Spin Echoes

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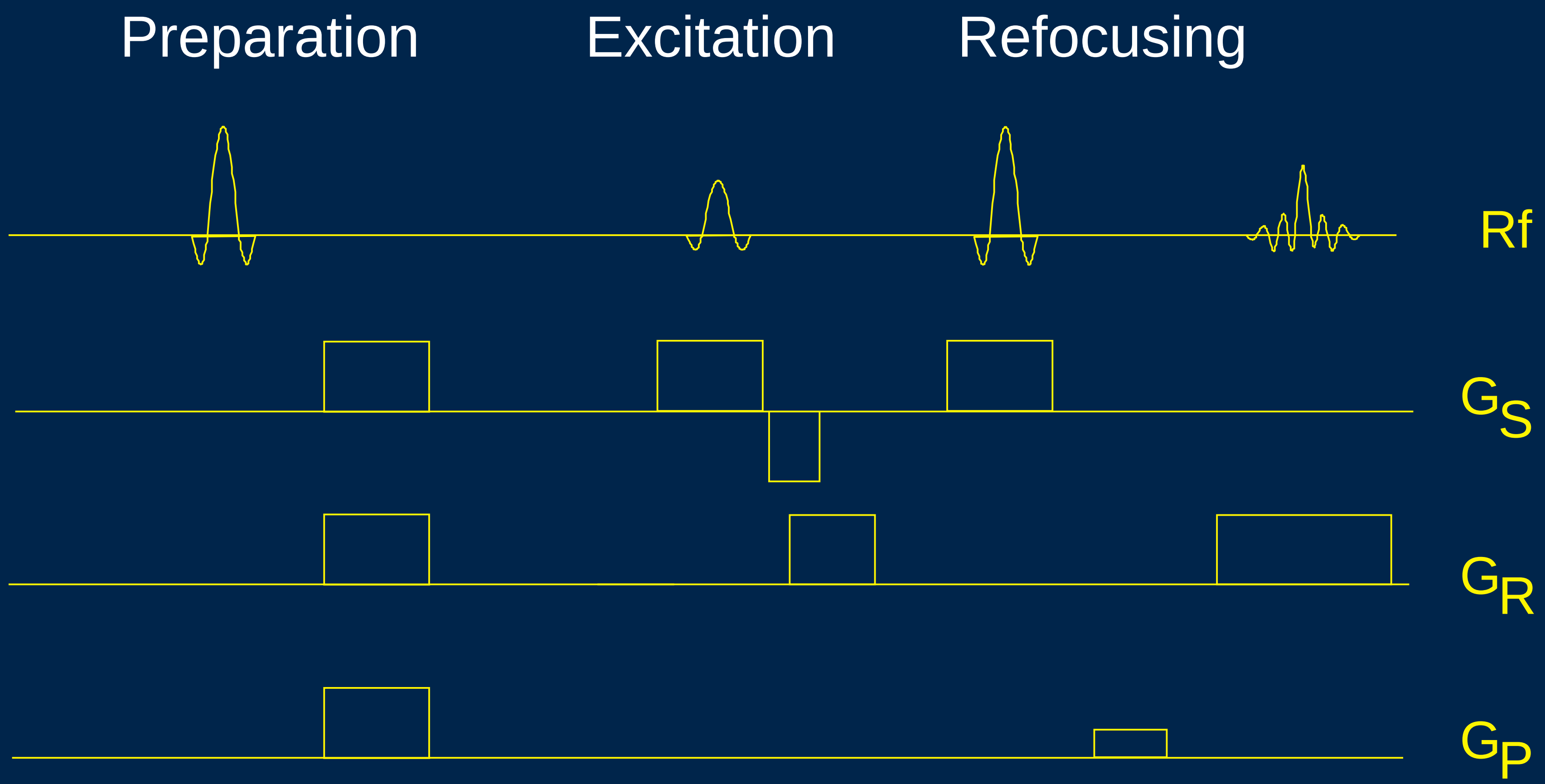
Overview

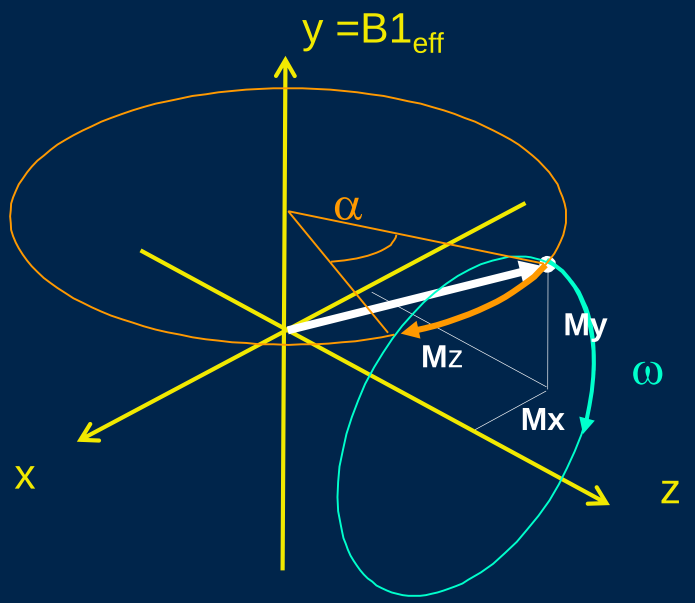
- RF pulses
- Spin echoes and stimulated echoes
- Multiple echoes
- Phase graphs and extended phase graphs
- CPMG and CP sequences
- TSE (FSE, RARE,…)
- Hyperechoes and TRAPS

RF Pulses in MR Sequences

MR-Sequences consist of a series RF-Pulses and gradients.
Pulses are categorized according to their functionality



Motion of Magnetization Vectors



Bloch equations:

$$\frac{dMx}{dt} = -\frac{Mx}{T_2} - \omega\, My - \frac{B_1}{\gamma} Mz$$

$$\frac{dMy}{dt} = -\frac{My}{T_2} + \omega\, Mx$$

$$\frac{dMz}{dt} = -\frac{(Mz - M_0)}{T_1} + \frac{B_1}{\gamma} Mx$$

with B_1-field along y.

A magnetization vector will

- rotate around the direction z of the magnetic field during free precession with a resonance frequency ω.

- rotate around the direction of an effective RF-field $B1_{eff}$ by a flip angle α during application of an RF-pulse. $B1_{eff}$ is orthogonal to z for on-resonance spins.

Take home message 1:

A Pulse

… is a pulse ….

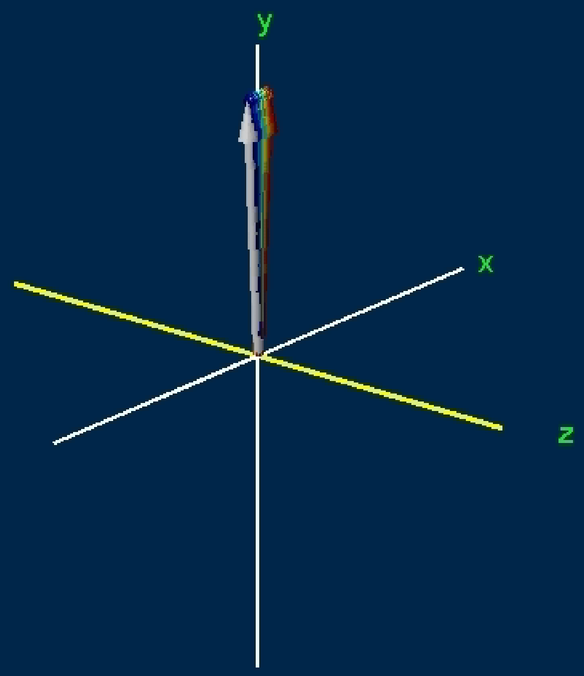
… is a pulse ….

… is a pulse ….

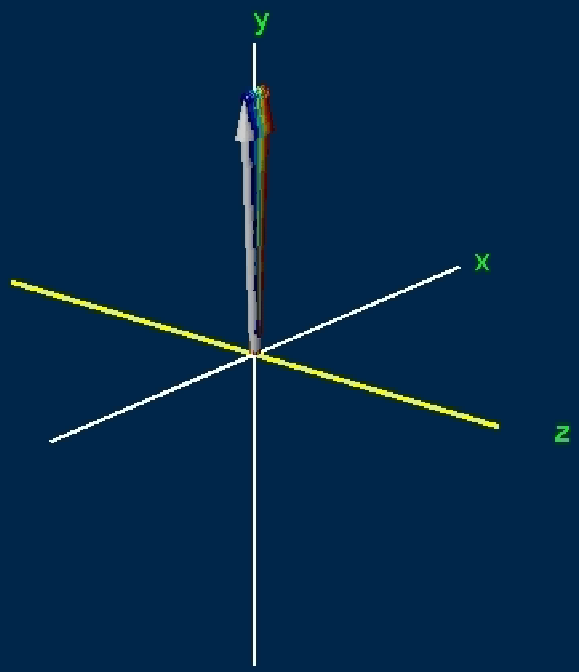
… is a pulse ….

… its effect depends on the context.

The 90°-90°-Spin Echo



The Stimulated Echo

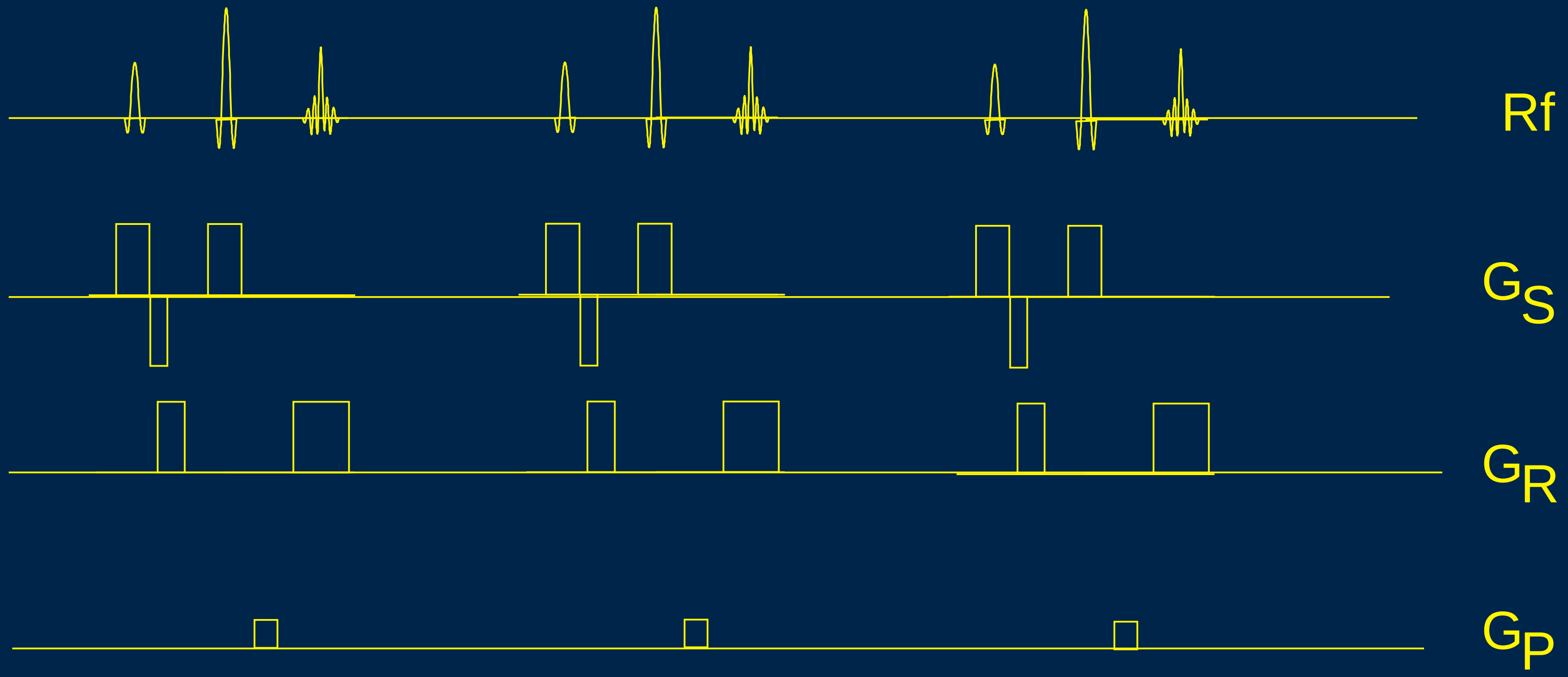


The 90°(x) – te – 90°(y) —————— tm —————— 90°(y) - Sequence

The truth about RF Pulses in MR Sequences

RF-pulses always act on all components of magnetization.

Whenever spin history builds up, all effects have to be considered.

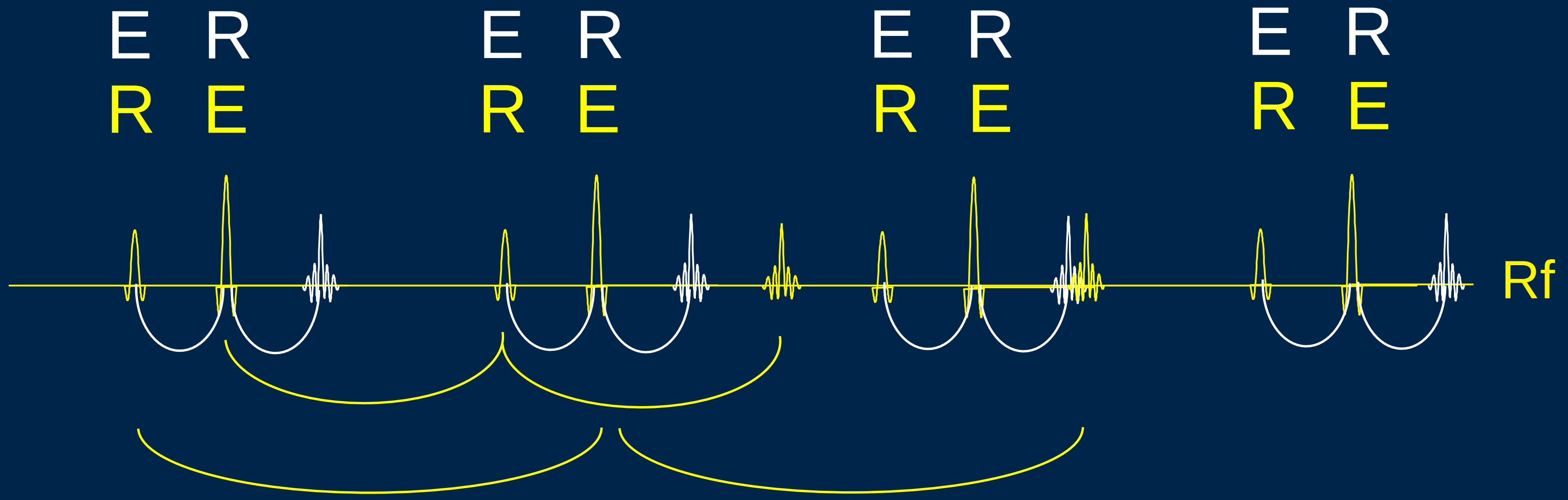


Take home message 2:

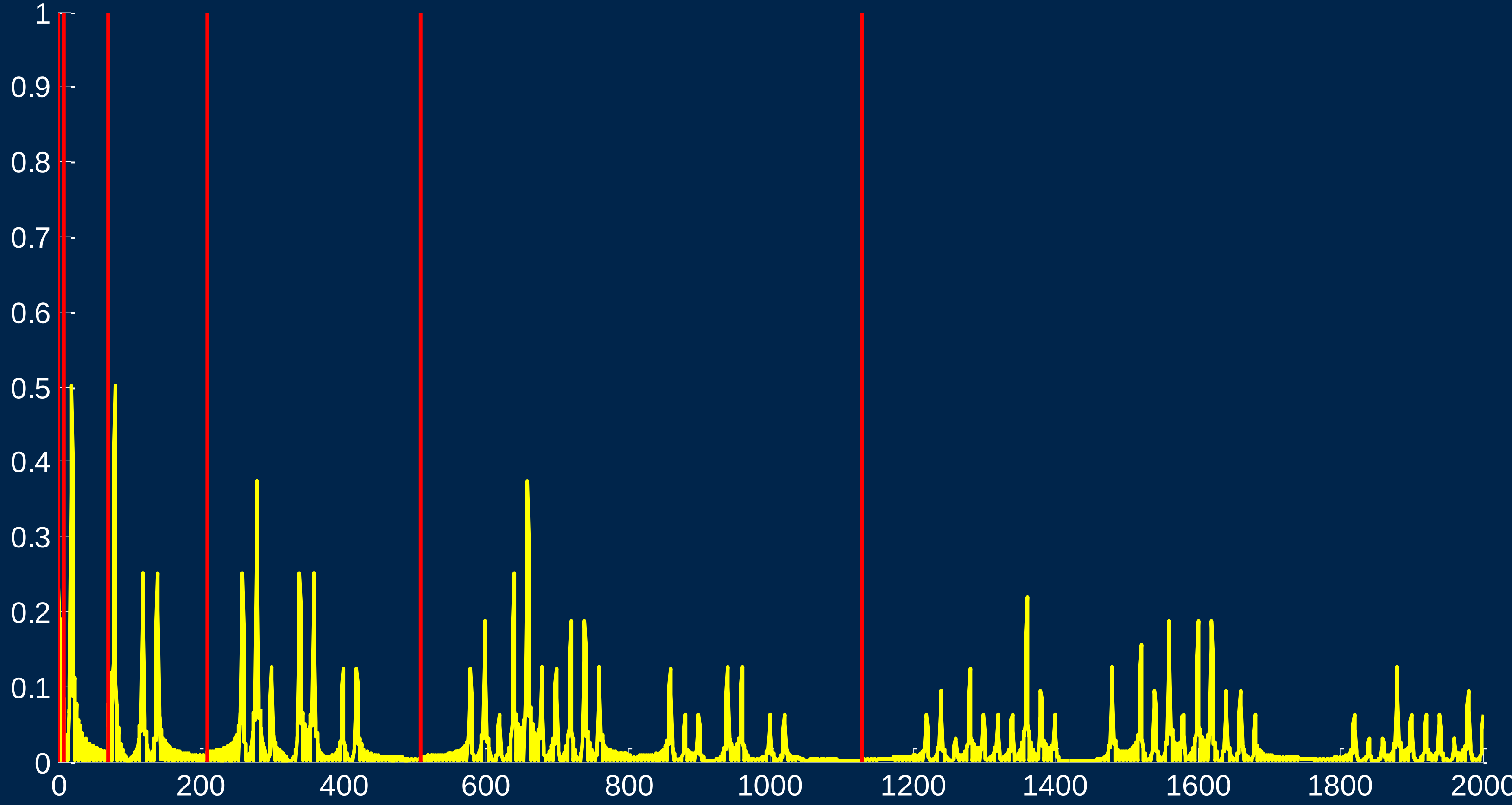
all excitation pulses act as refocusing pulses on previously created transverse magnetization.

all refocusing pulses act as excitation pulses for still existing z-magnetization.

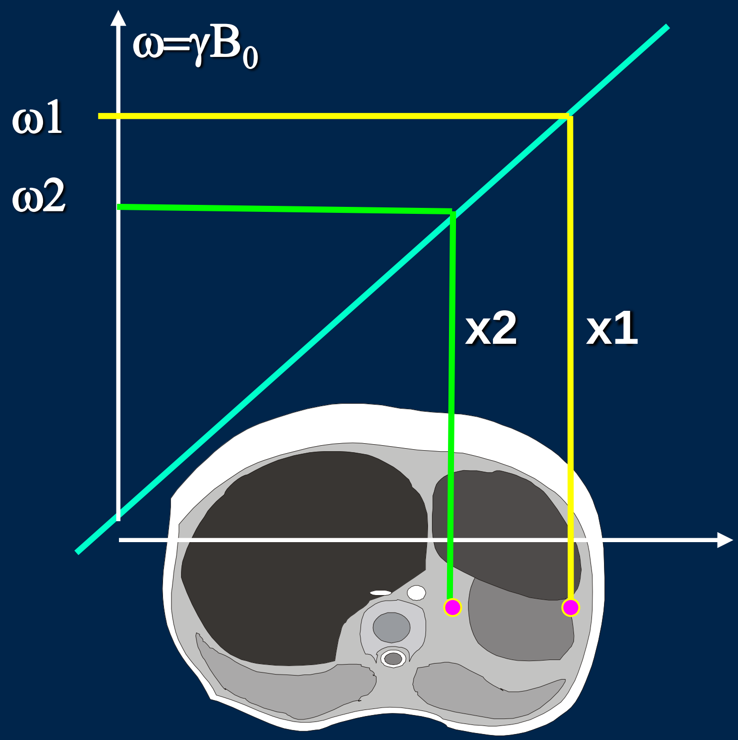
...and don't forget stimulated echoes.

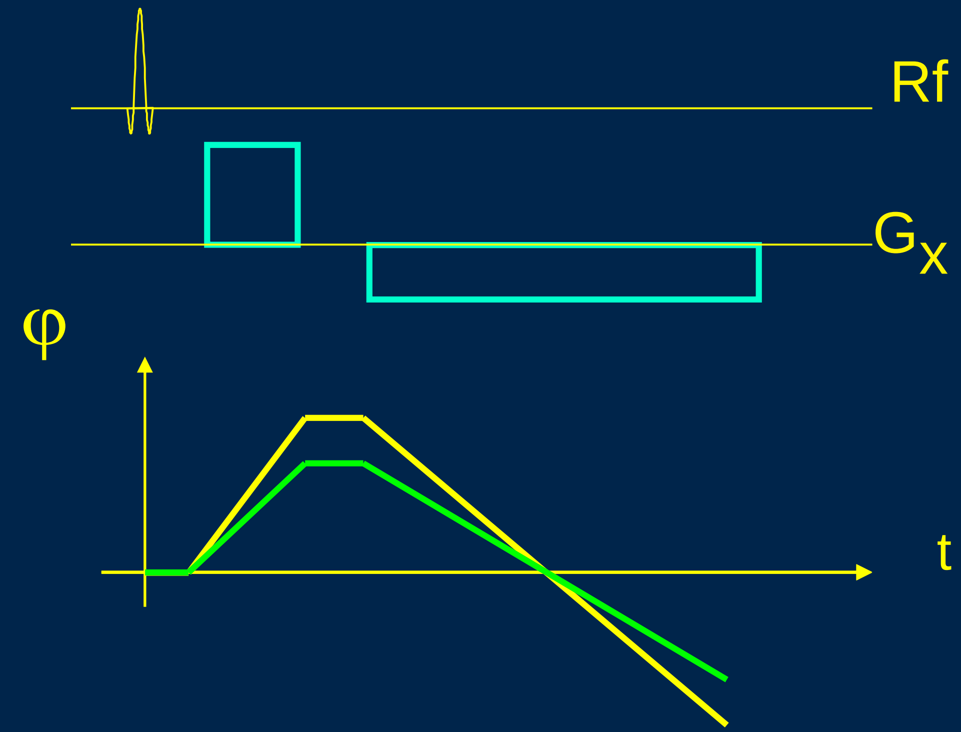


....even more Echoes



The Phase Graph

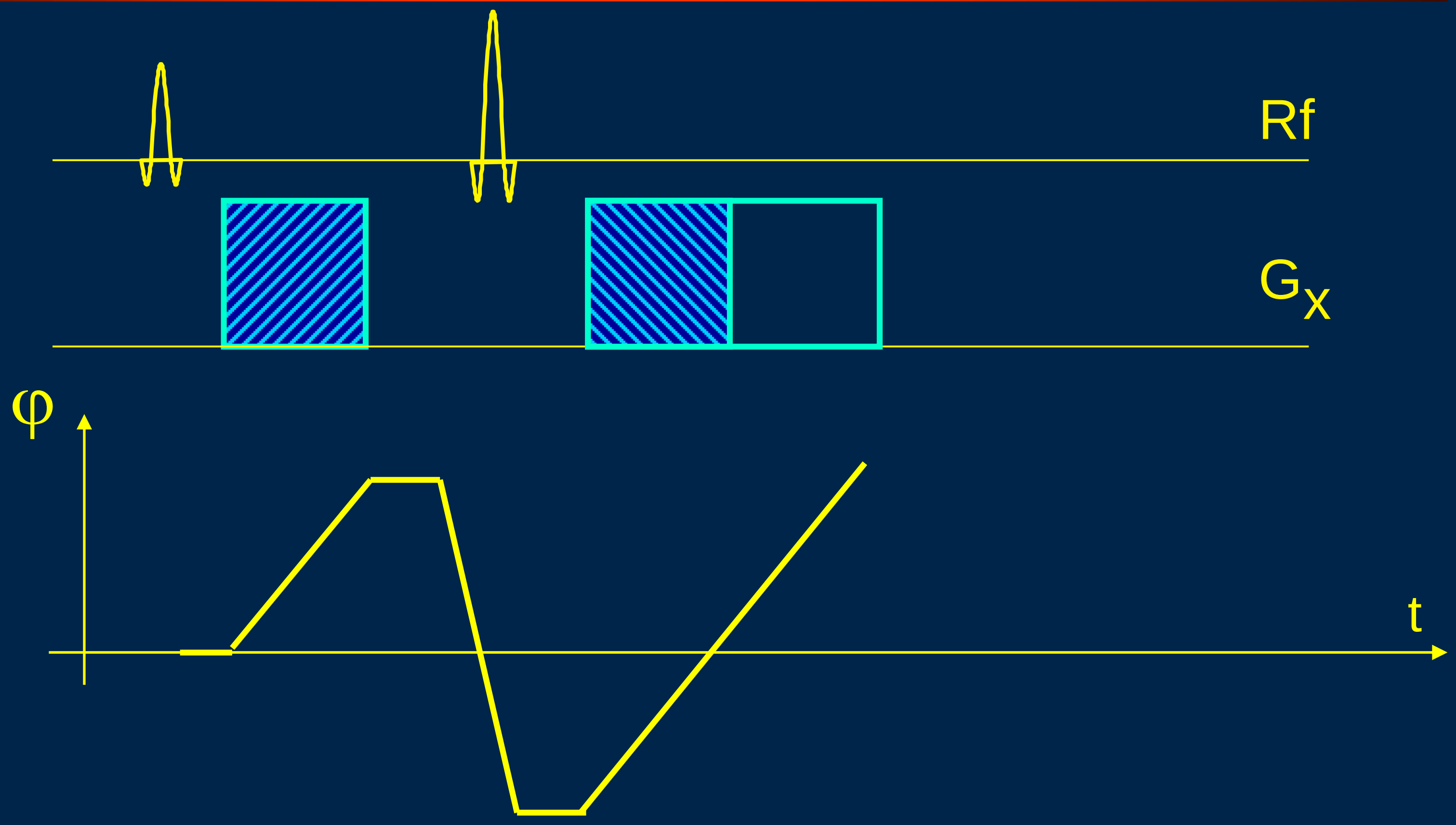




The Phase Graph is a bookkeeping device to track the phase of isochromats:

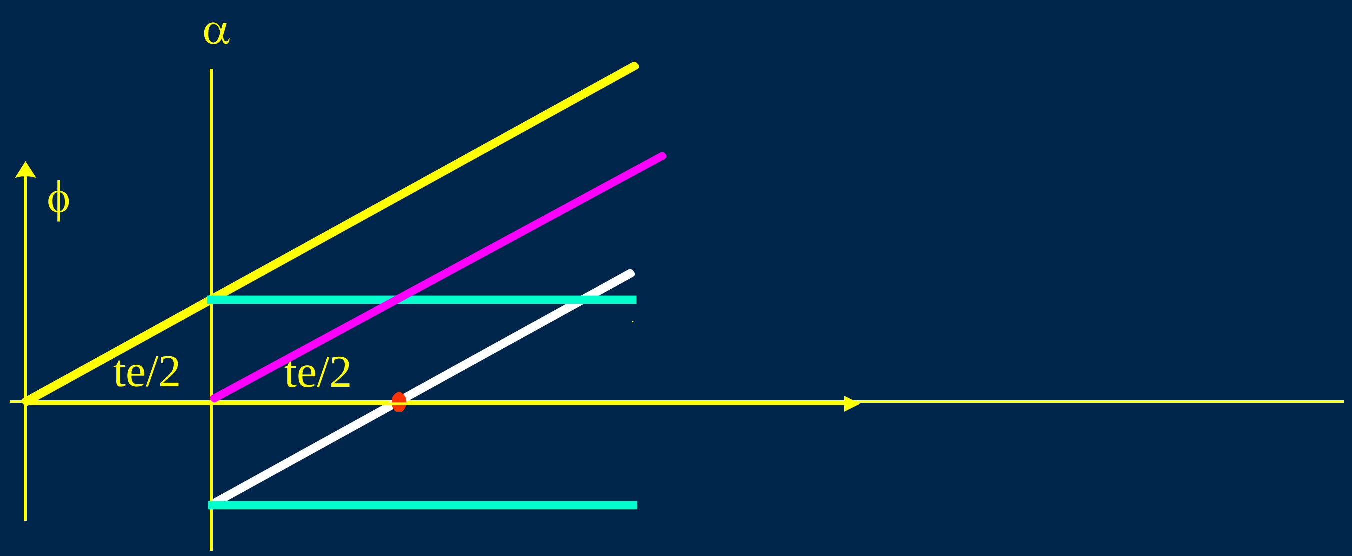
- Pick any spin
- Follow its phase development
- Whenever there is zero crossing a signal will occur

The Phase Graph: Refocussing



A refocusing pulse inverts the phase.
A spin echo is formed by applying identical gradients before and after the refocusing pulse

