Echoes and Spoilers: Pitfalls of Gradient and Spin Echoes

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Pulse Sequence Overview

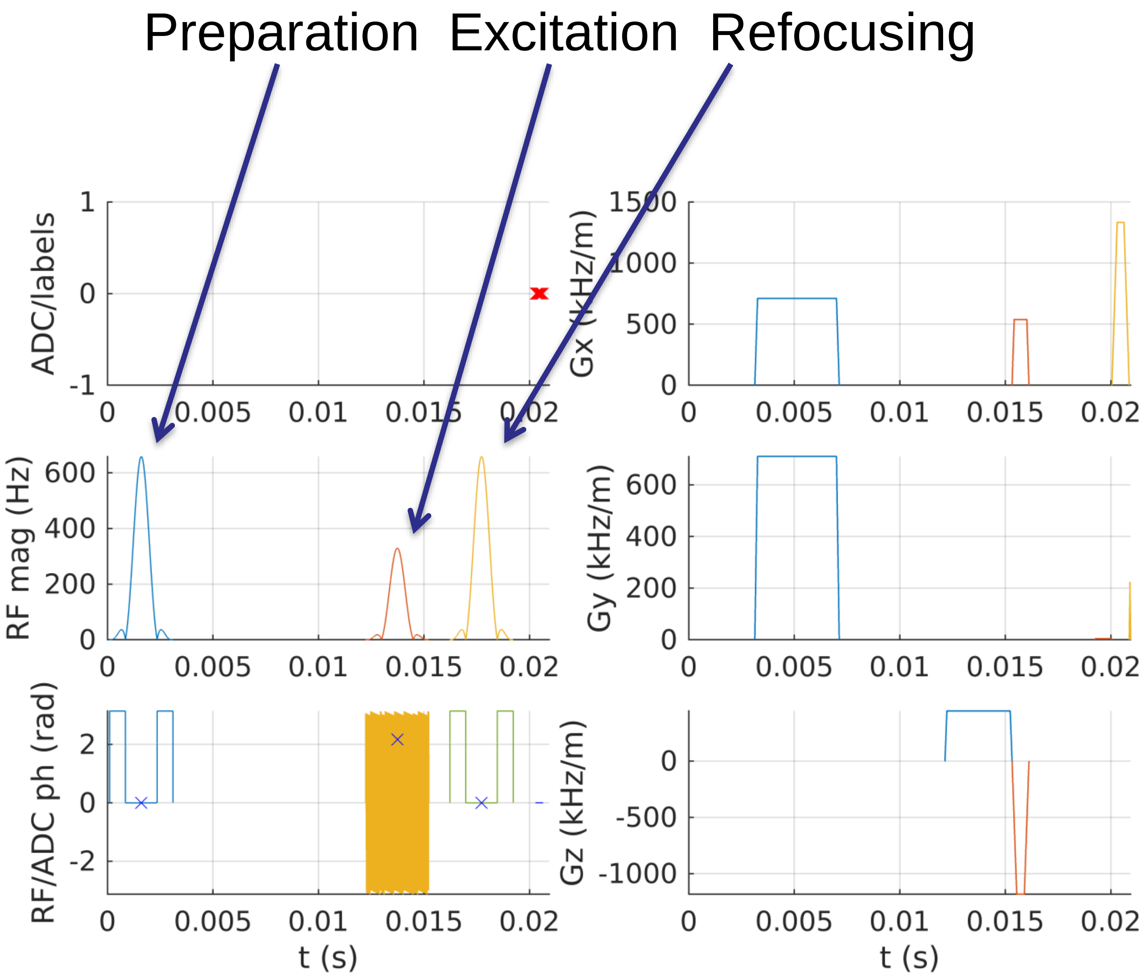
- Gradient Echo
  - RF spoiled GE
    - FLASH/SPGR
    - T1-FFE/FastFE
    - MPRAGE
    - 3D TFE/3DFastFE
    - 3DFastFE
    - 3DGRE
    - …
  - Refocused GE
    - FISP/FFE/GRASS
    - PSIF/CEGRASS
    - CISS/Fiesta-C
    - DESS
    - MEDIC/MERGE
    - M-FFE
    - …
  - EPI
    - PWI
    - DWI
    - DTI
    - fMRI
    - …
- Spin Echo
  - TSE/FSE
    - FLAIR
    - STIR
    - TIR
    - HASTE
    - SingleShot TSE
    - …

Overview

- RF Pulses in MR
- Gradient Echoes
  - Steady-State
  - RF spoiling
  - Balanced and unbalanced sequences
- Spin Echoes
  - Echo Paths
- ~~Echo Planar Imaging (EPI)~~

RF Pulses in MR

- Pulses are categorized according to their functionality
- RF-pulses always act on all components of magnetization
- Whenever spin history builds up, all effects have to be considered.



Small tip angle approximation and slice-selection

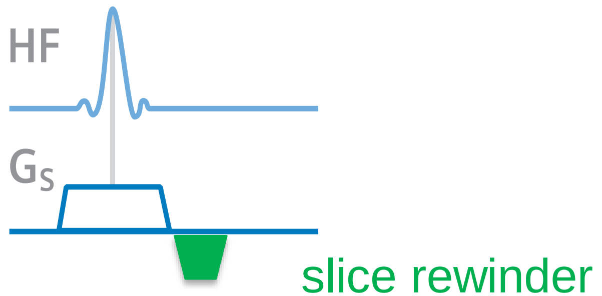
- Small tip angle approximation $M_z(t) \approx M_0$
- Off-resonance from slice selection gradient $\Delta\omega = \gamma G z$

⇒ Decoupled Bloch equation: $\dot{M} = \dot{M}_x + \mathrm{i}\dot{M}_y = -\mathrm{i}\Delta\omega M + \mathrm{i}\omega_1 M_0$

Solution after RF-pulse of duration τ

the RF-pulse is the Fourier Transform of the slice profile

$$
\begin{aligned}
M(\tau, \Delta\omega) &= \mathrm{i}M_0 \mathrm{e}^{-\mathrm{i}\Delta\omega\tau/2} \int_{-\tau/2}^{\tau/2} \mathrm{e}^{\mathrm{i}\Delta\omega t} \omega_1(t + \tau/2) dt \\
&= \mathrm{i}M_0 \boxed{\mathrm{e}^{-\mathrm{i}\Delta\omega\tau/2}} \mathcal{F}^{-1}_{t\to\Delta\omega} \left[\omega_1(t + \tfrac{\tau}{2})\right]
\end{aligned}
$$



