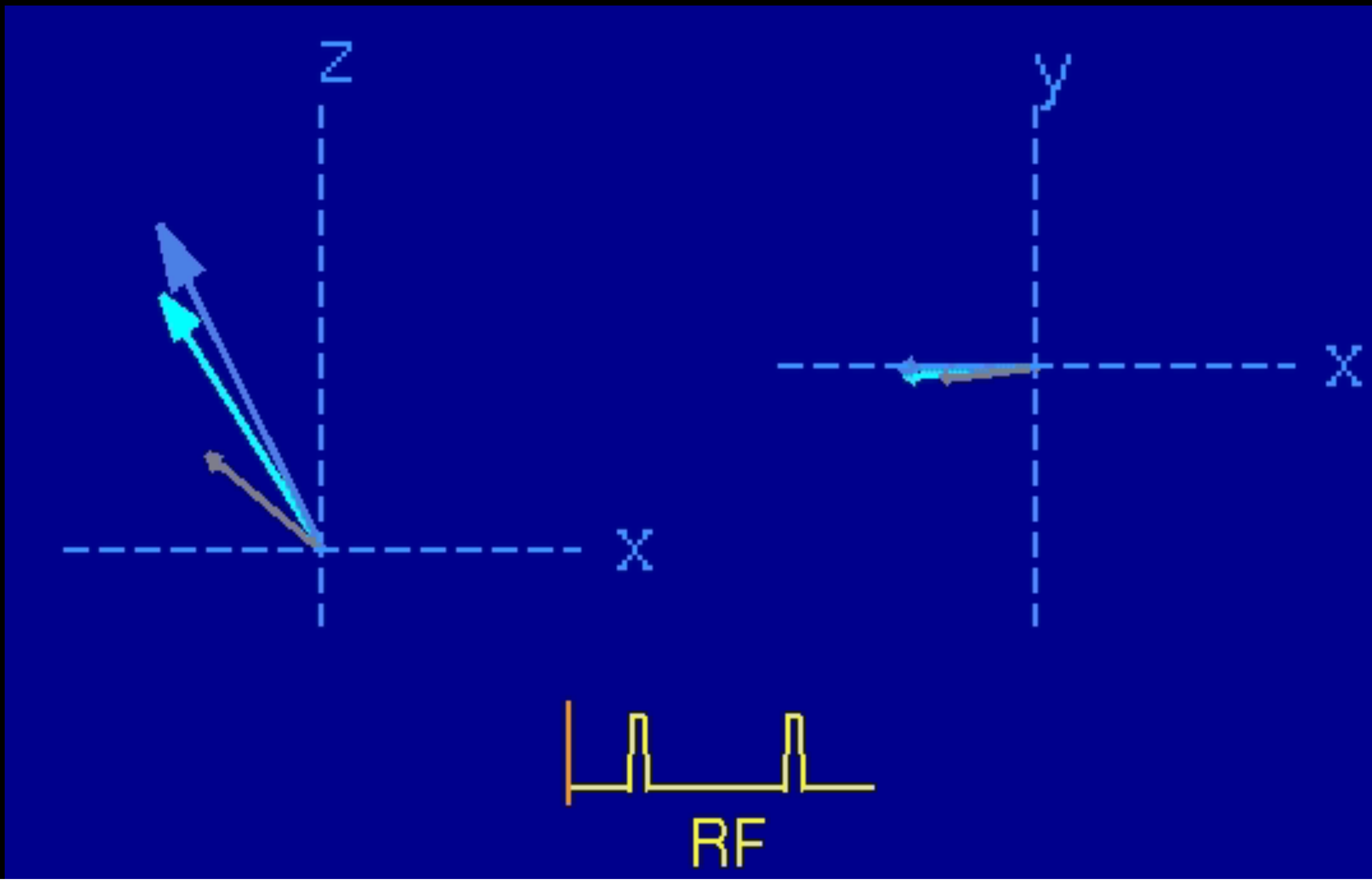
Steady State: No Precession



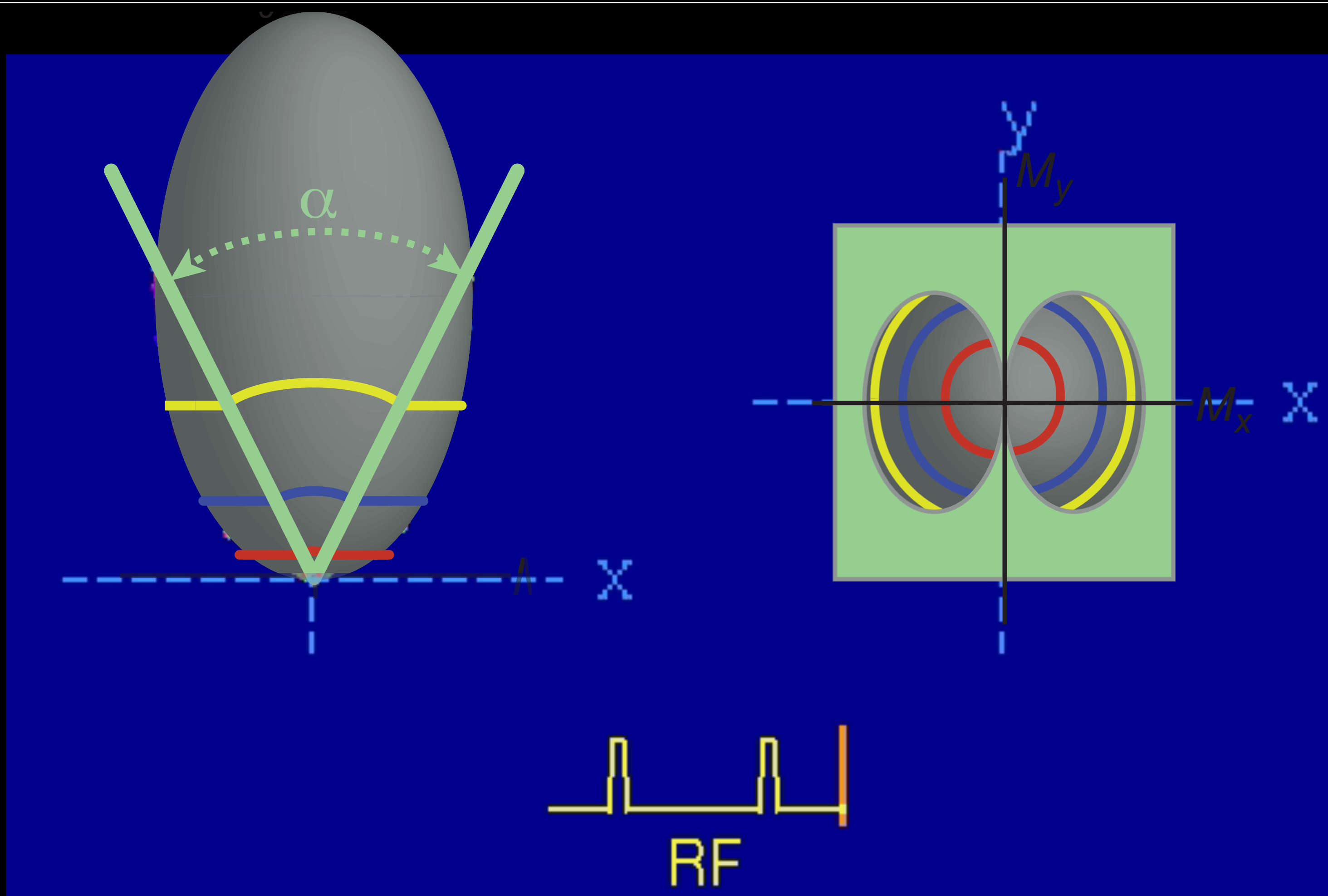
Off-Resonance: Precession



Increasing Precession



Full Frequency Distribution



The mangetization moves on the surface of an ellipsoid, with the RF flipping between 2 planes an angle α apart

Signal Solution - On Resonance

- Relaxation does not change length:

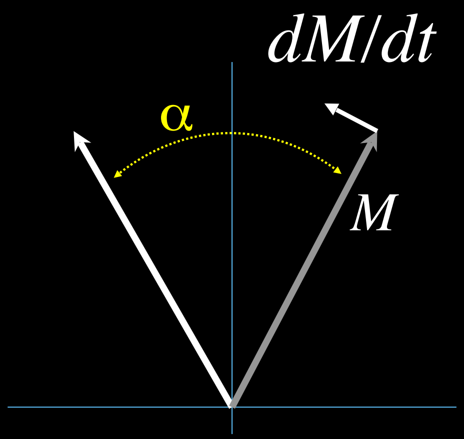
$$dM/dt \cdot M = 0$$

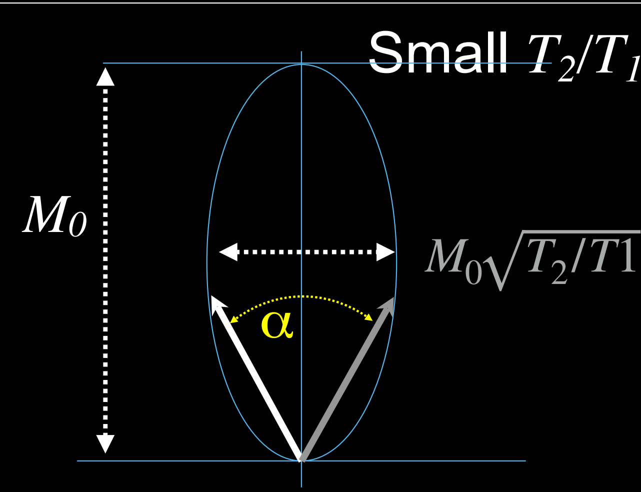
Substitute from Bloch equation:

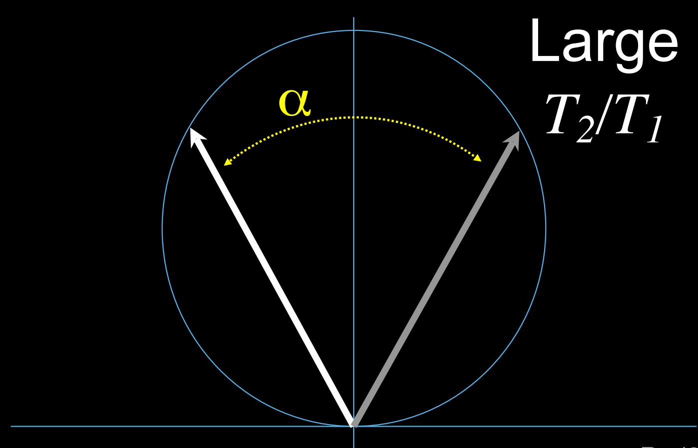
$$\frac{-M_x^2 - M_y^2}{T_2} + \frac{M_0 - M_z}{T_1} M_z = 0$$

Multiply by T_1 and rearrange:

$$\left(M_z - \frac{M_0}{2}\right)^2 + \frac{M_x^2 + M_y^2}{T_2/T_1} = \left(\frac{M_0}{2}\right)^2$$