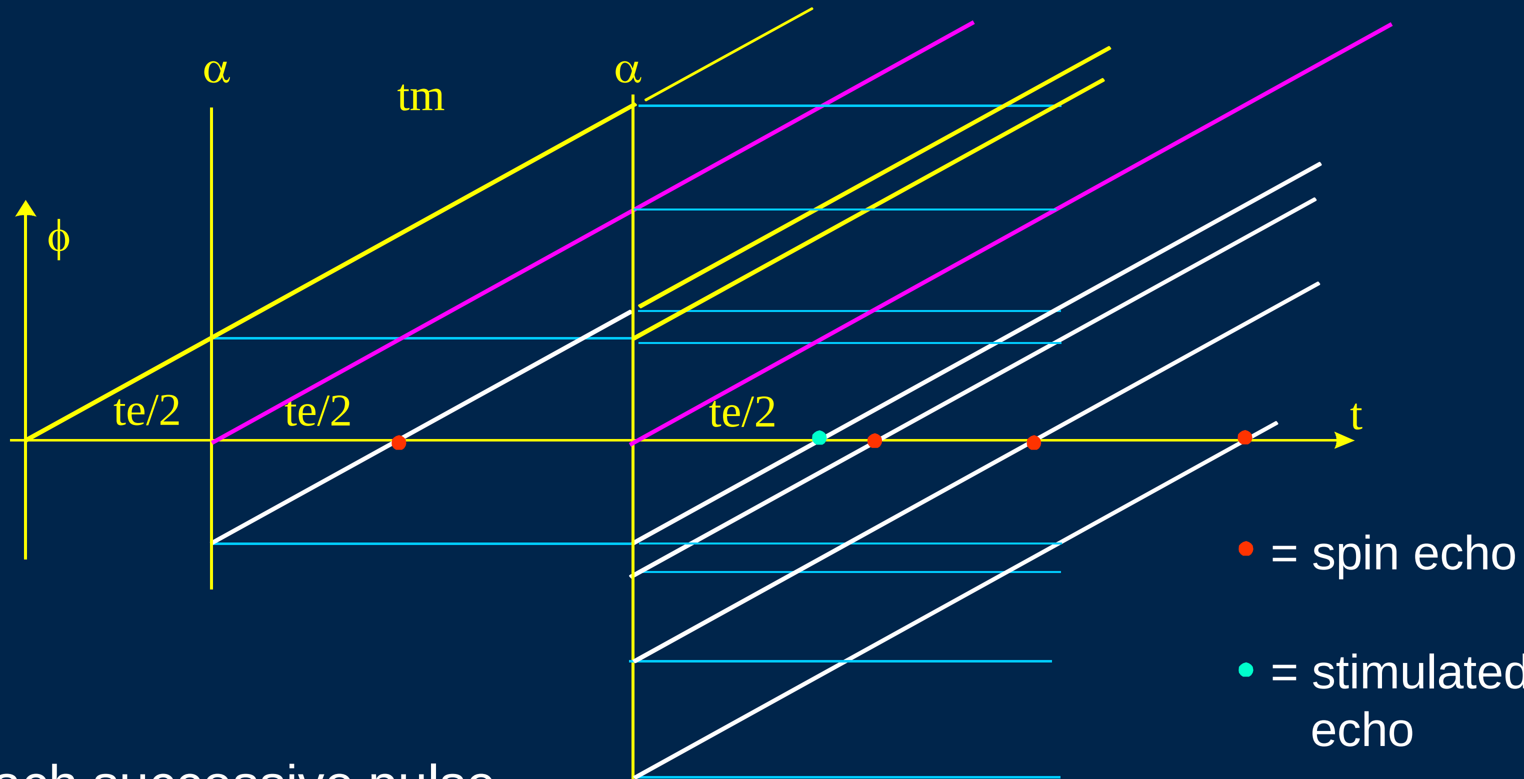
Phase Graph for RF Pulses



At each RF-pulse transverse magnetization will be split into 4 parts:

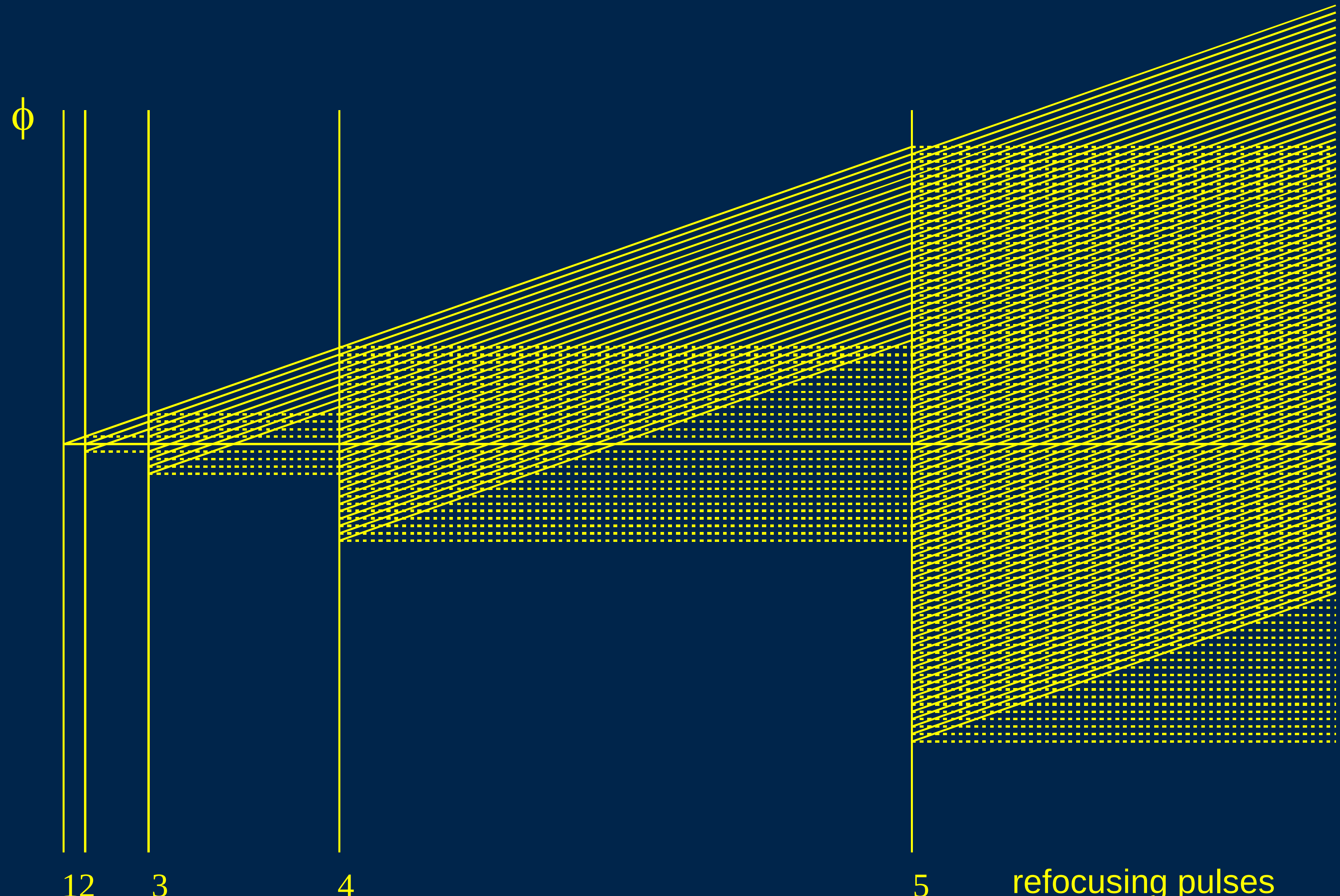
- refocused transverse magnetization ($\sin^2 \alpha/2$)
- unchanged (dephasing) transverse magnetization ($\cos^2 \alpha/2$)
- modulated z-magnetization ($1/2 \sin \alpha$)
- in addition new transverse magnetization will be created from residual z-magnetization

Phase Graph for Multiple Pulses



At each successive pulse

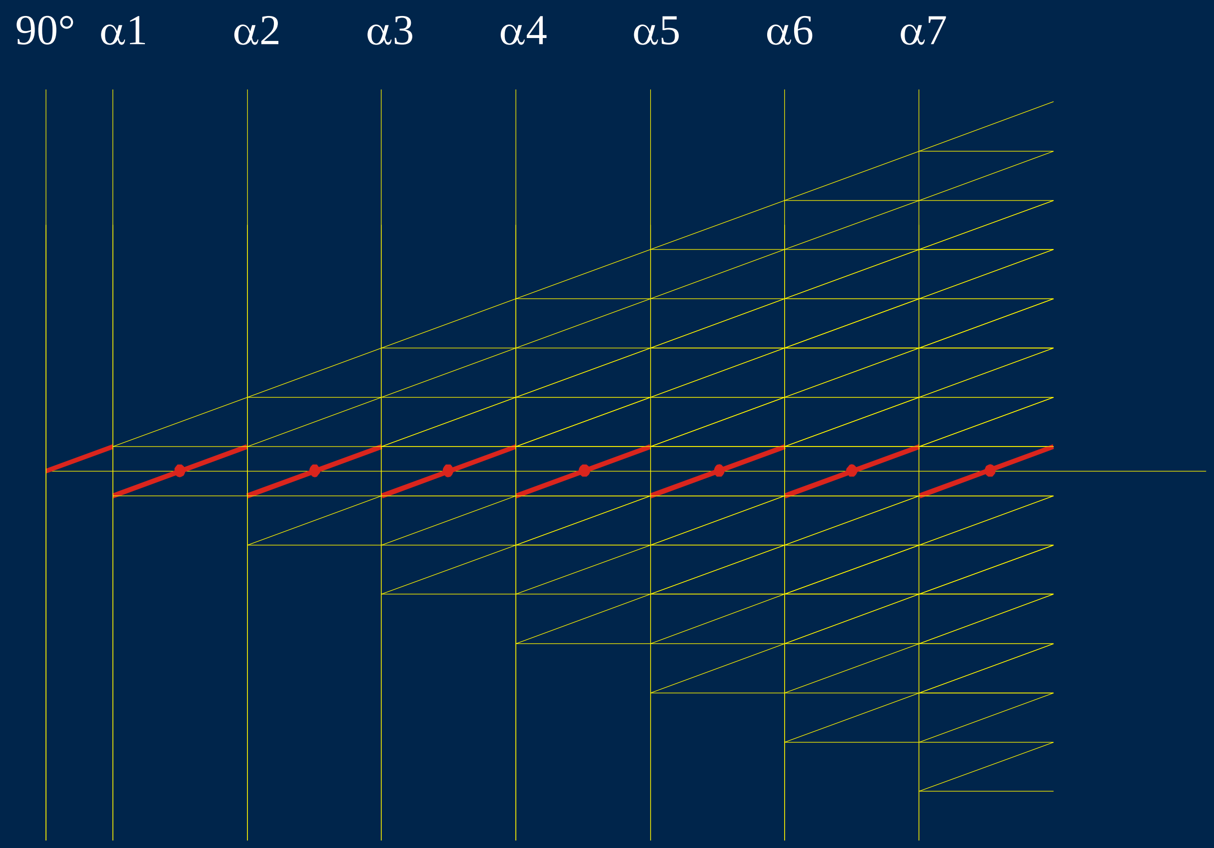
- each transverse magnetization pathway will be split again
- additionally transverse magnetization will be created from each modulated z-magnetization pathway
- new transverse magnetization will be created



The number of pathways grows with 3^{n-1}

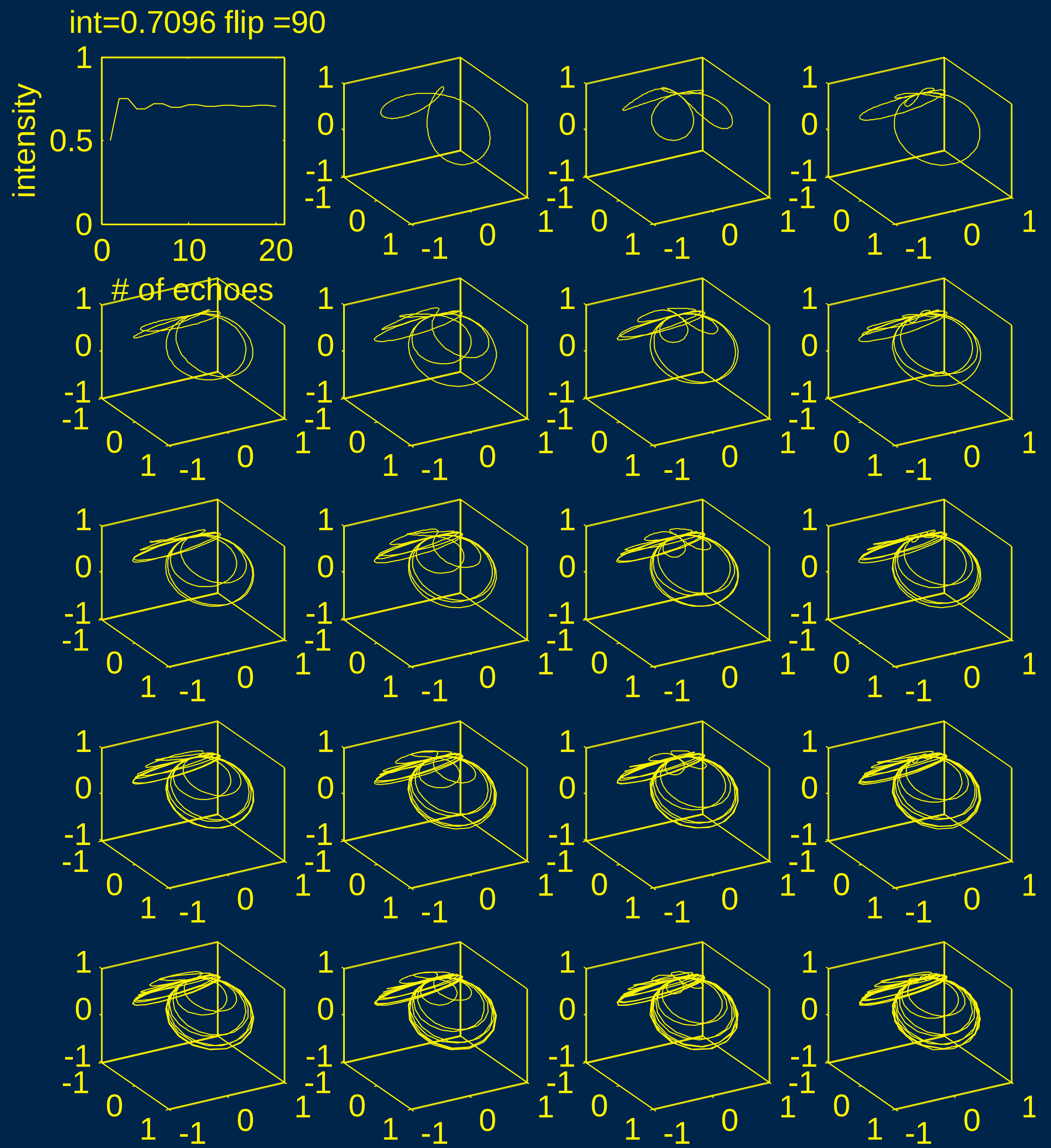
After ~ 50 pulses there are more echoes than spins !