RF Pulse Implementation in Pulseq

- “Basic” pulses implemented in Pulseq, e.g. “*mr.makeSincPulse*”
- More sophisticated pulses: python toolbox “*sigpy.mri.rf*”
- Available are:
  - Sinc
  - Gauss
  - Block
  - SLR
  - Adiabatic
- Arbitrary RF pulses possible

  “*mr.makeArbitraryRf*”

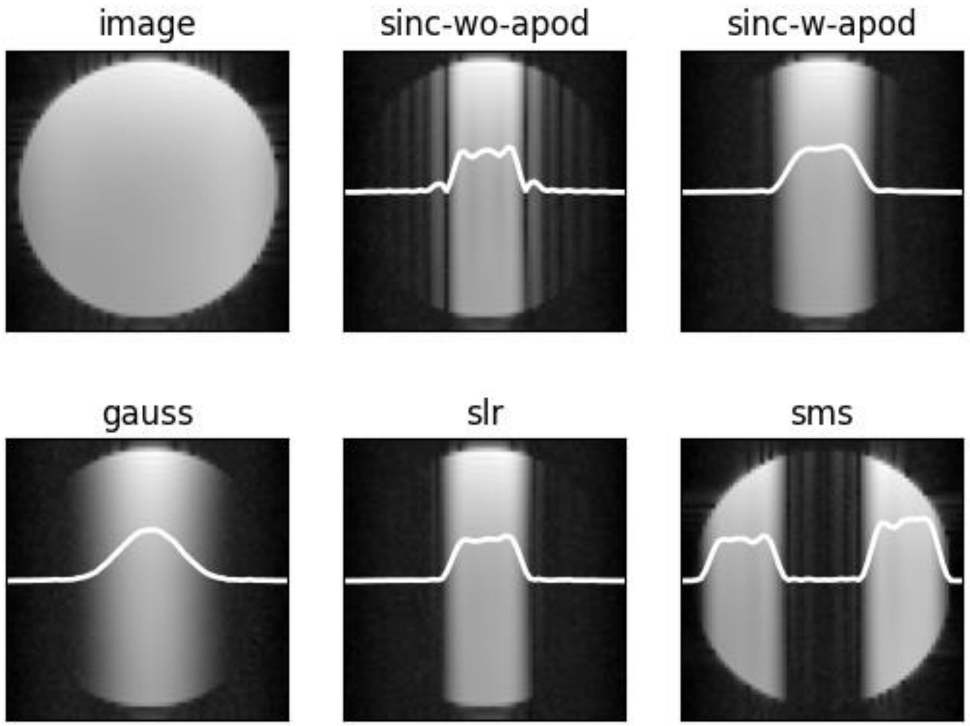


Image courtesy of Tony Stöcker

Example excitation slice profiles

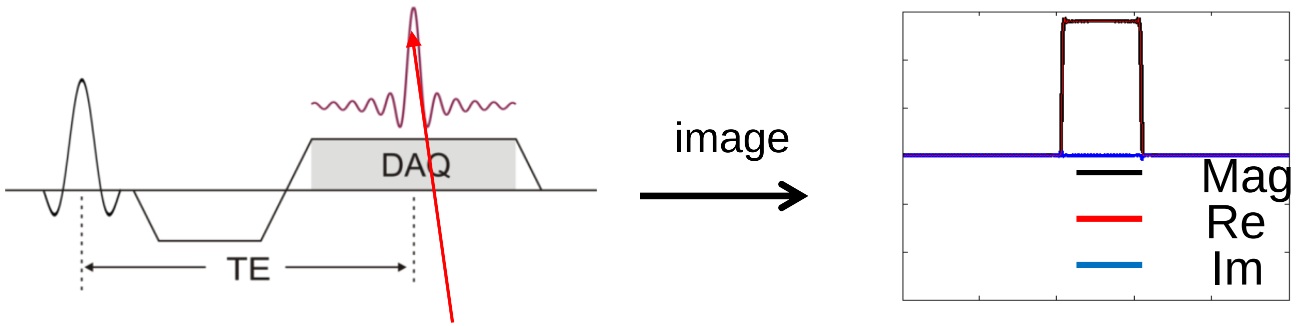
Gradient “Echoes”: Why Do We Use Them?

Fourier transform properties!

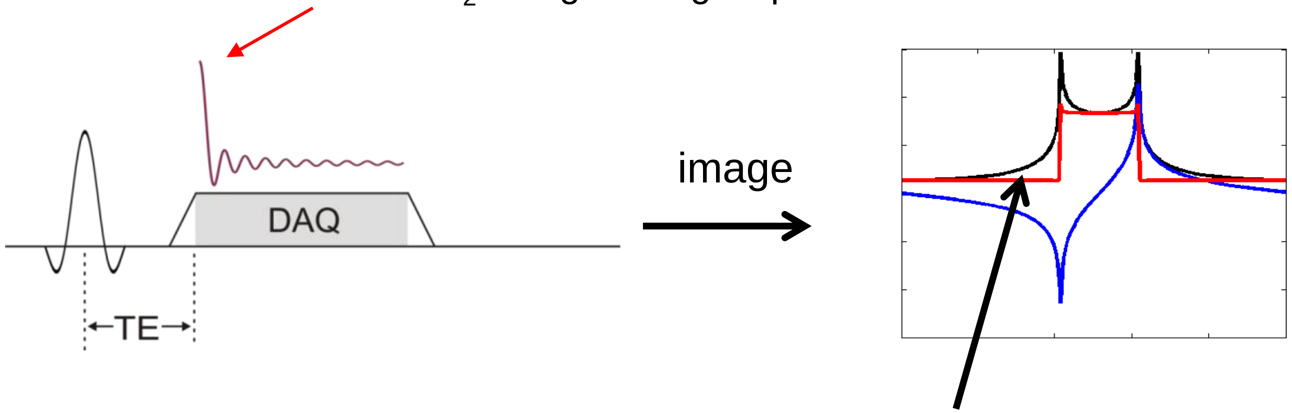
a) Spinecho: refocusing of static offresonances -> T_2 weighting

b) Gradientecho (i.e. applying prephasing gradient): exploiting Fourier transform properties

- distortion free magnitude image (no need for cumbersome correction)
- Signal gain of factor 2