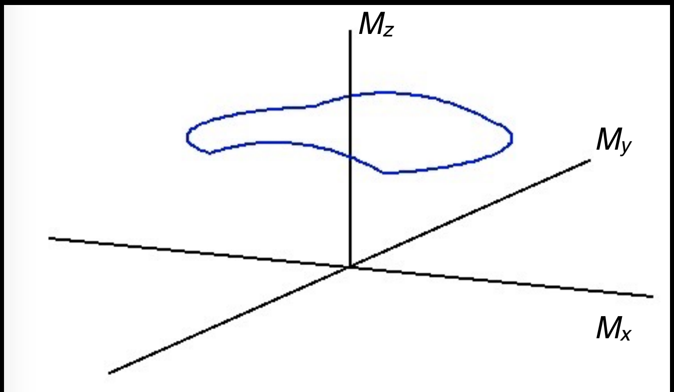
- Ellipse, eccentricity $\sqrt{T_2/T_1}$, width $M_0/2\sqrt{T_2/T1}$
- Intersection based on α
- T_2/T_1 contrast

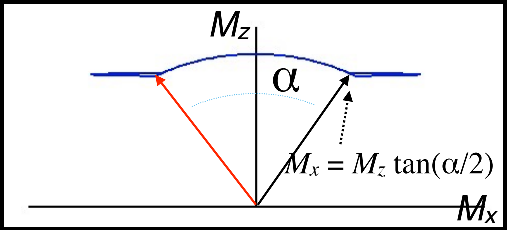
Assuming the magnetization length does not change leads to an ellipsoid solution for the signal. Hargreaves, JMRI 2012

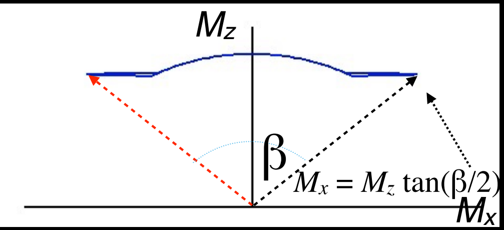
Question 2: Signal levels

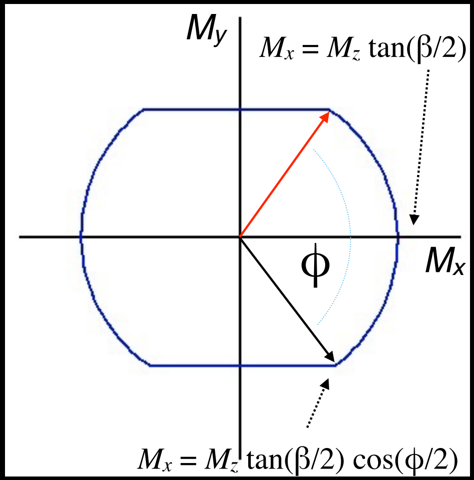
RF Nutation and Precession

- RF is balanced by relaxation and precession
- Length is still relatively unchanged over TR
- Ignore relaxation for now…