Phase Graph for CPMG-Sequence

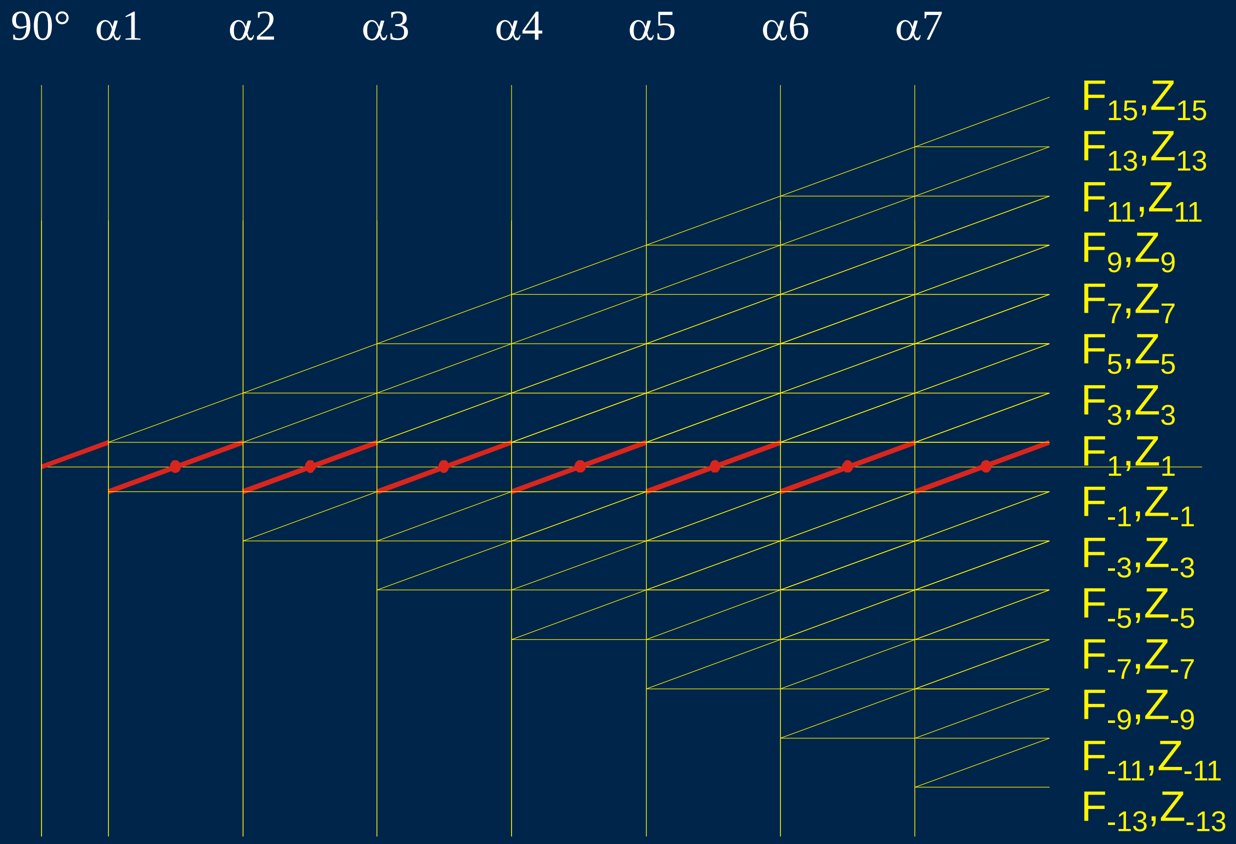


In a CPMG-sequence signals are formed via a superposition of multiple individual signal formation pathways. Calculation of signal amplitudes requires calculation of all 3n-1 individual pathways (‚partition state method‘)

90°-Multiecho



Extended Phase Graph for CPMG-Sequence



In the EPG-method the magnetization states at each echo are labelled according to the degree of dephasing. Signal evolution can then be described by transition matrices linking connected states. The number of calculations increases linearly with the number of echoes.

Extended Phase Graphs

Effect of RF-pulses is calculated by a transition matrix acting on configuration states of identical k:

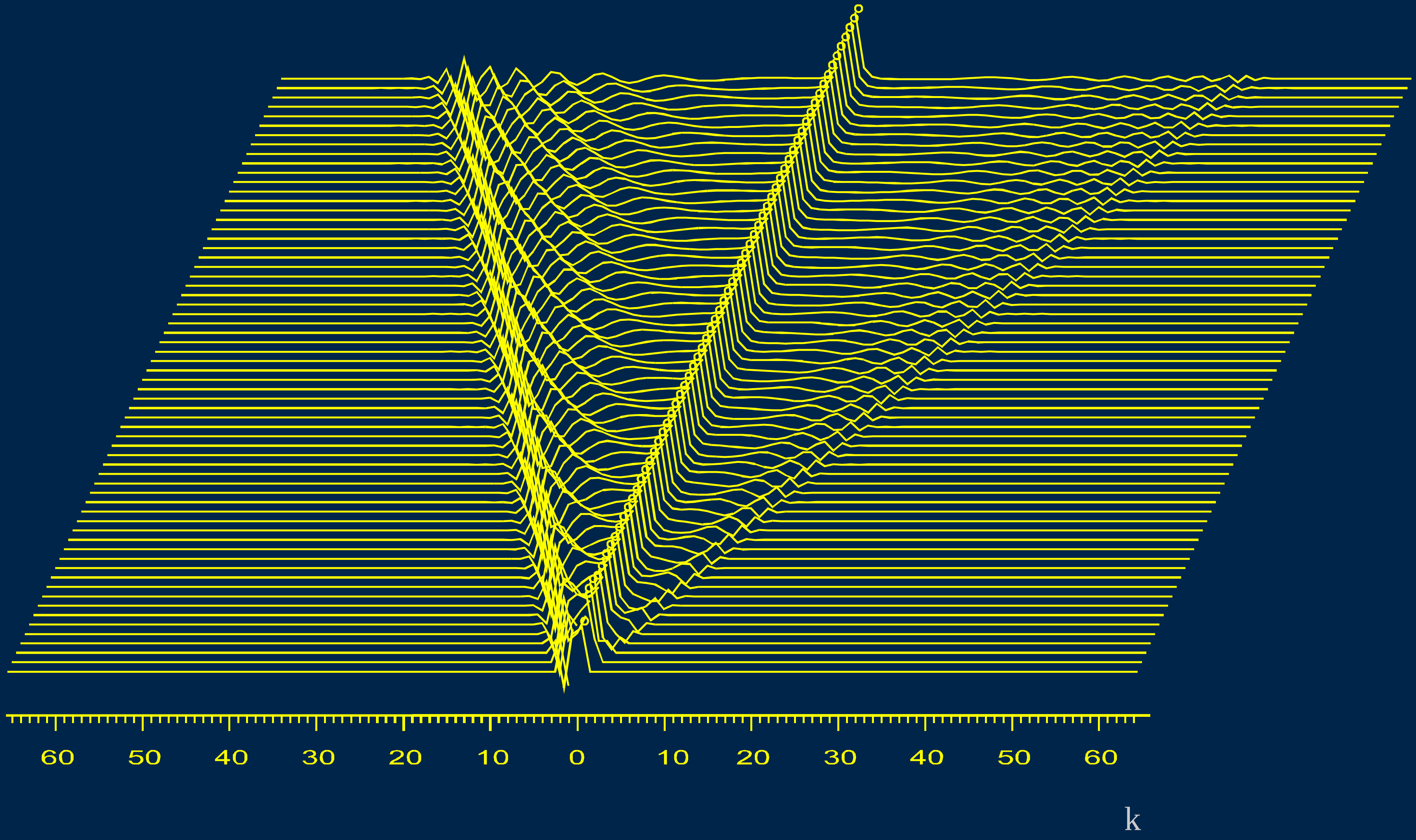
$$\begin{bmatrix} F_+ \\ F_- \\ Z \end{bmatrix}^+ = \begin{bmatrix} cos^2(\frac{\alpha}{2}) & sin^2(\frac{\alpha}{2}) & -\mathrm{i}\sin(\alpha) \\ sin^2(\frac{\alpha}{2}) & cos^2(\frac{\alpha}{2}) & \mathrm{i}\sin(\alpha) \\ -\frac{\mathrm{i}}{2}\sin(\alpha) & \frac{i}{2}\sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{bmatrix} F_+ \\ F_- \\ Z \end{bmatrix}^- \qquad [1]$$

This can be calculated from

$$\begin{bmatrix} F_+ \\ F_- \\ Z \end{bmatrix}^+ = \left\{ \begin{bmatrix} 1 & i & 0 \\ 1 & -i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(a) \\ 0 & -\sin(a) & \cos a \end{bmatrix} ½ * \begin{bmatrix} 1 & 1 & 0 \\ i & -i & 0 \\ 0 & 0 & 2 \end{bmatrix} \right\} \begin{bmatrix} F_+ \\ F_- \\ Z \end{bmatrix}^-$$

M. Weigel, Extended Phase Graphs: Dephasing, RF Pulses, and Echoes - Pure and Simple, J. Magn. Reson. Imaging. 41 (2015) 266–295.

Evolution of f(k),f(k)* with a 90°-refocussing pulse



Evolution of f(k),f(k)* with a 30°-refocussing pulse

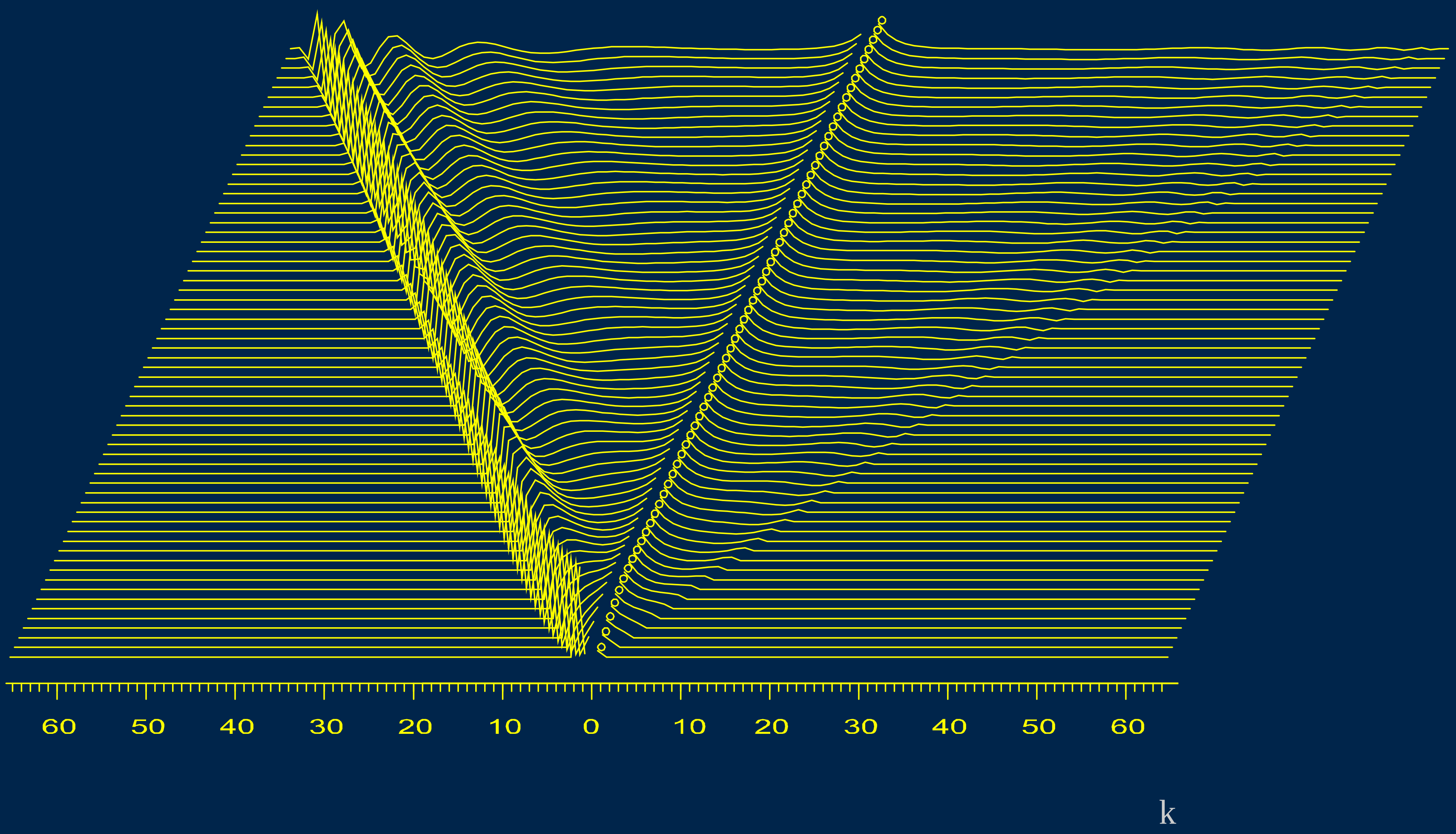
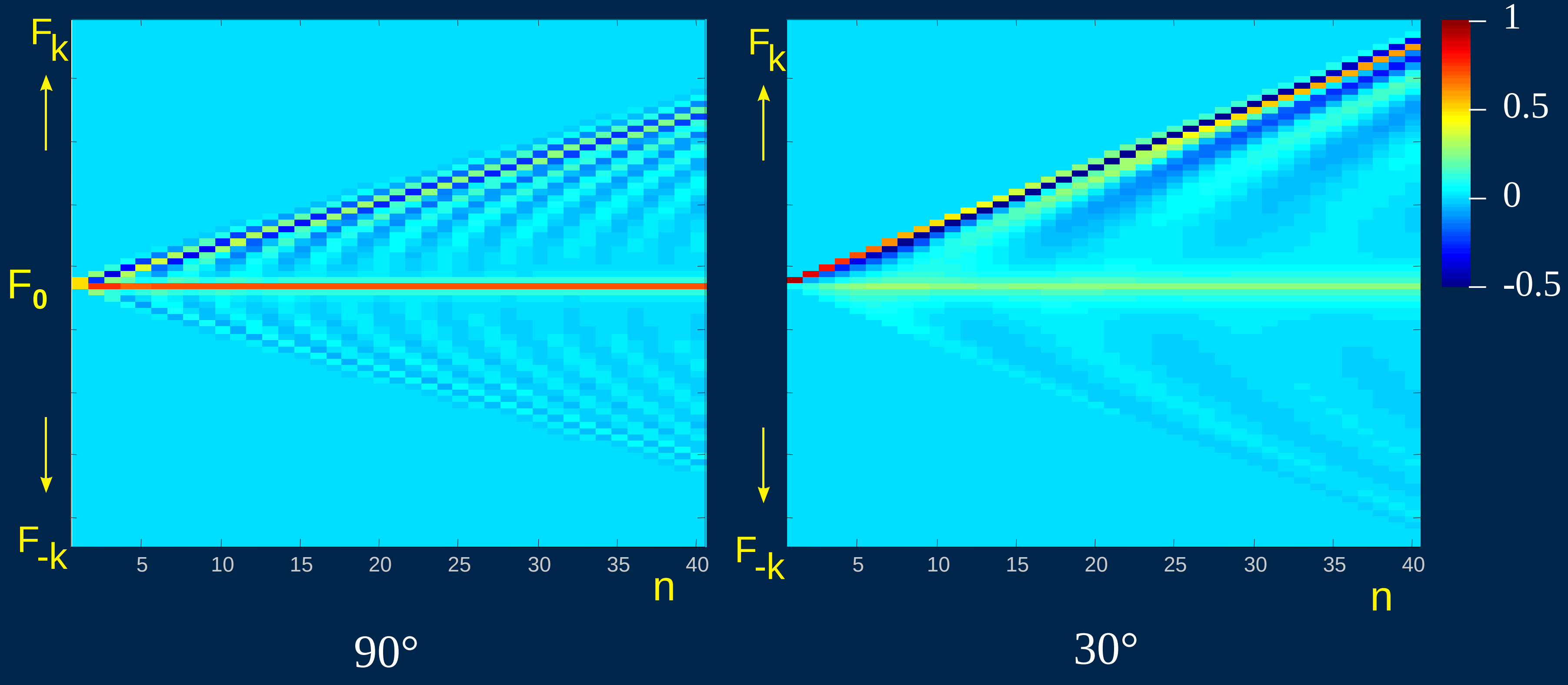
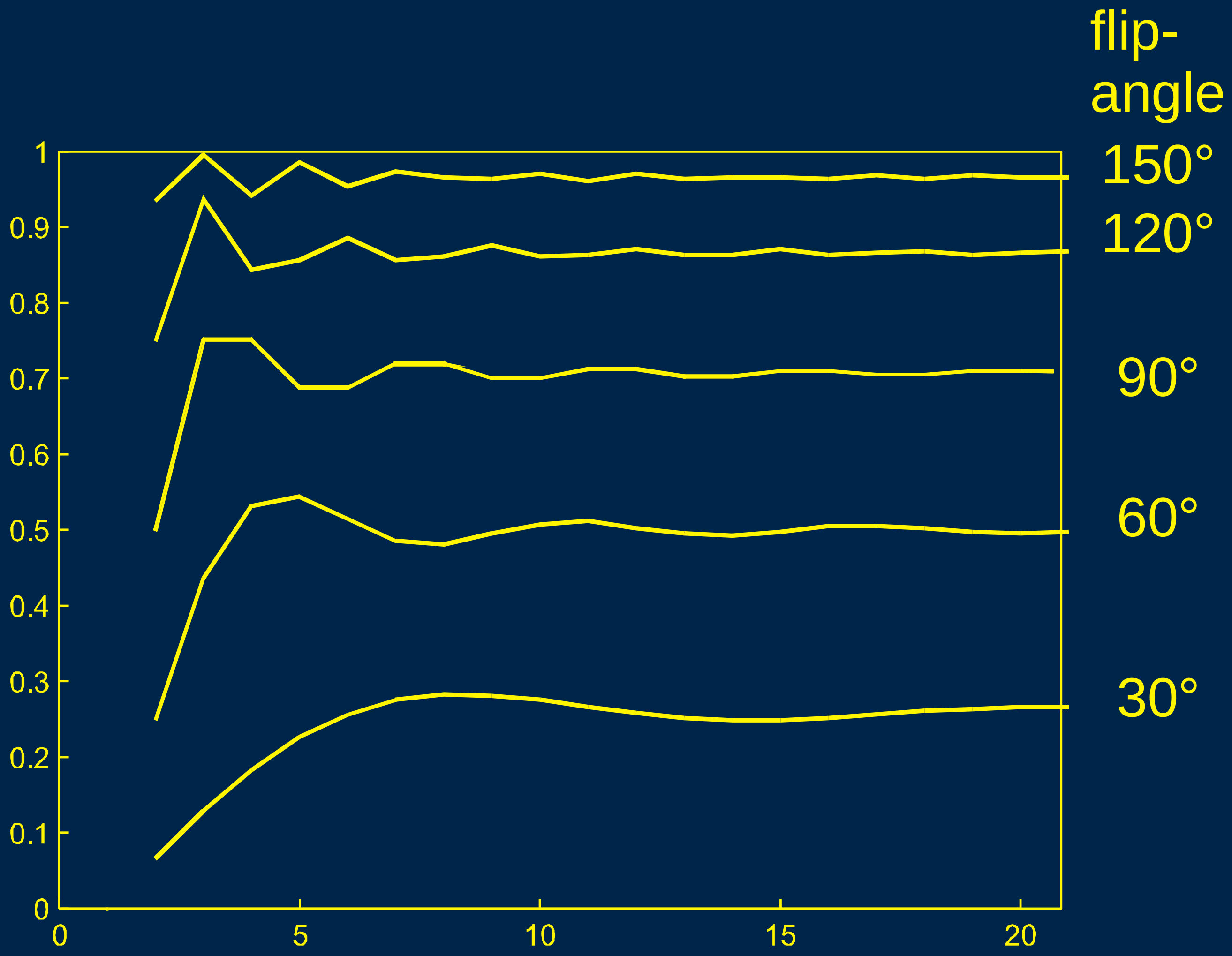