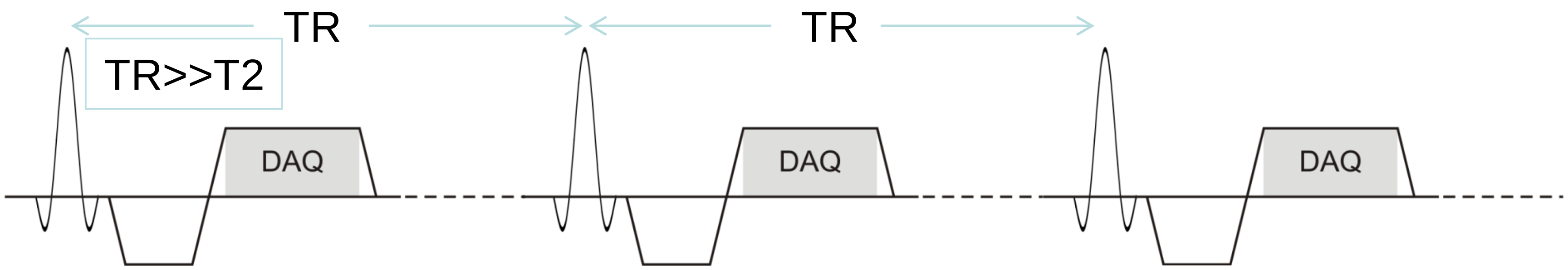


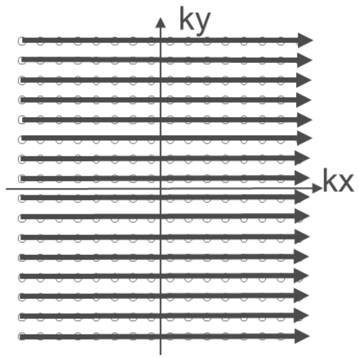
S~exp(-TE/T_2*)
T_2*-weighted signal peak!

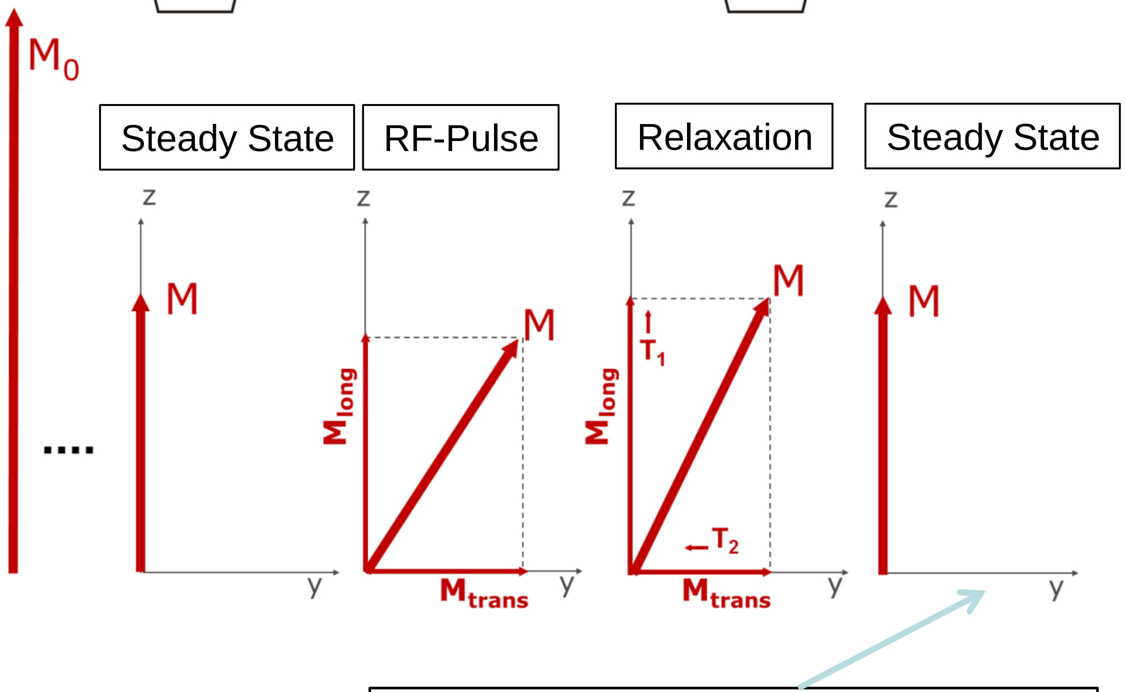


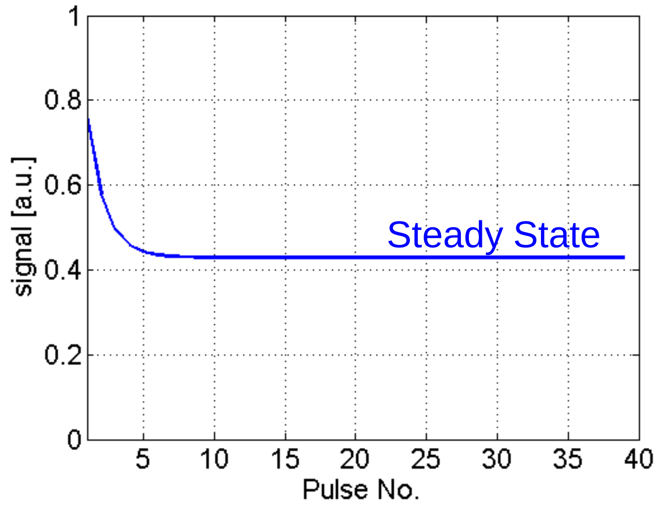
distortion of magnitude image!
signal loss (x 2)!