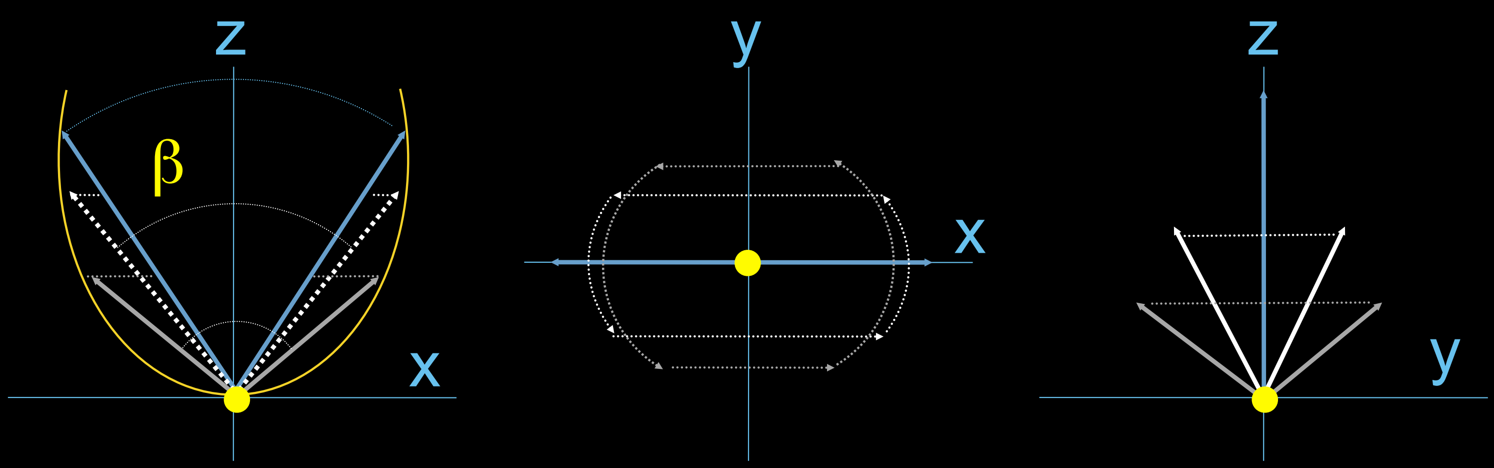




$$\tan(\alpha/2) = \tan(\beta/2)\cos(\phi/2)$$

Schmitt MRM 2006, Zun, ISMRM 2006

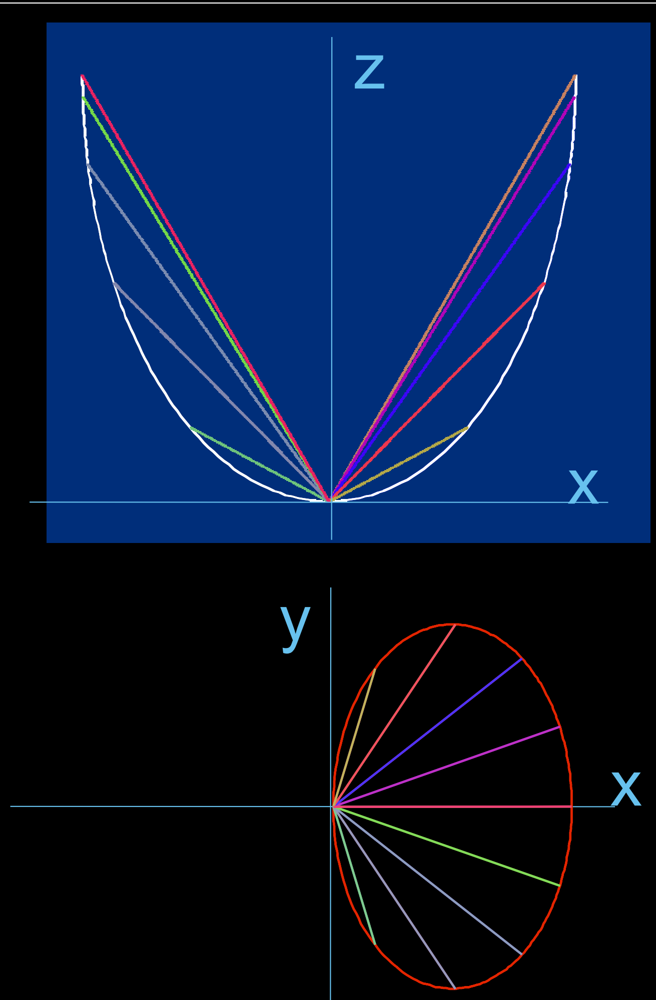
Precession and "Effective flip angle"

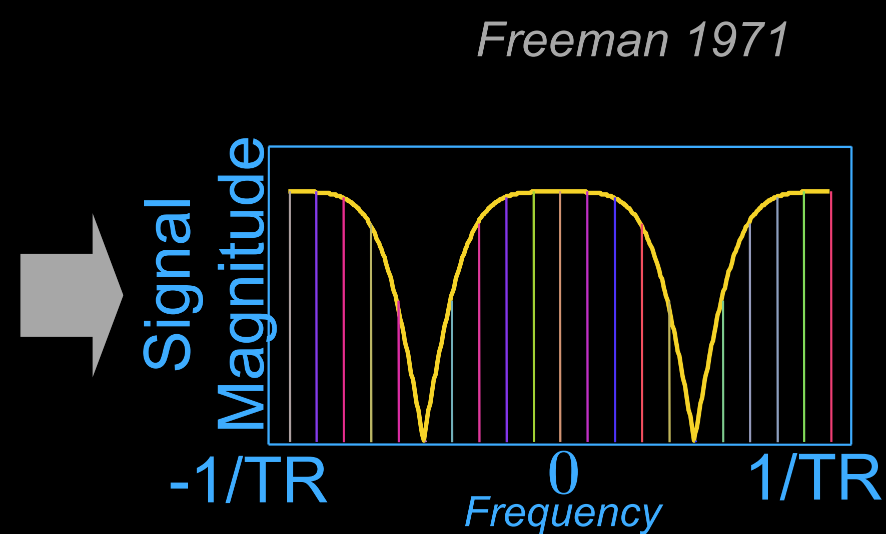


- $\tan(\alpha/2) = \tan(\beta/2)\cos(\phi/2)$ $(\beta >= \alpha)$
- Larger precession (ϕ) gives a larger "effective flip," β
- Can replace flip (α) with effective flip (β) for all calculations
- Limiting case (•) where $\beta = 180°$