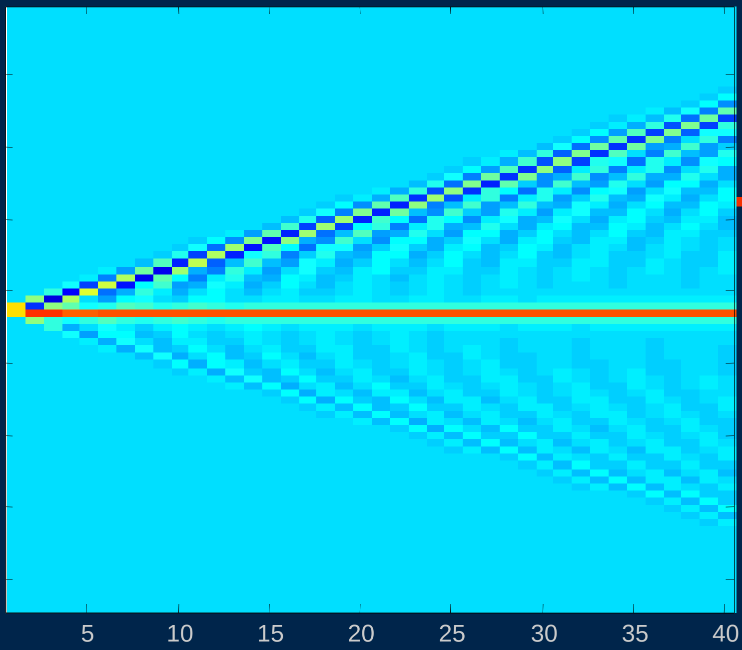
Image Display of EPG



Pseudo steady states in CPMG-multiecho experiments with constant refocusing flip angles

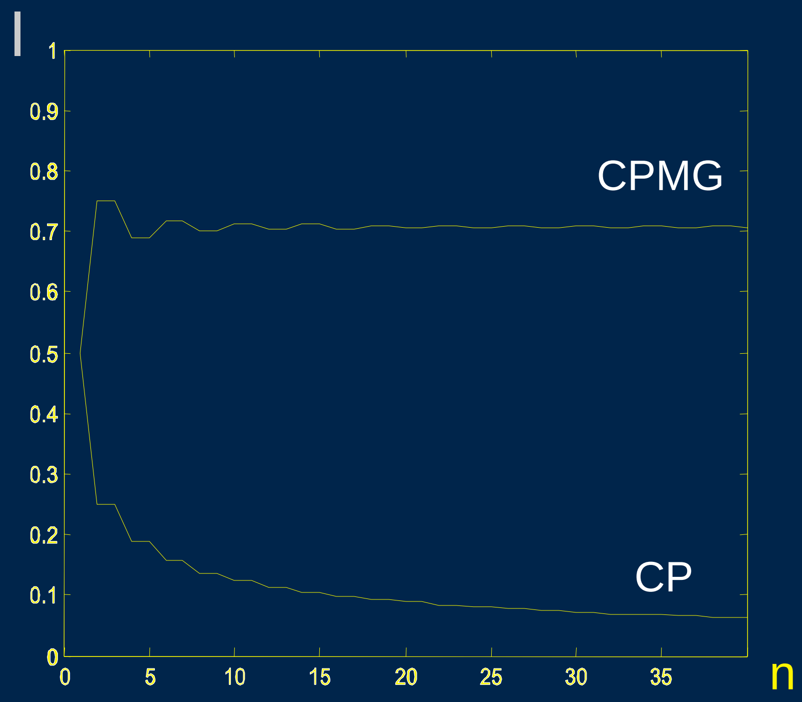


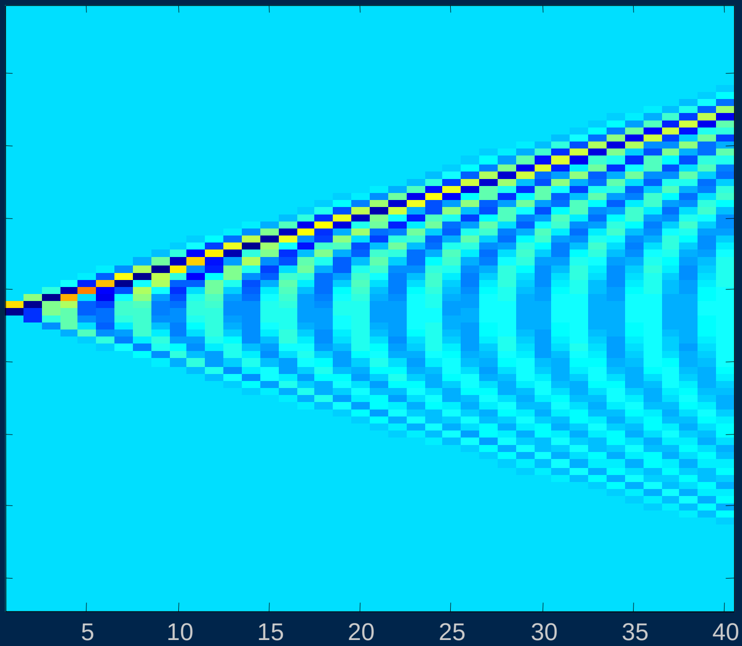
Hennig, J., Multiecho Imaging Sequences with Low Refocusing Flip Angles. J. Mag. Res.; 78: 397 (1988)



EPG of CP- vs. CPMG-sequence

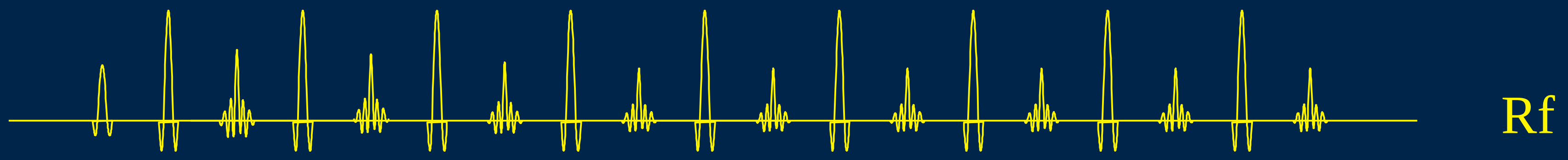
CPMG (Phase of the refocusing pulses is orthogonal to phase of the excitation pulse)





CP (all pulses have the same phase)

Using a CPMG-Echotrain for Imaging: RARE(TSE, FSE…)



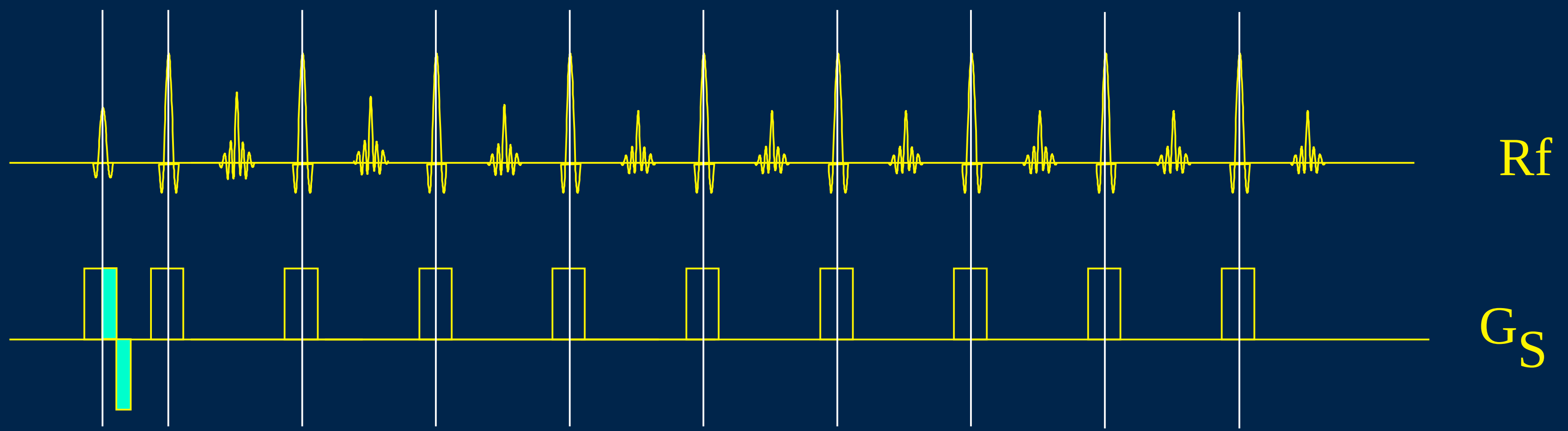
Acquiring different phase encoding steps in each echo, the acquisition time of spin echo imaging can be reduced by a factor of ETL, where ETL is the echo train length.

In order to use a CPMG-sequence for imaging, gradients are applied, such that

- Conditions for image encoding are met

- CPMG-conditions are met.

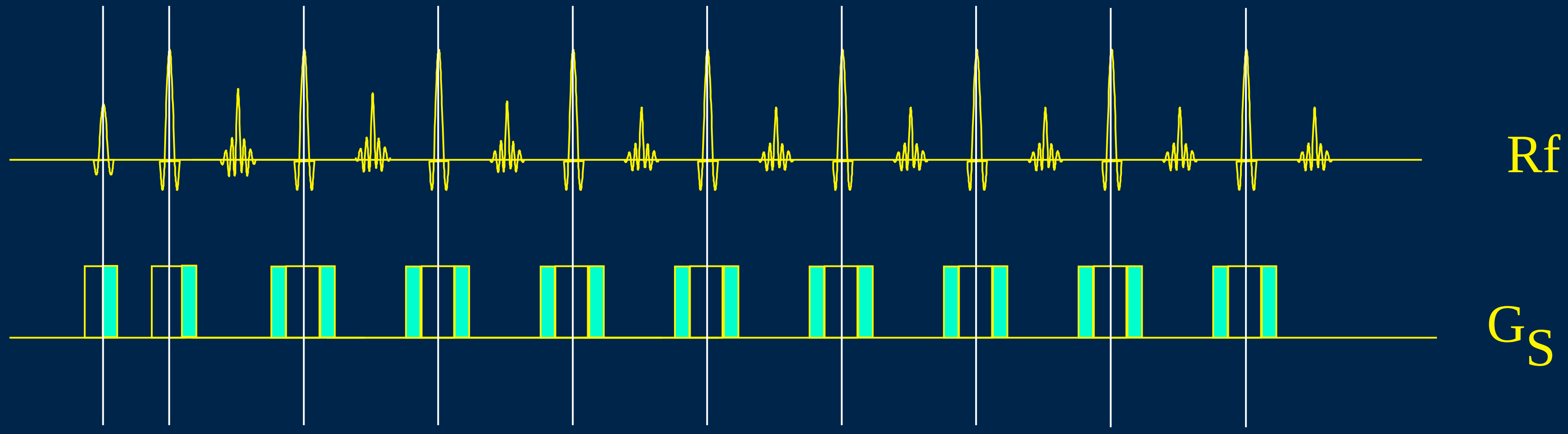
RARE(TSE, FSE…): balancing gradients



all gradients need to be properly balanced in order to avoid interference of signals generated via different refocusing pathways.