Simple gradient echo sequence









No transverse magnetisation before the RF-pulse! -> TR>>T2

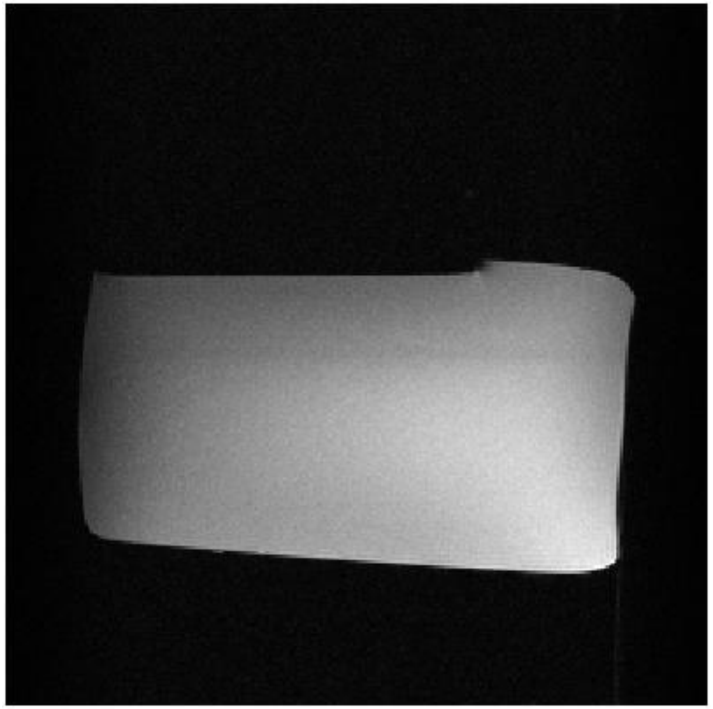
$$S = M_0 \sin\alpha \frac{1 - e^{-TR/T_1}}{1 - e^{-TR/T_1} \cos\alpha}$$

(„Ernst-equation“)

TR<T2: My GRE image looks strange!?

⇒ Transverse coherences from cycle to cycle

⇒ Spoiling: Disruption of transverse coherences / Reduce transverse components of steady-state magnetization



Possible spoiling methods

1. Long *TR* spoiling: *TR*>>T2*
2. Gradient spoiling.
3. RF-spoiling

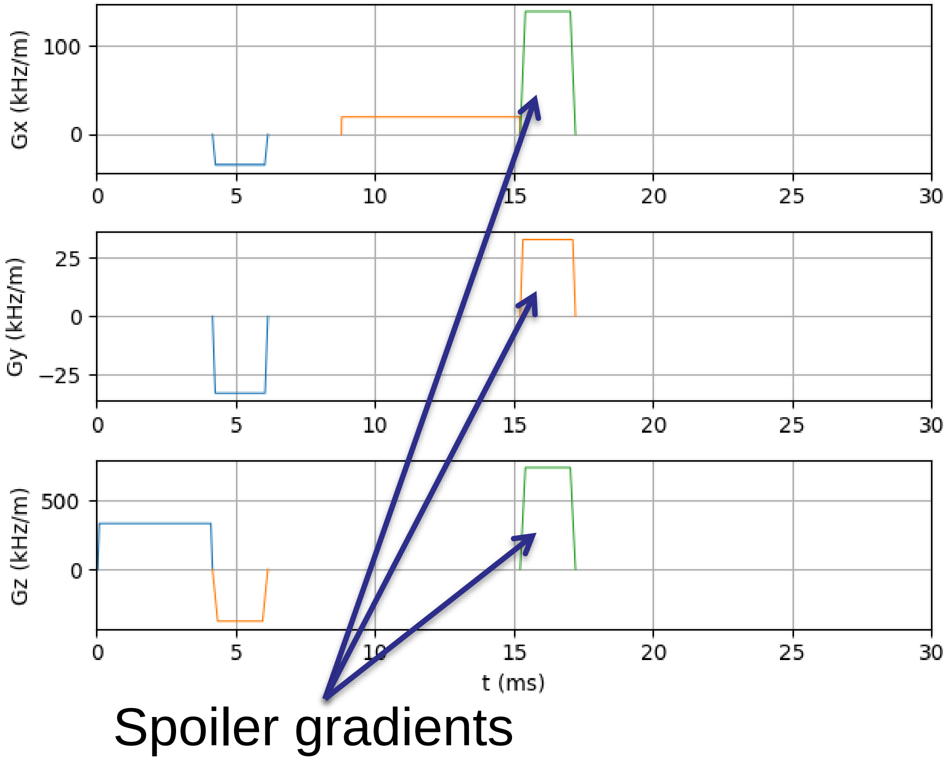
Long *TR* spoiling (*TR*>>T2*)

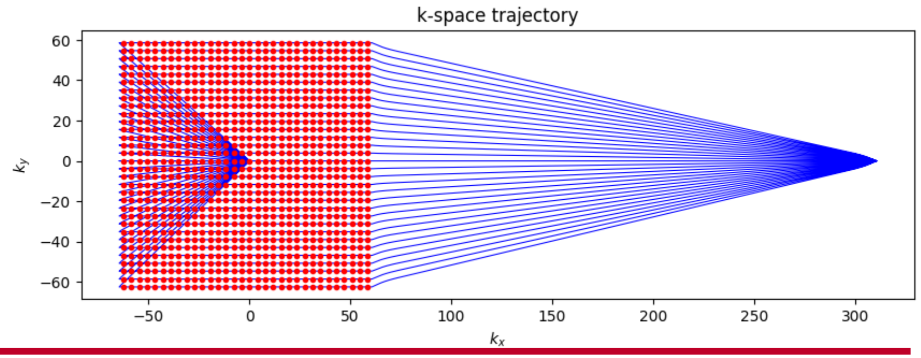
- Transverse magnetization will decay to zero by the end of the cycle
- 2D multi-slice sequences with enhanced spoiling from off-resonant effects from RF-pulses for other slices :
  - Siemens: MEDIC
  - GE: MPGR and MERGE
  - Philips: multi-FFE.

- Not feasible for certain contrasts and acquisition times

Gradient spoiling

- Applying slice-select (and sometimes readout) gradients with variable amplitudes at the end of each cycle, before the next RF pulse
- Strong dephasing: Shift signals in k-space out of acquisition window
- Transverse Magnetization is not “gone” and can be refocused(!)