Schmitt MRM 2006, Zun, ISMRM 2006

Signal vs Precession/Frequency



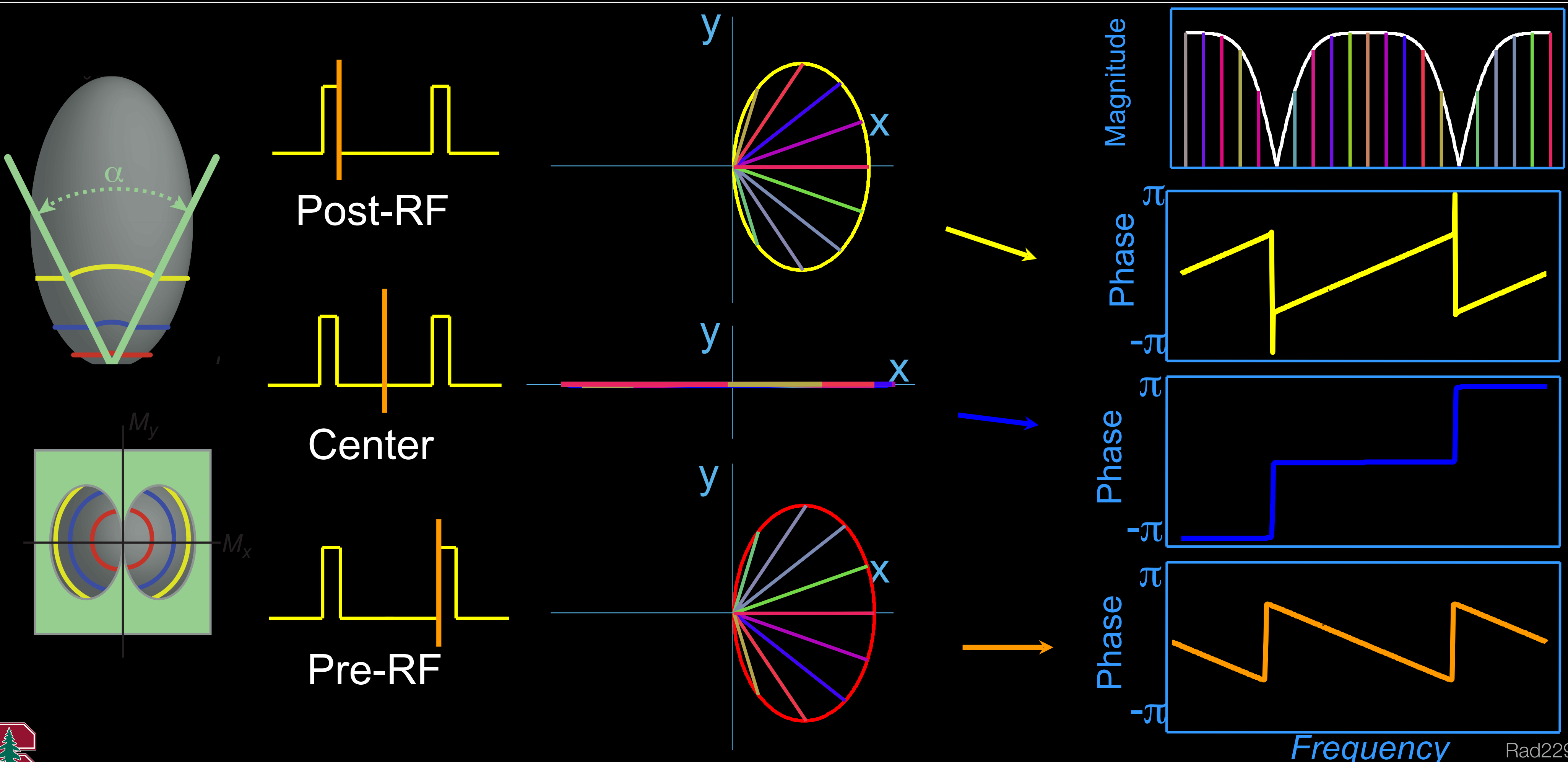


Signal depends on many factors:

- *Resonant frequency*
- T1, T2 (contrast)
- RF flip / phase
- TR, TE

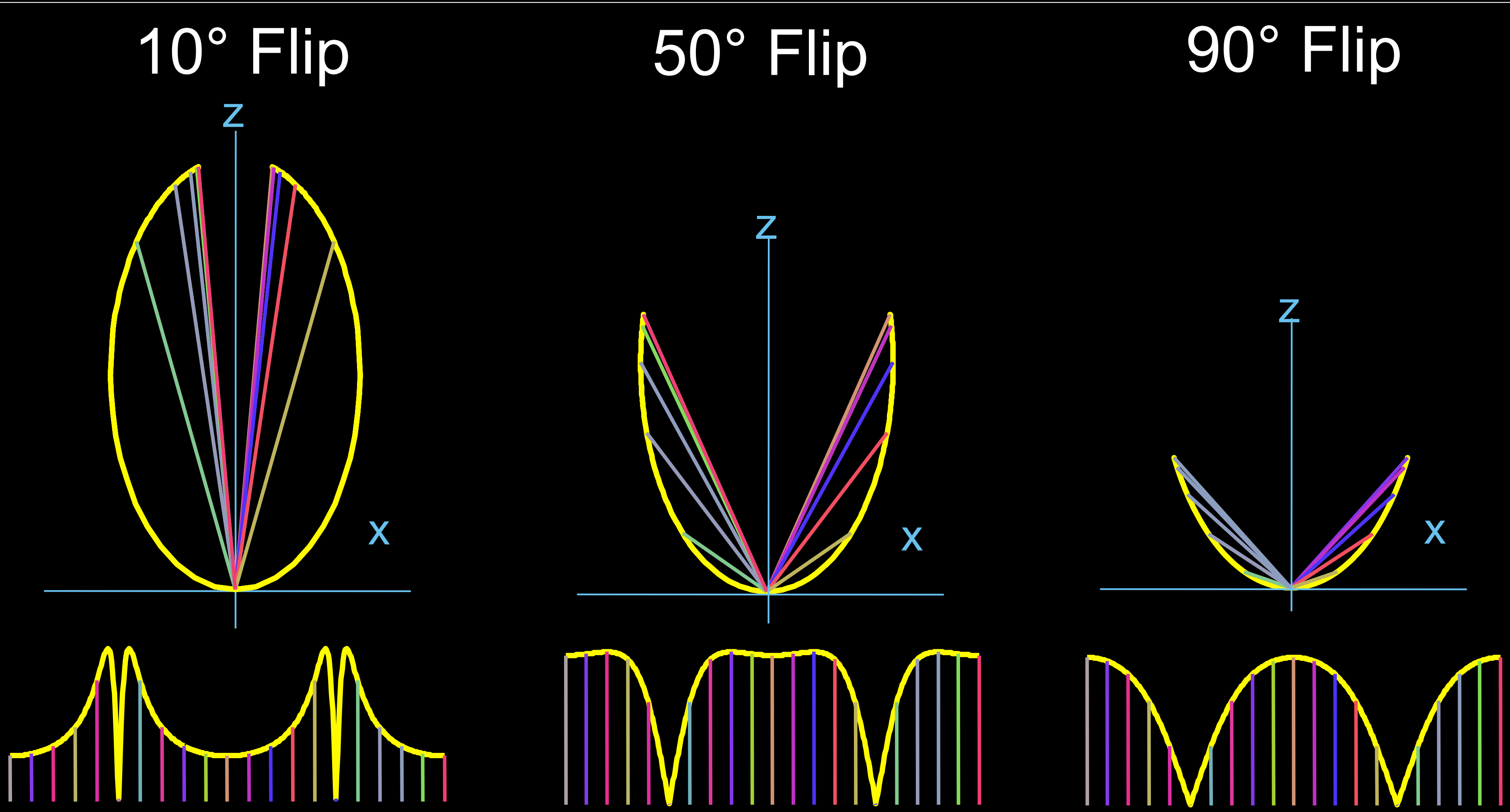
As |ϕ| the steady-state moves down the ellipsoid. We can plot signal vs frequency (ϕ/TR)

Signal vs Frequency: Phase



The transverse mangetization moves from an elliptical to refocused to elliptical distribution over TR