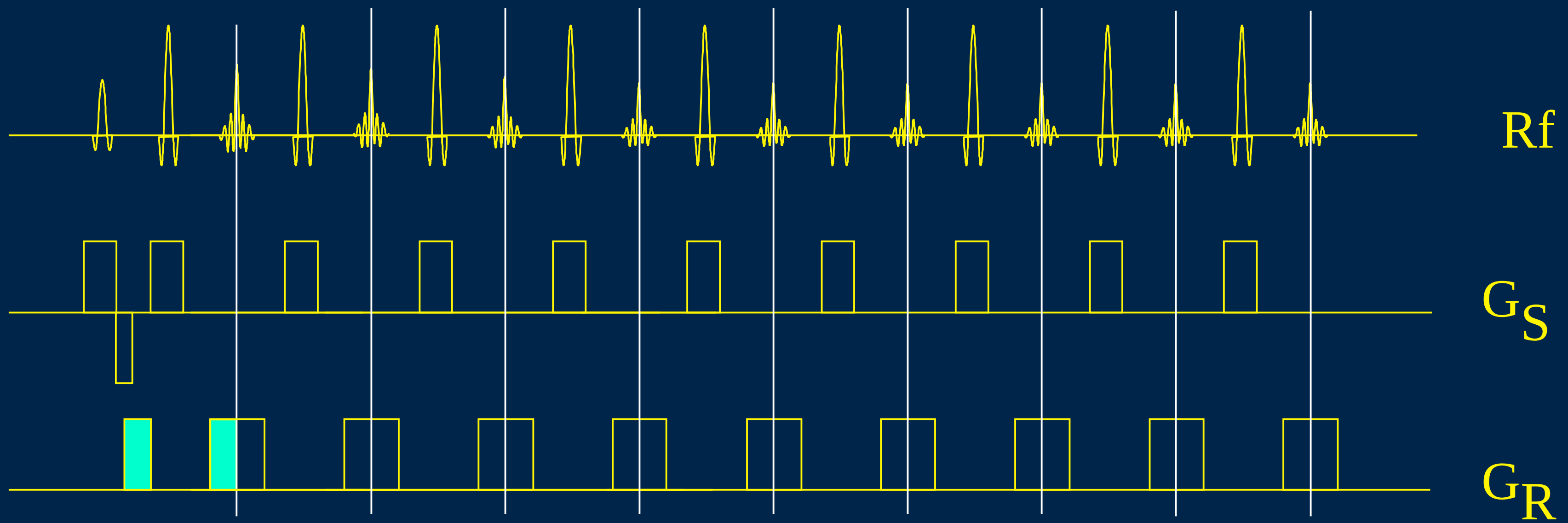
slice selection gradient: the slice selection gradient is placed symmetrically around the refocusing pulses.
the slice selection gradient under the excitation pulse is compensated by an appropriate 'trim'-gradient.

RARE(TSE, FSE…): balancing gradients



the trim gradient can be moved after the refocusing pulse.
Slice selection gradients for all following refocusing pulses have to be modified accordingly.

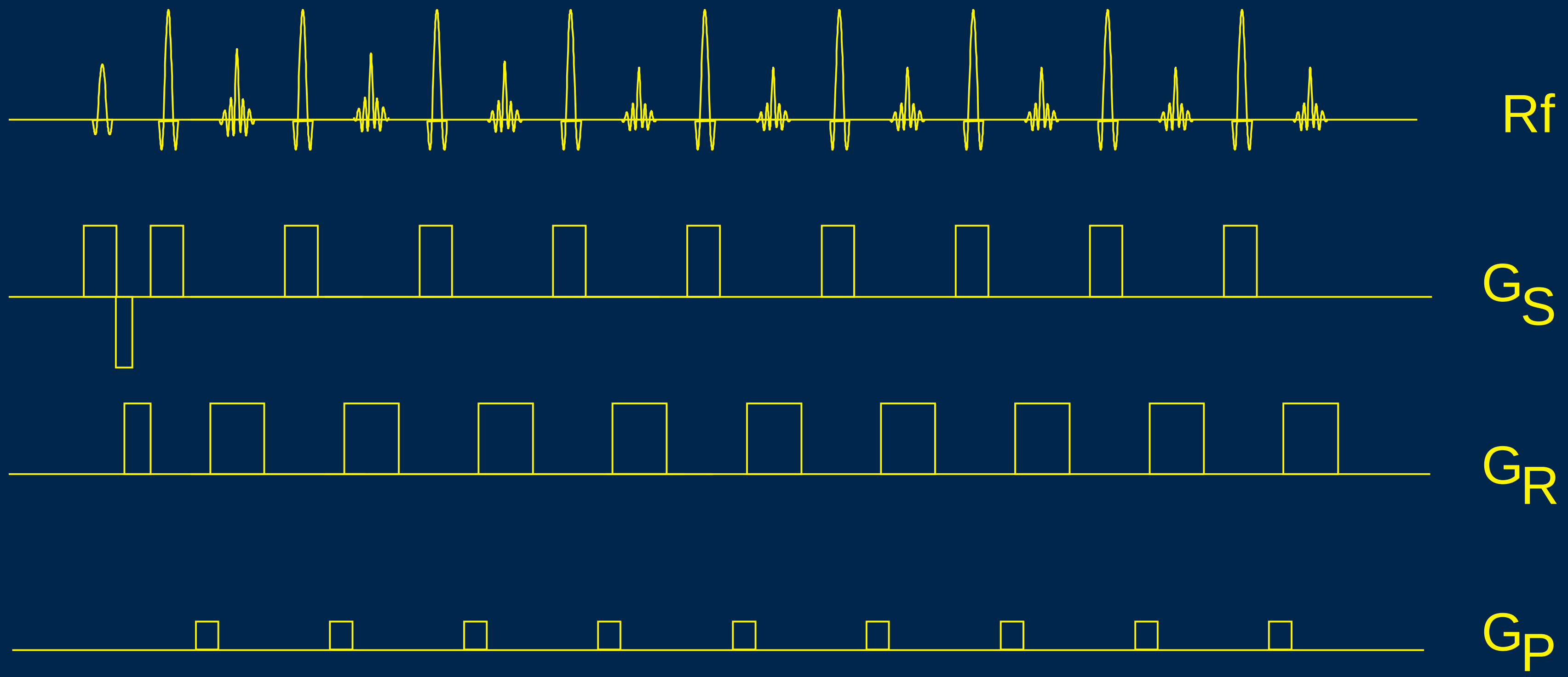
RARE(TSE, FSE…): balancing gradients



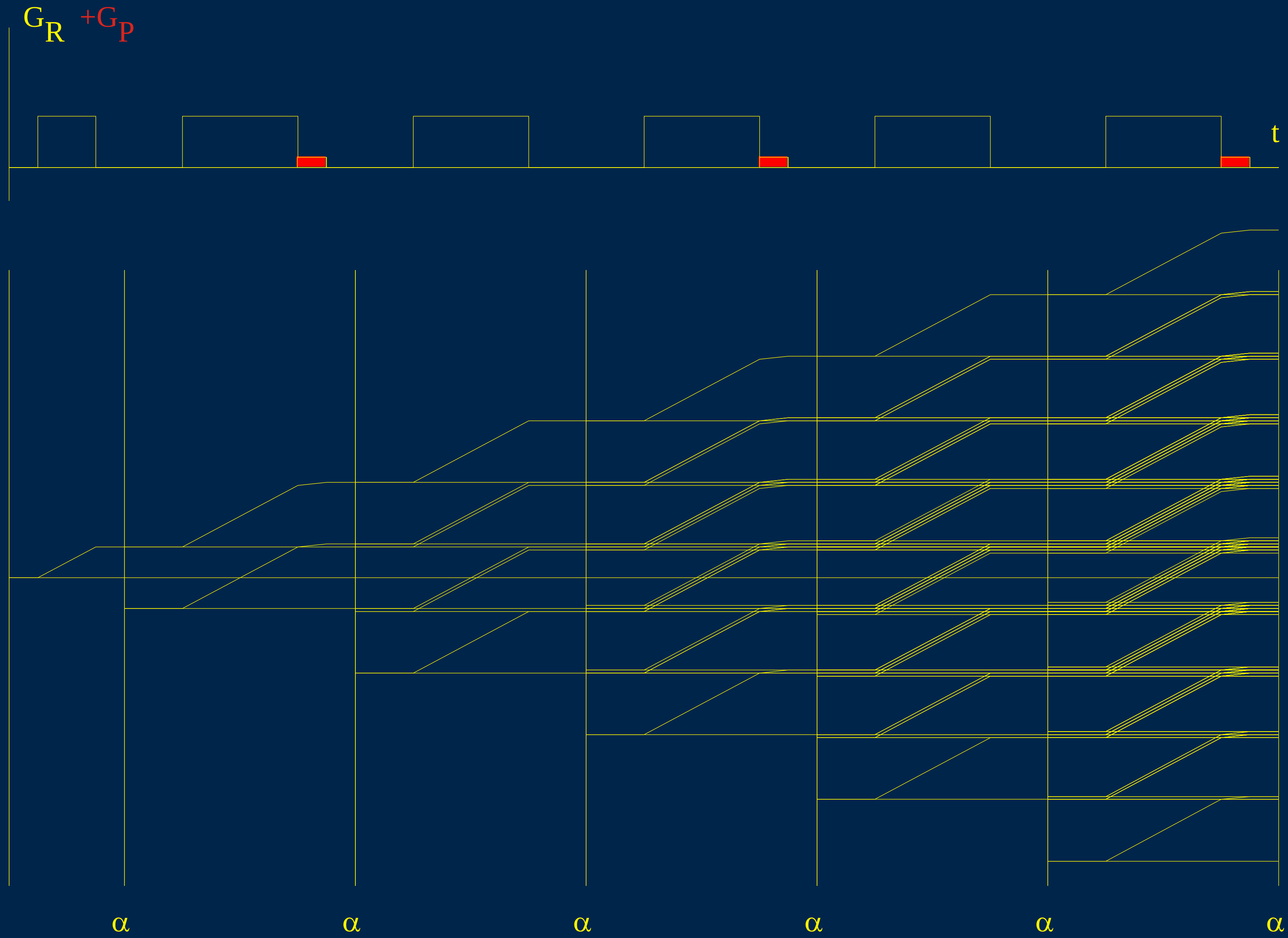
readout gradient: the area under the readout gradient between the excitation pulse and the first refocusing pulse is half the area of the readout gradient between successive refocusing pulses.

The gradients are placed such, that the echo occurs at the center of each refocusing interval.

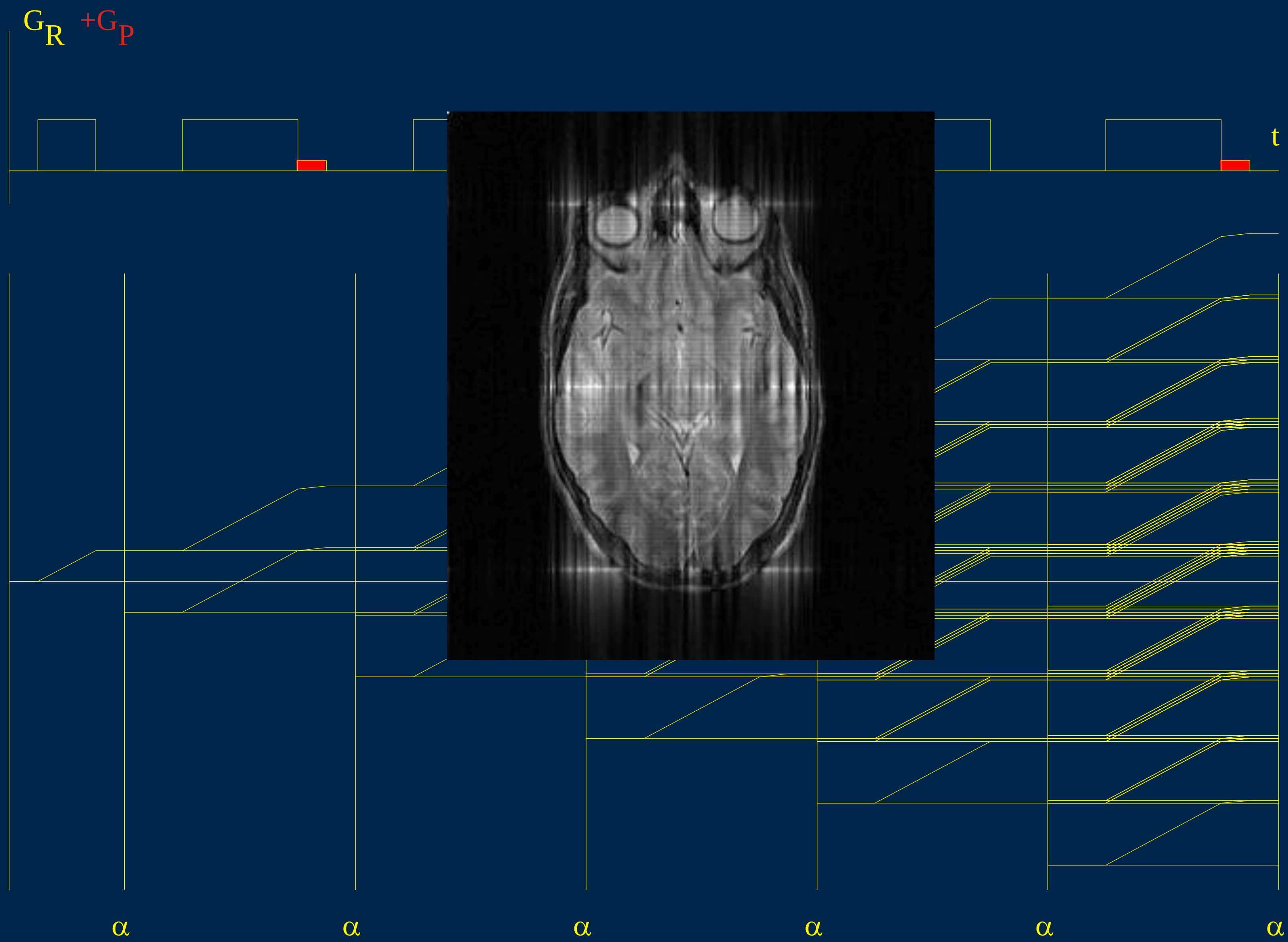
RARE(TSE, FSE…): balancing gradients ?