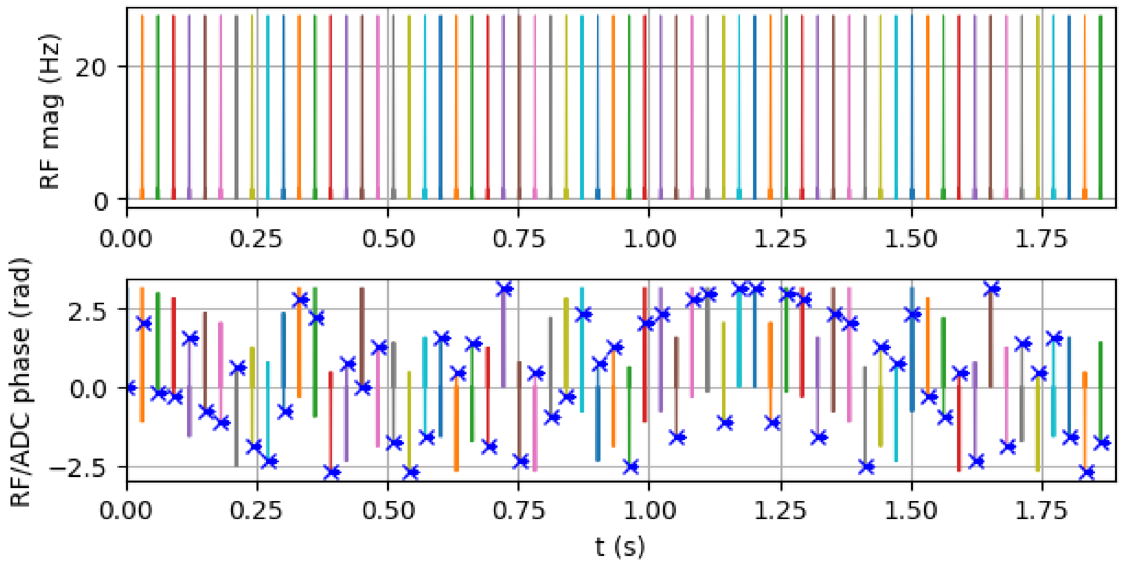


RF spoiling

- Variation of the RF pulse phase for subsequent excitations

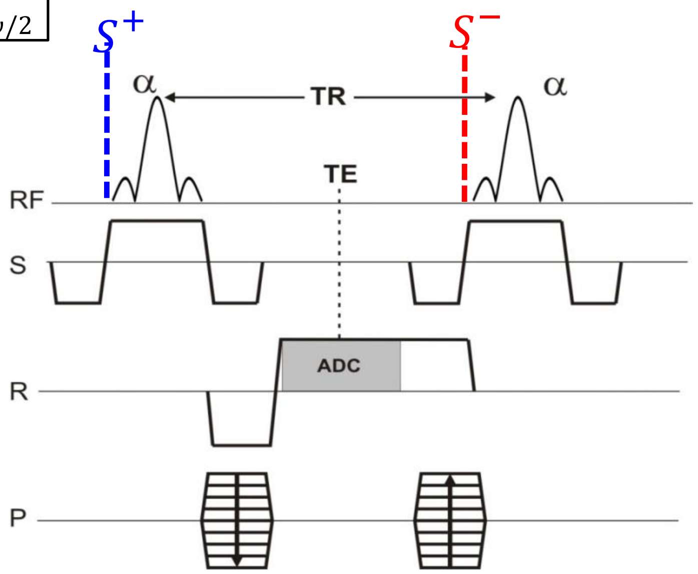
⇒ **„mimics“** TR>>T_2 scenario !

- “RF spoiling is an attempt to restore the contrast properties of long-TR GRE techniques”
- “RF-spoiling manipulates the 3D magentization vector (per voxel) such that the measured signal obeys approximately the Ernst equation“



RF – spoiling with phase difference increment ψ

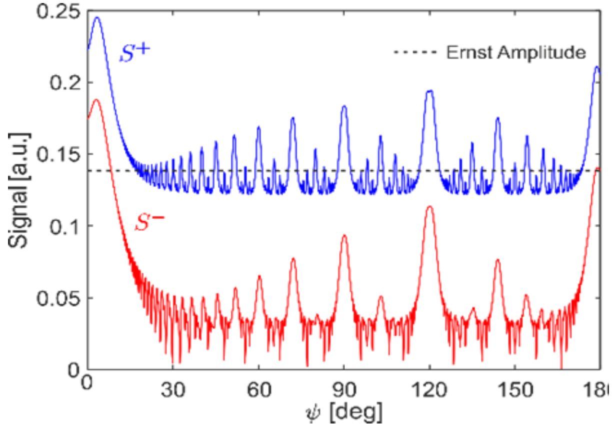
RF phase cycle
$\varphi = n(n-1)\psi/2$



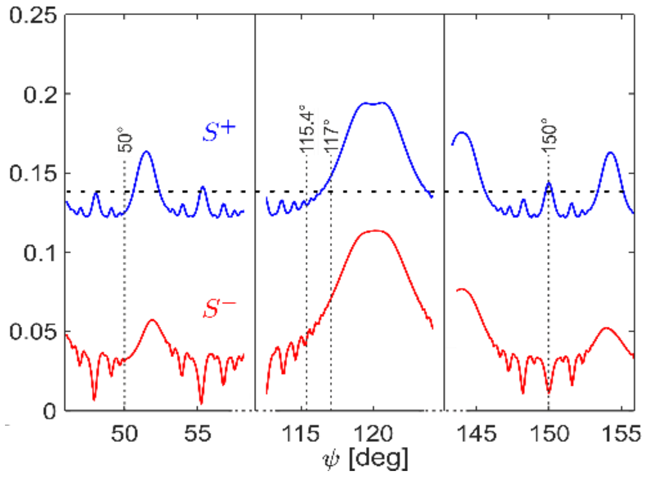
$$S^+ = \int_{-\pi}^{\pi} M_T^{\ +}(\theta)\,\mathrm{d}\theta$$