Flip Angle Effects



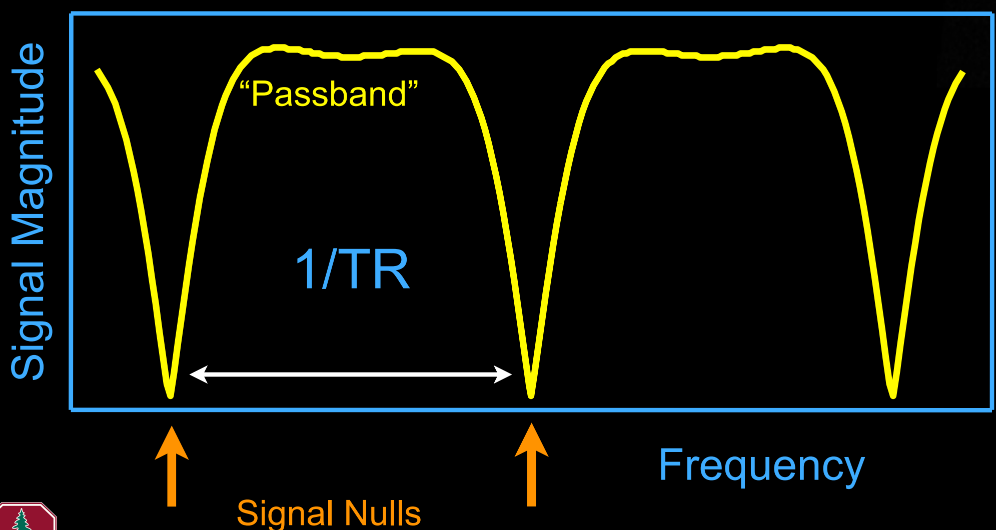
As the flip angle increases, less of the ellipsoid is used and the signal does not always reach the peak

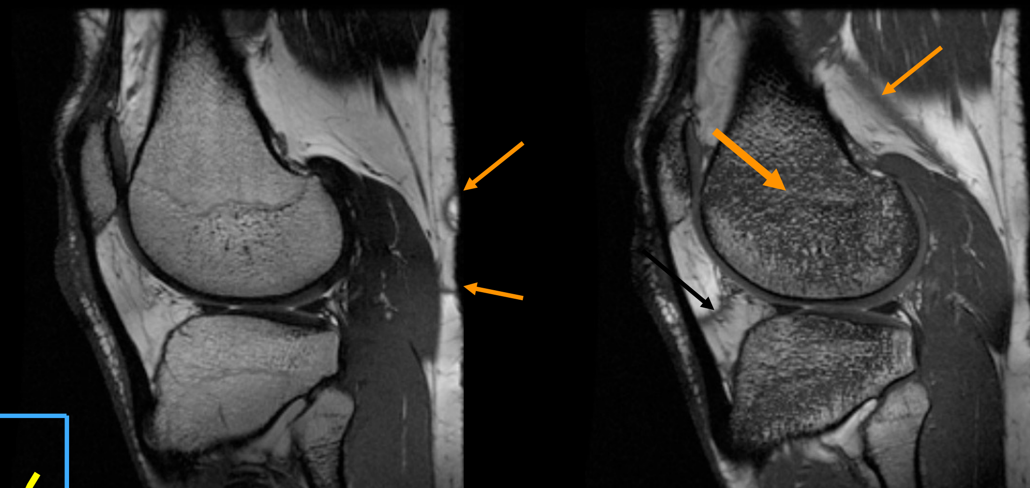
bSSFP Dark Bands

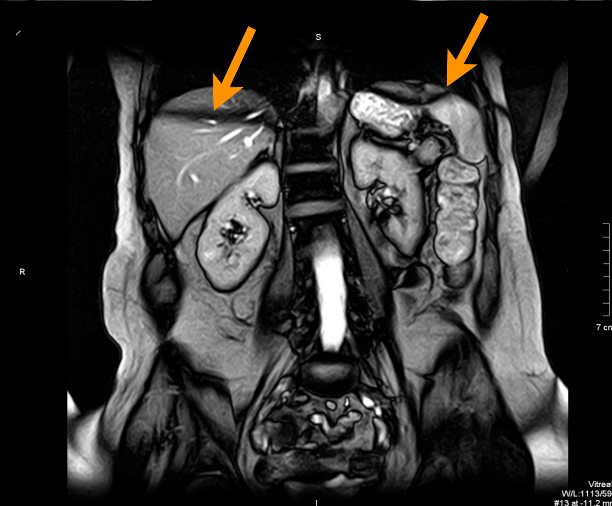
- Must limit precession:

  Short TR

- Limits resolution

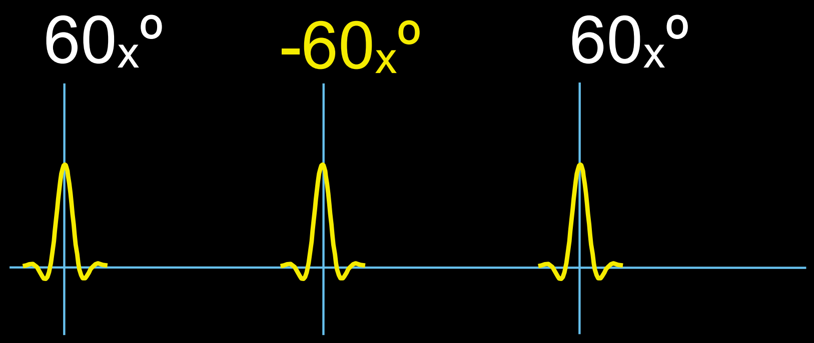


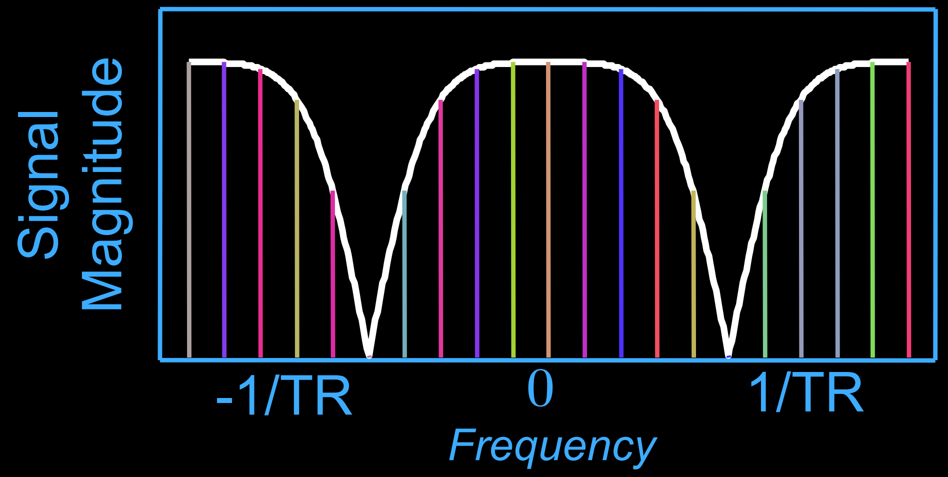


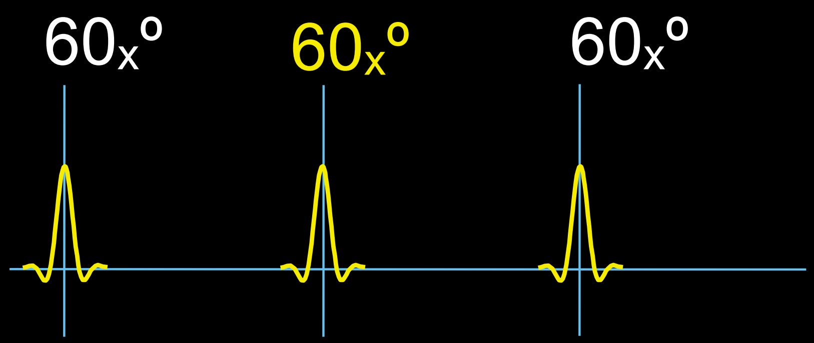


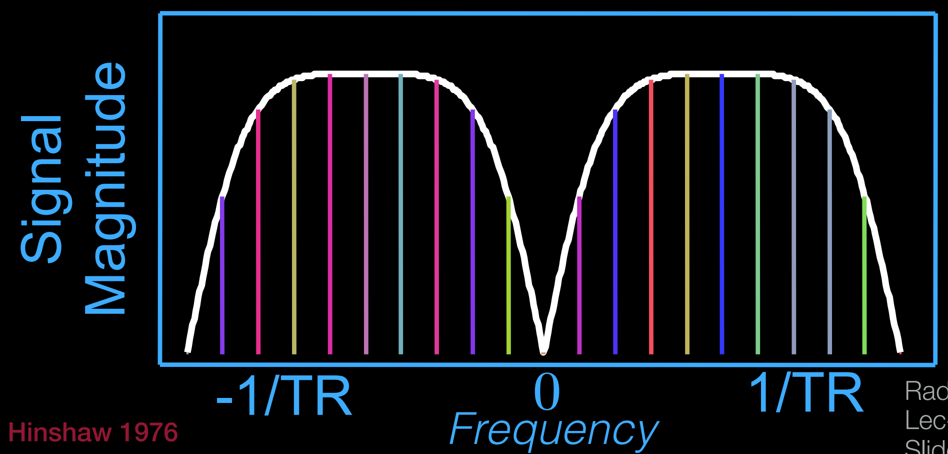
The signal-vs-frequency variation causes dark bands. Freeman 1971

Phase Cycling









A linear phase increment ϕ (per TR) shifts the profile by (ϕ/2π)/TR.