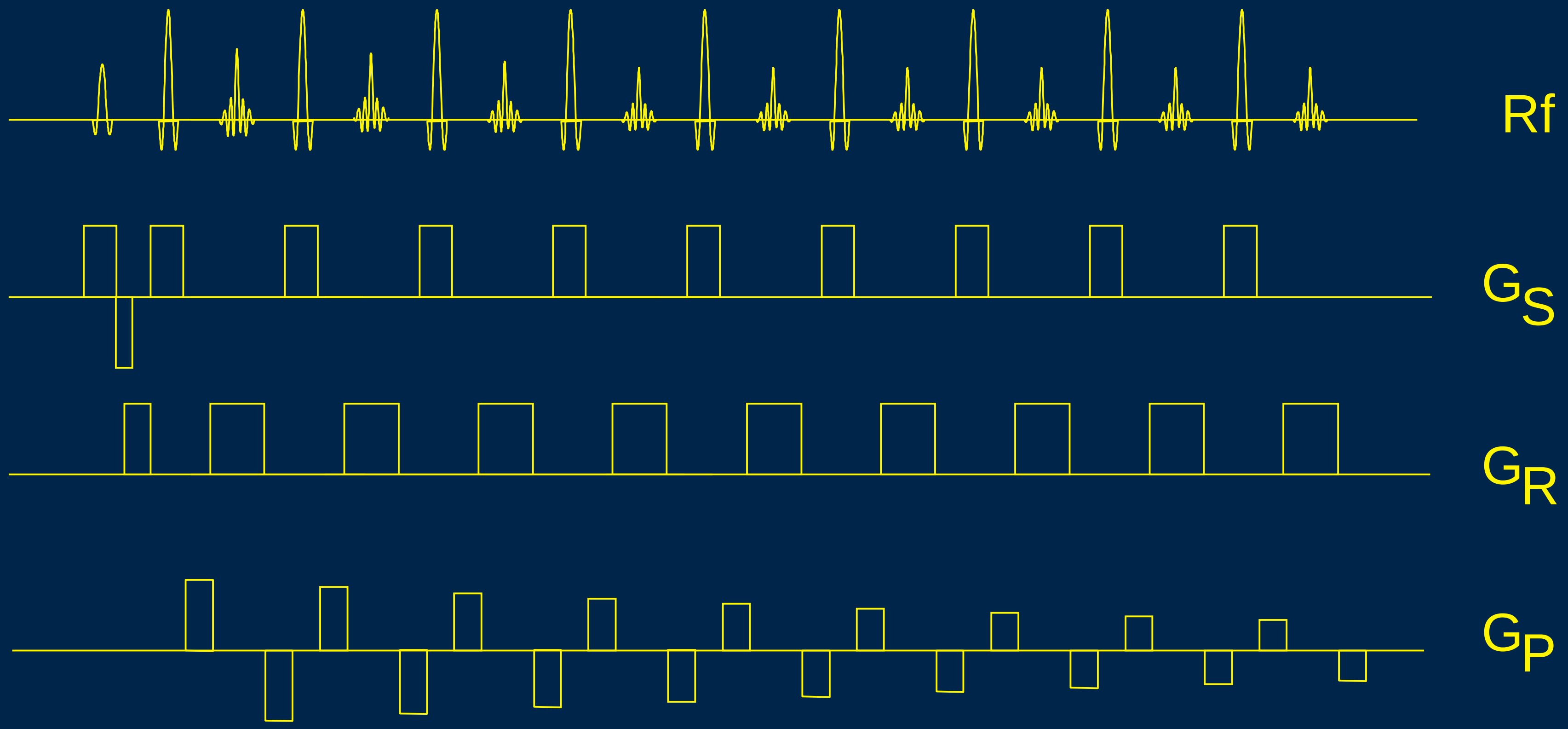
Splitting of EPG by the combined effect of readout- and phase encoding gradient



Splitting of EPG by the combined effect of readout- and phase encoding gradient

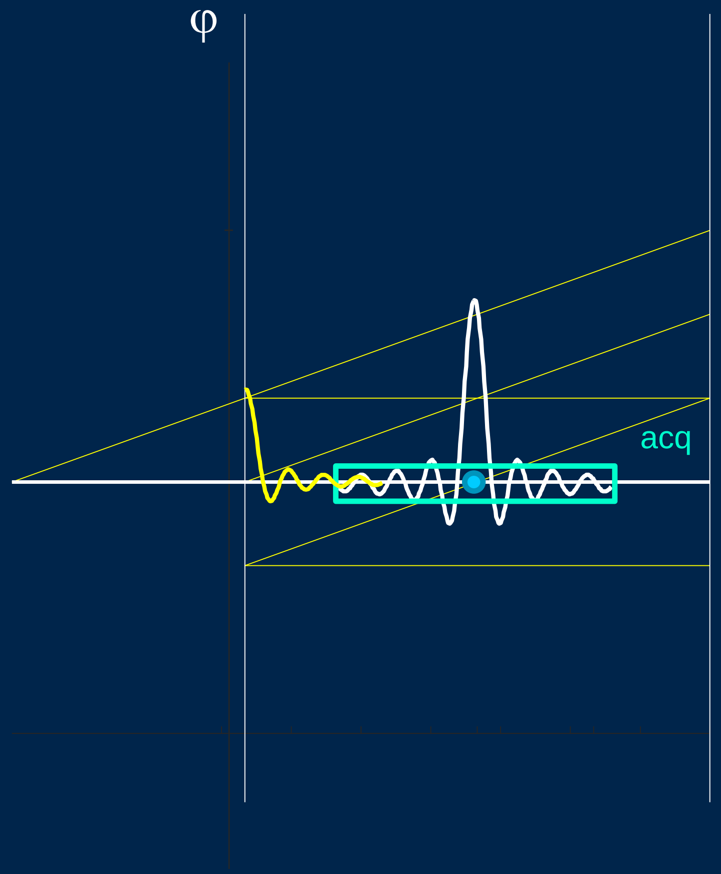


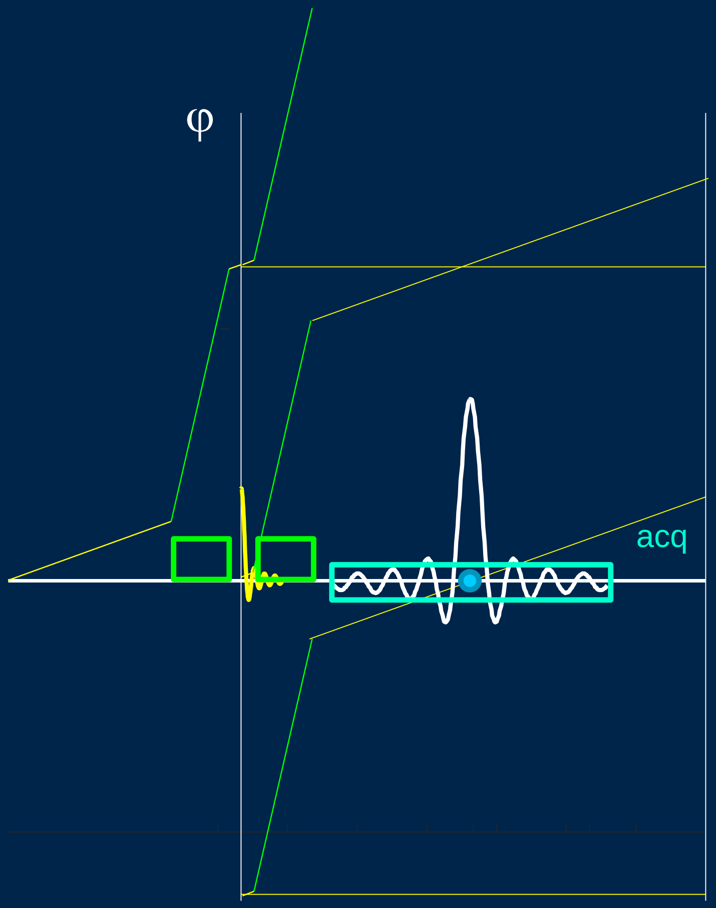
RARE(TSE, FSE…): balancing gradients



phase encoding gradient: The phase encoding gradient must be rewinded before the next refocusing pulse.

What do do about FIDs ?



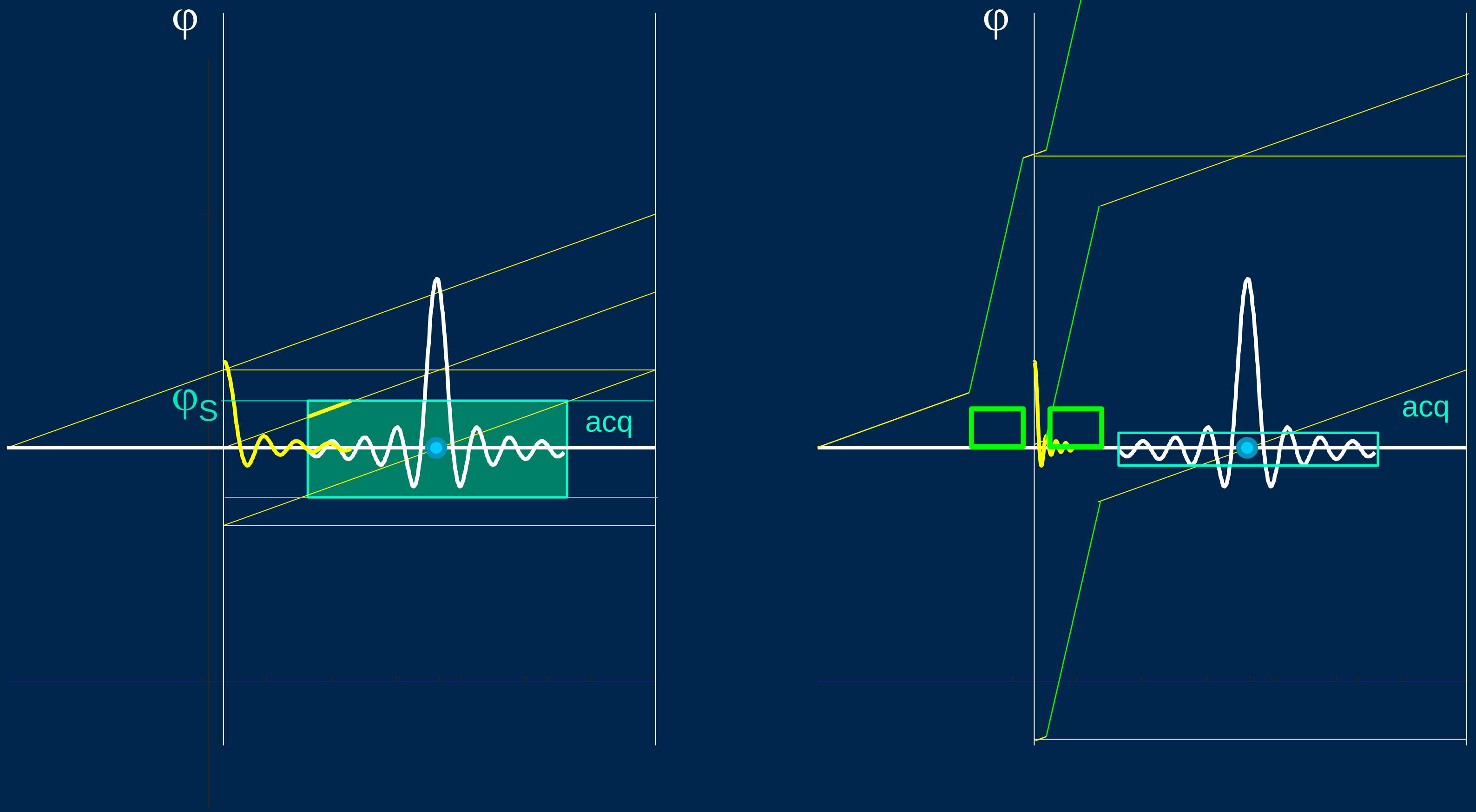


The phase graph indicates the echo maximum
The echo extends over the acquisition window
The FID will interfere with the echo

A spoiler gradient placed symmetrically around the refocusing pulse removes the FID, but leaves the echo intact.

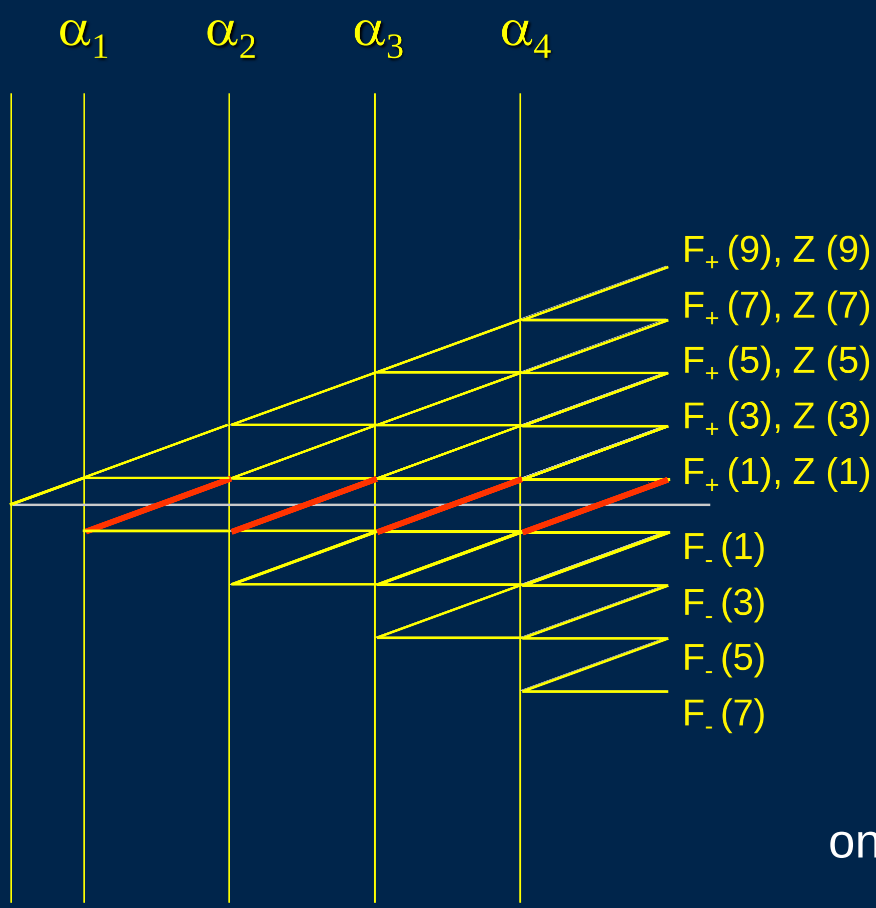
How to curb the number of echo pathways

use gradients to select the desired pathway and to push undesired patways out of the acquisition window



no part of the phasegraph of undesired pathways should be within the shaded area defined by the dephasing of the proper echo over the acquisition window

Algorithm for prescribed echo amplitudes



Calculate flip angle α_1 for first echo.

Calculate EPG for α_1

Calculate flip angle α_2 for 2nd echo.