$$S^- = \int_{-\pi}^{\pi} M_T^{\ +}(\theta) e^{i\theta}\,\mathrm{d}\theta$$

Transverse magnetization before and after RF-pulse

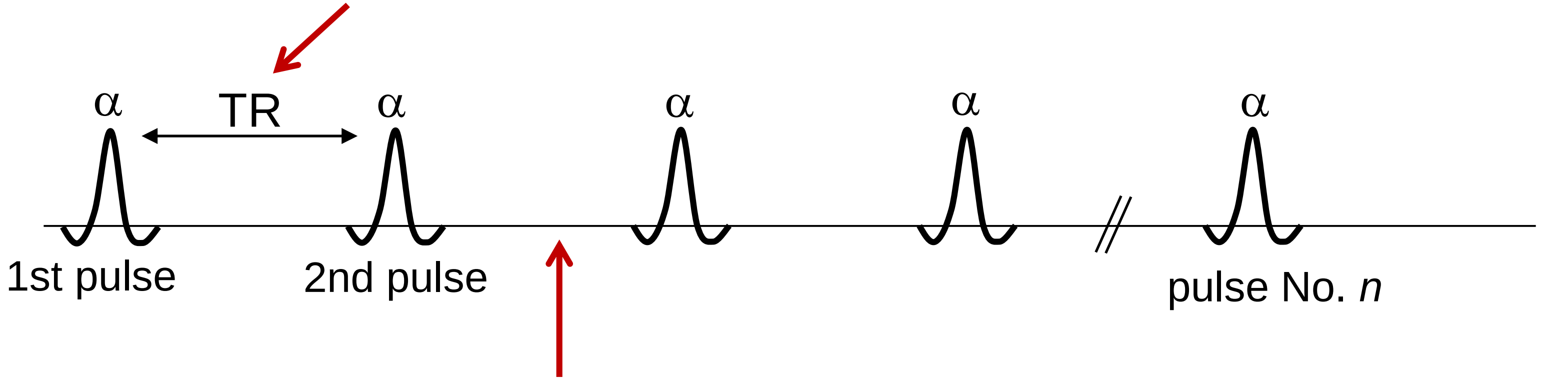


Vendors' choices:
Siemens: ψ = 50°
GE: ψ = 115.4°
Bruker: ψ = 117°
Philips: ψ = 150°



Going faster: SSFP: Steady State Free Precession

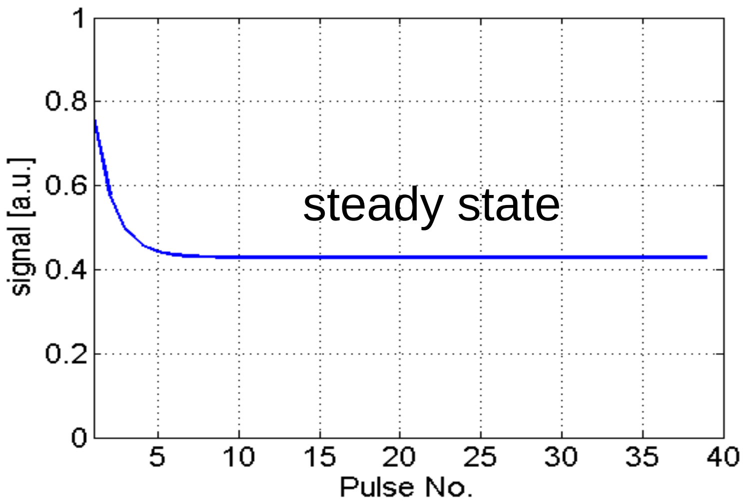
Steady State: Magnetisation not returning to equilibrium (M_0) during TR (~TR<3T1)



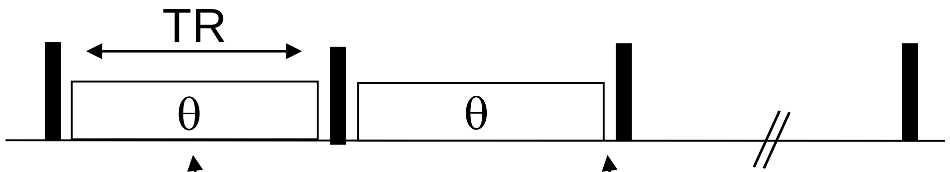
Free Precession: Magnetisation precesses around (local!) B_0 with B_1 switched off

(Forced Precession: B_1 switched on)

From now on: Transversal magnetization at the end of interval is **not** zero, TR<T2 !
Ernst equation is no longer valid



SSFP: RF pulses and dephasing

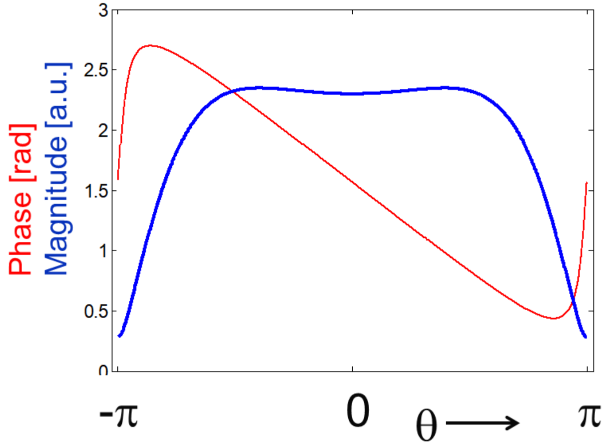


distribution of
θ angles (isochromats)

Transverse Mag.
present at end of
interval

Steady state for

$$M_{\mathrm{T}}^{+}(\theta) = M_x^{+} + iM_y^{+}$$



α=40°, T_1=0.5s, T_2=0.1s, TR=0.01s

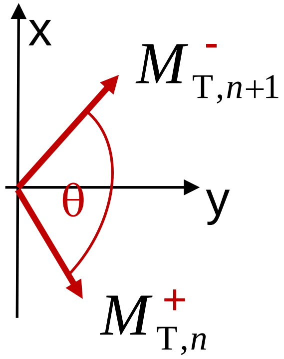
$$M_x^{+} = M_0(1-E_1)E_2 \sin\alpha \sin\theta / D$$

$$M_y^{+} = M_0(1-E_1)(1-E_2\cos\theta)\sin\alpha / D$$

$$D = (1 - E_1\cos\alpha)(1 - E_2\cos\theta) - (E_1 - \cos\alpha)(E_2 - \cos\theta)E_2$$

$$E_1 = \exp(-TR/T_1), \quad E_2 = \exp(-TR/T_2)$$

Transverse plane:



M_{T} before pulse No. n+1

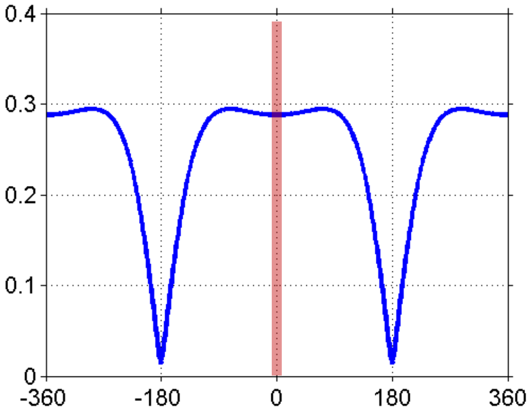
M_{T} travels by angle θ during TR

$$\theta = \omega \cdot \mathrm{TR}$$

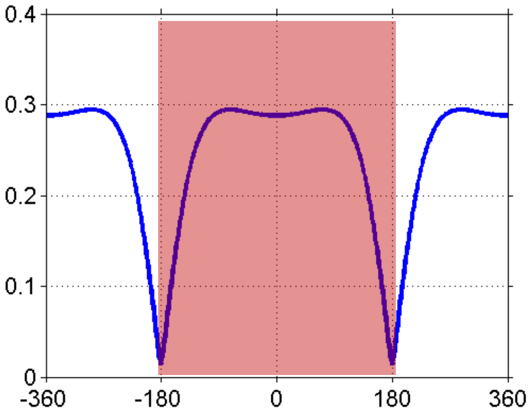
M_{T} after pulse No. n

Two principle strategies to make a sequence based on SSFP

1. Selecting a single frequency on the profile: *balanced SSFP*



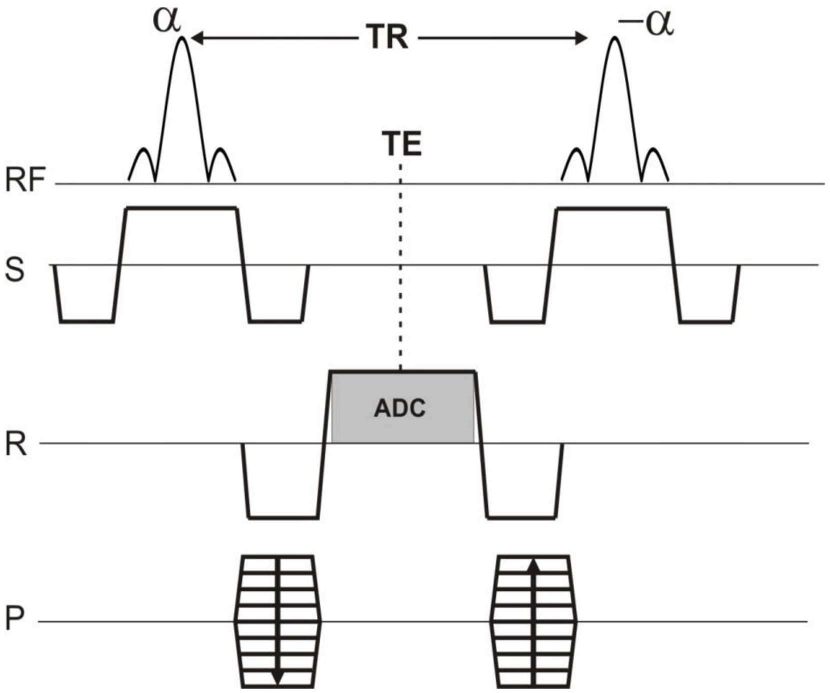
2. Integration over the profile: *unbalanced SSFP*



Balanced SSFP sequence diagram

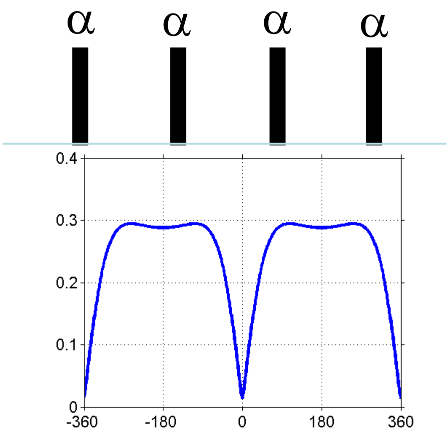
For multidimensional k-space acquisition, gradients in all directions are needed:

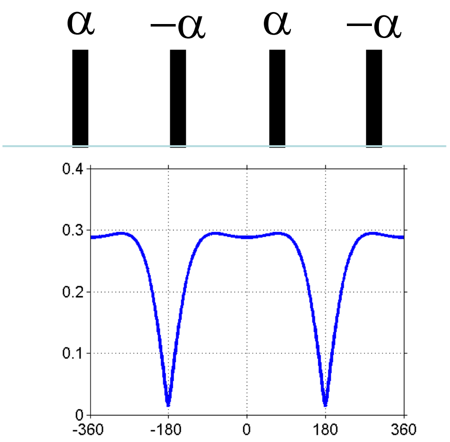
2D bSSFP



„balanced“ gradients!