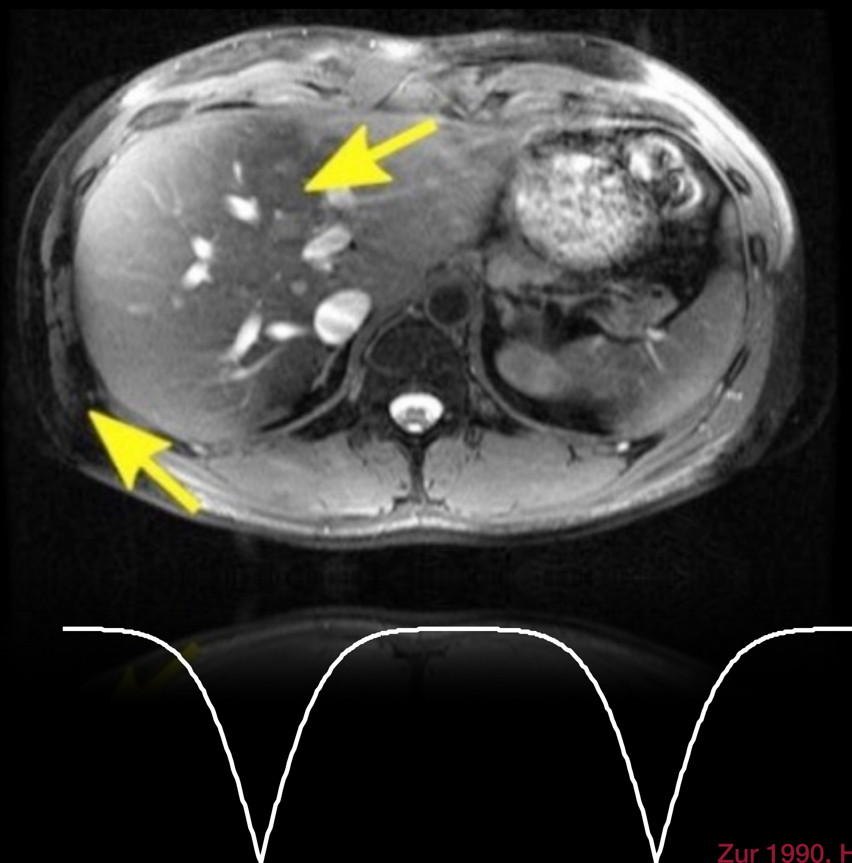
Hinshaw 1976

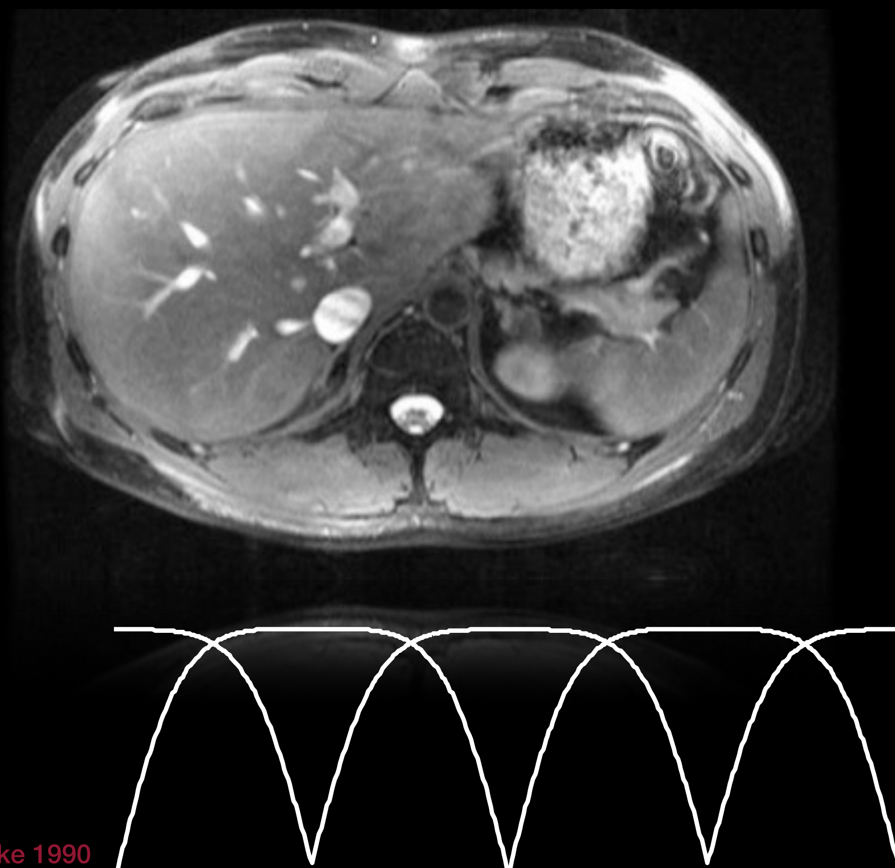
Question 3: Phase Cycling

Combined Acquisitions

Alternating RF

Combined Acquisition

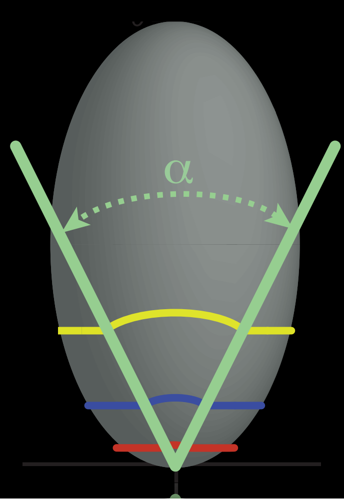


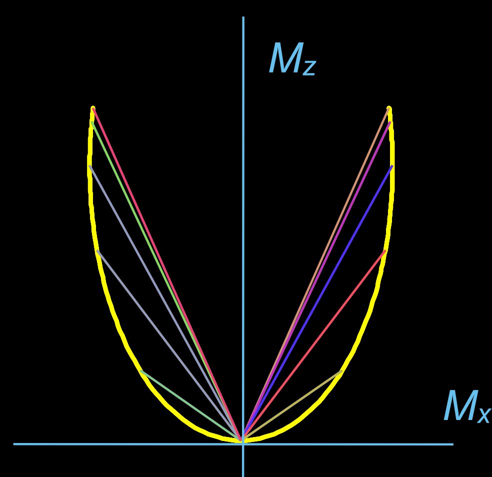


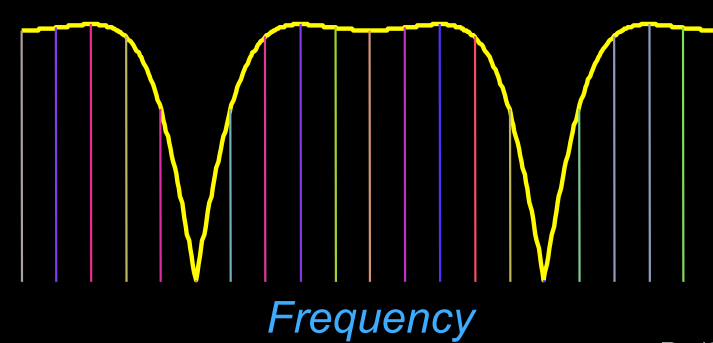
Zur 1990, Haacke 1990

bSSFP Steady-State: Summary

- Ellipsoidal distribution: shape given by T2/T1
- Path depends on flip angle and precession
- Signal very sensitive to resonant frequency
- TrueFISP, FIESTA, Balanced FFE, BASG, True SSFP







What are mathematical descriptions of Balanced SSFP dynamics?

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