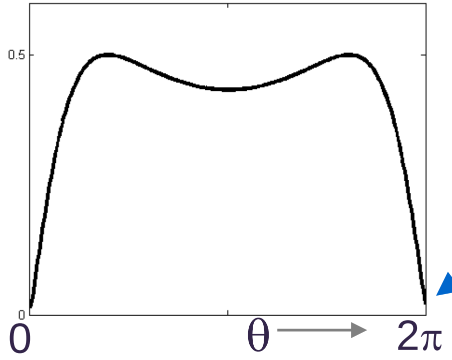
RF-pulses with alternating sign…



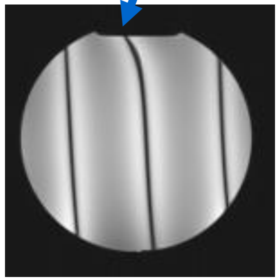


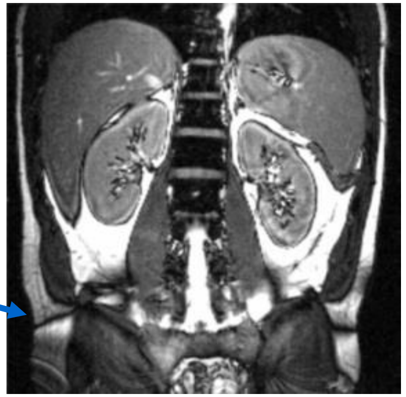
…shift the passband to on-resonance

The stripe artefact in bSSFP images



If θ is located in the „stopband“, a dark stripe appears in the image





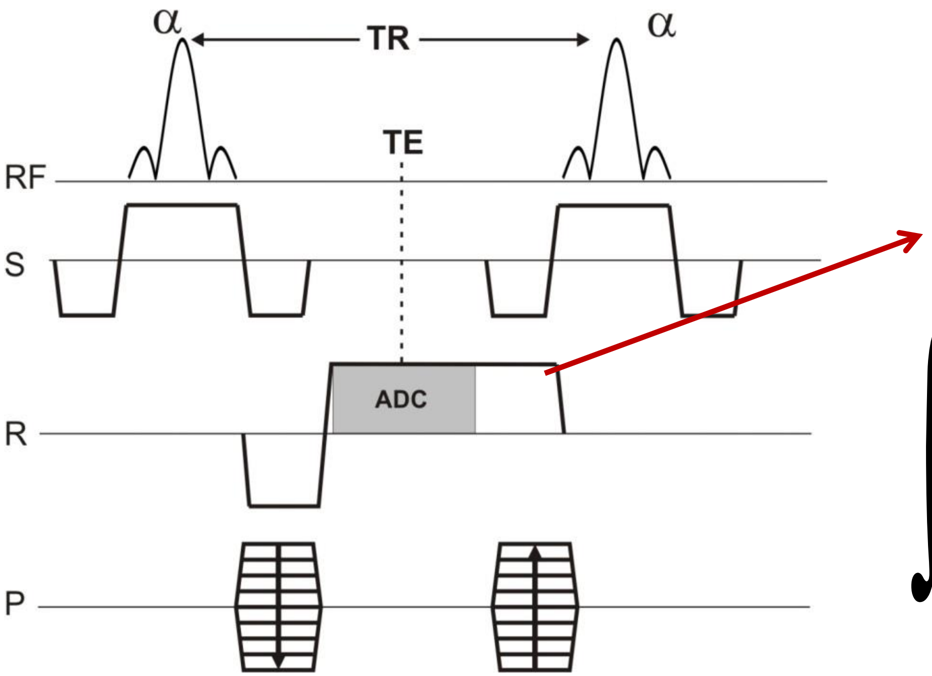
Distance of the stopband from on-resonance (center of passband) in Hz:

$$\Delta f = \frac{1}{2 \cdot TR}$$

Example: *TR* = 4 ms -> Δ*f* = 125 Hz

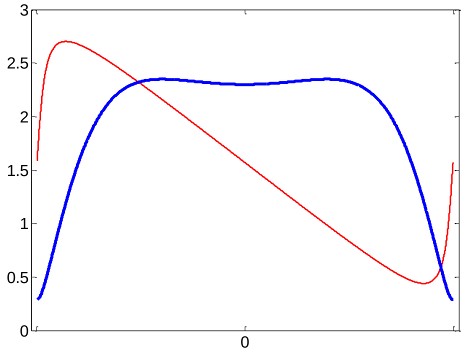
Good shim is required to avoid dark stripes!
Short TR needed!

Unbalanced SSFP: FISP sequence



The unbalanced area of all gradients must distribute the isochromats such that the voxel signal is the integration over the profile!

$$\int$$



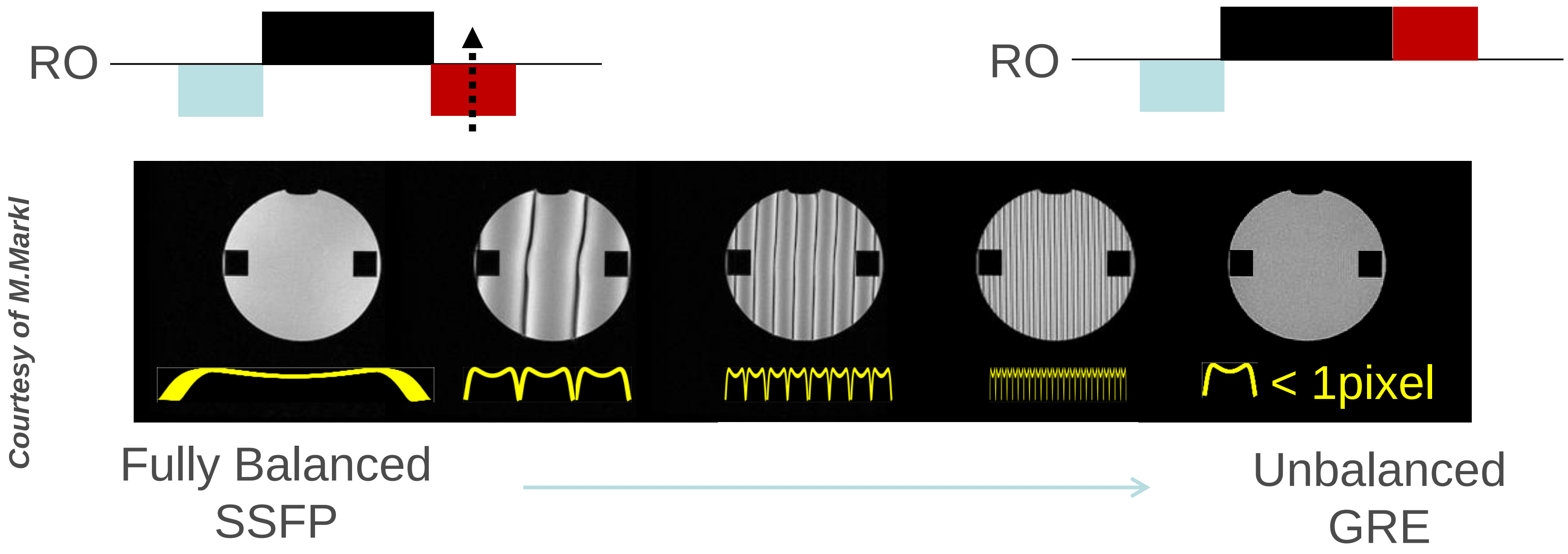
$$\mathrm{d}\theta = \text{const.}$$

-> Need for spoiler gradient(s)!

$$S_{\mathrm{FISP}} = \int_{-\pi}^{\pi} M_{\mathrm{T}}^{+}(\theta)\,\mathrm{d}\theta = \frac{M_0 \sin\alpha\, e^{-TE_{\mathrm{FISP}}/T2}}{1+\cos\alpha}\left[1-D'(E_1-\cos\alpha)\right]$$

with $D' = \dfrac{\sqrt{1-E_2^2}}{\sqrt{1-E_1^2E_2^2-2E_1(1-E_2^2)\cos\alpha+(E_1^2-E_2^2)\cos^2\alpha}}$

FISP Signal = „profile squeezed into one voxel"



The FISP Signal is the integration of the after-pulse SSFP signal and shows a mixed T_1/T_2-contrast!

Credits

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