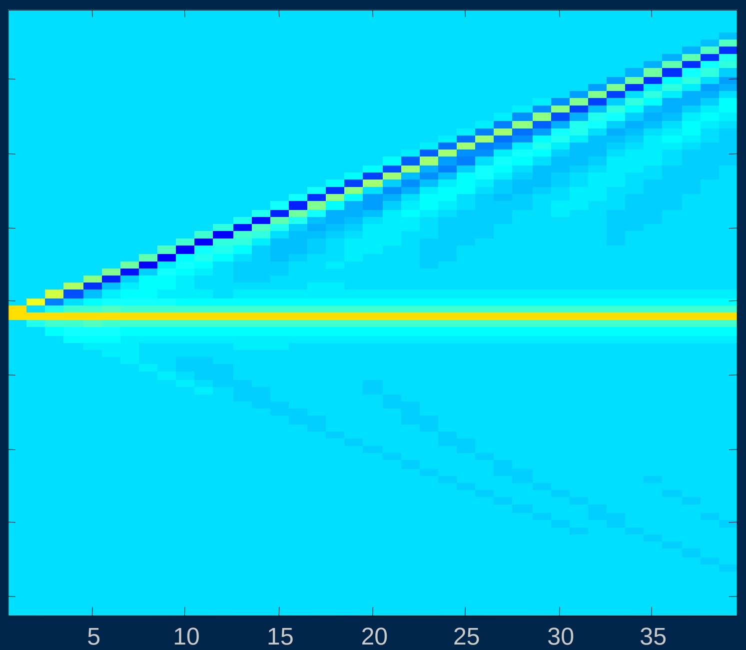
Calculate EPG for α_2

……

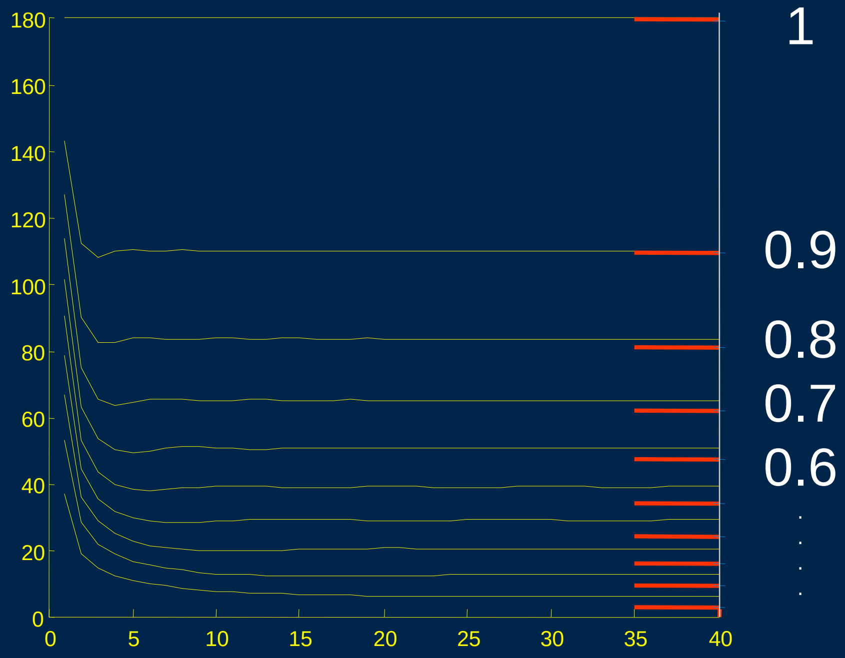
only the $F_-(1)$ needs to be calculated:

$$\begin{bmatrix} F_+(1) \\ F_-(1) \\ Z_+(1) \end{bmatrix}^+ = \begin{bmatrix} cos^2(\frac{\alpha}{2}) & sin^2(\frac{\alpha}{2}) & -\mathrm{i}\sin(\alpha) \\ sin^2(\frac{\alpha}{2}) & cos^2(\frac{\alpha}{2}) & \mathrm{i}\sin(\alpha) \\ -\frac{\mathrm{i}}{2}\sin(\alpha) & \frac{i}{2}\sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{bmatrix} F_+(1) \\ F_-(1) \\ Z_+(1) \end{bmatrix}^-$$

1-ahead solution for constant amplitudes



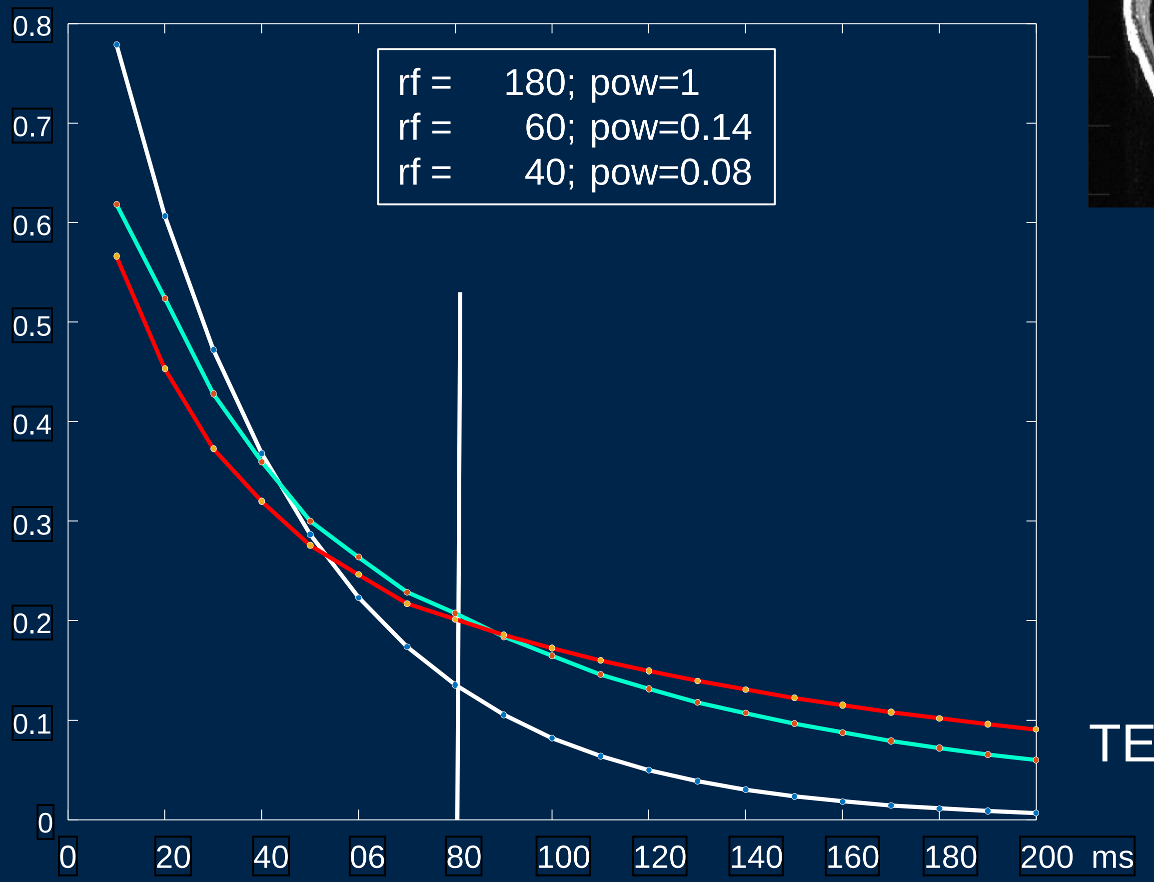
EPG for I=0.5

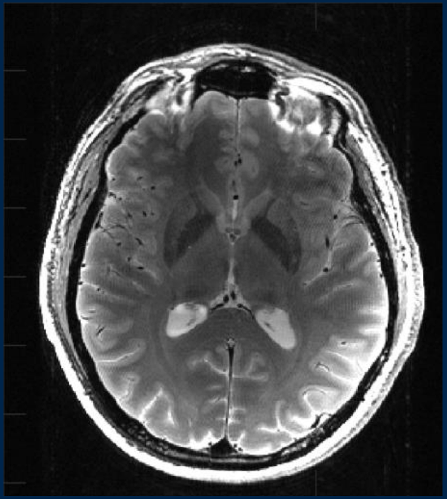


flip angles for constant amplitudes

Why Low Refocusing Flip Angles ?

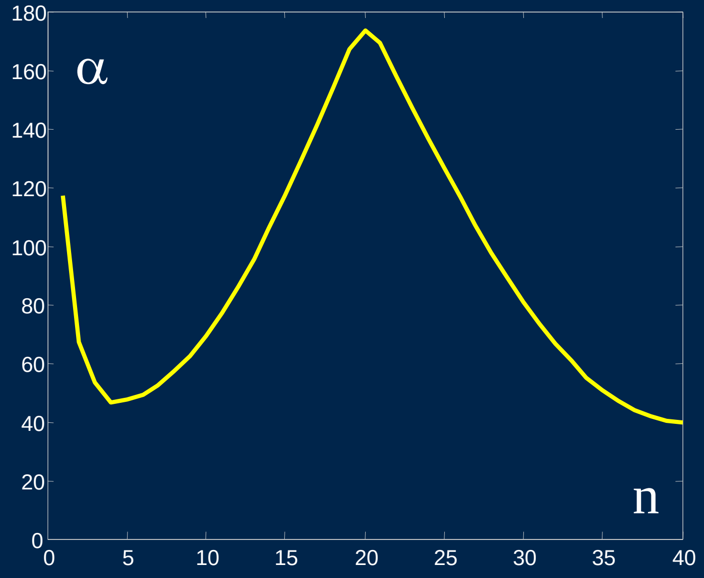
- Lower SAR
- more signal at effective echo time
- better point spread function

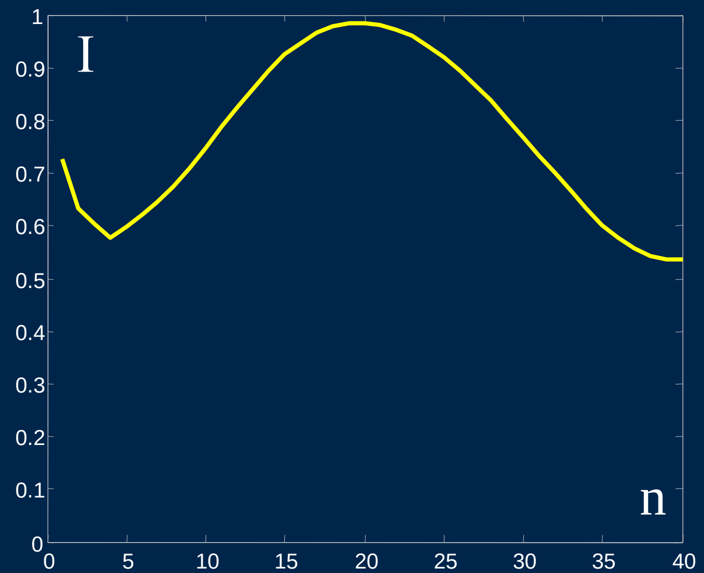


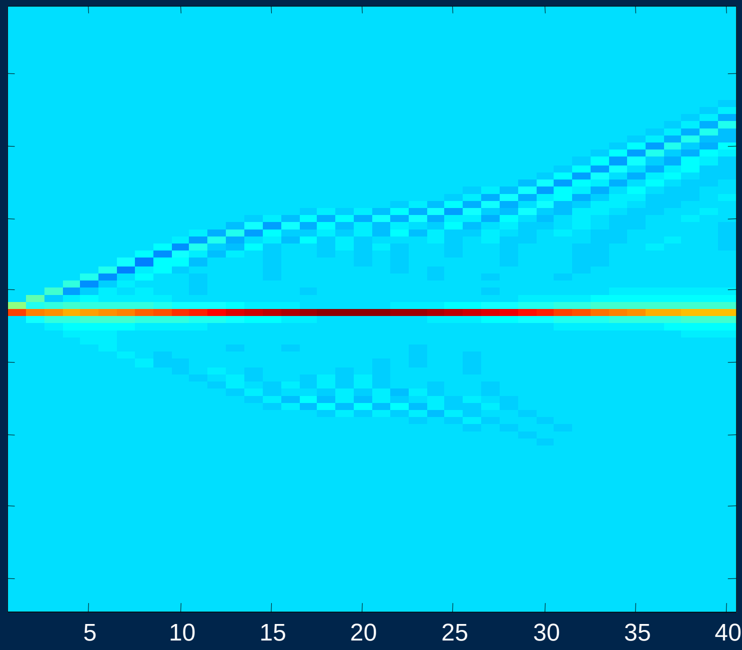


TSE @ 7T

Optimization of signal amplitudes with TRAPS

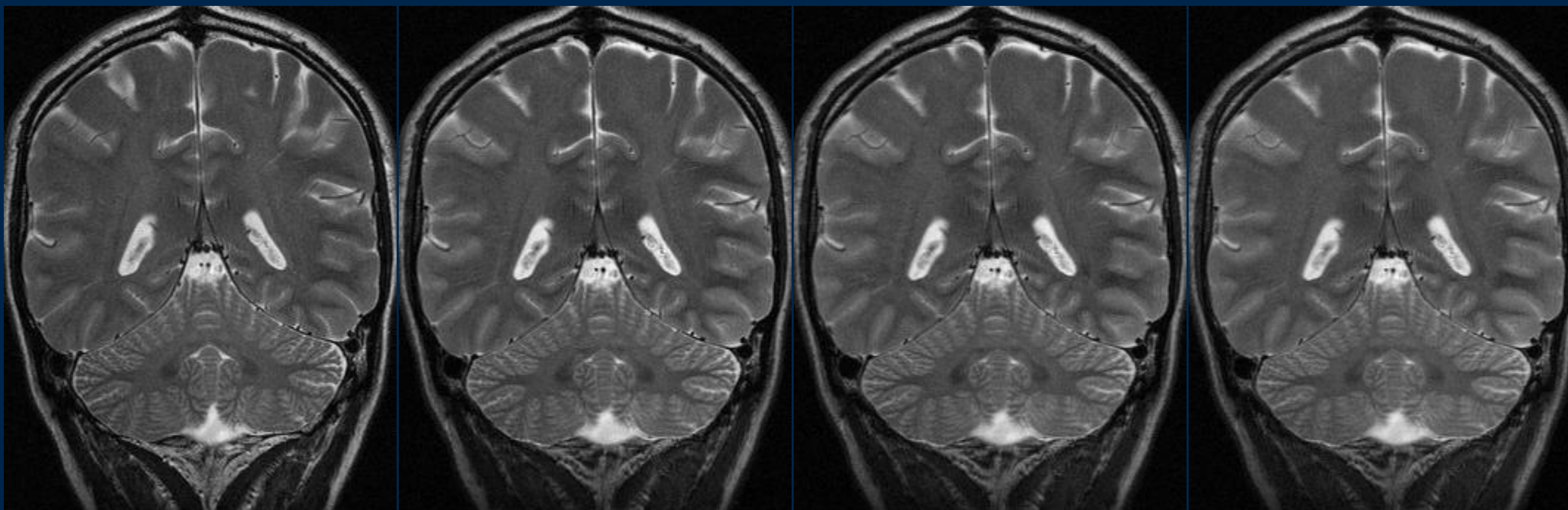






Hennig J, Weigel M, Scheffler K. Multiecho sequences with variable refocusing flip angles: Optimization of signal behavior using smooth transitions between pseudo steady states (TRAPS). Magn Reson Med. 2003 Mar;49(3):527-35

Comparison of volunteer images with matched TE



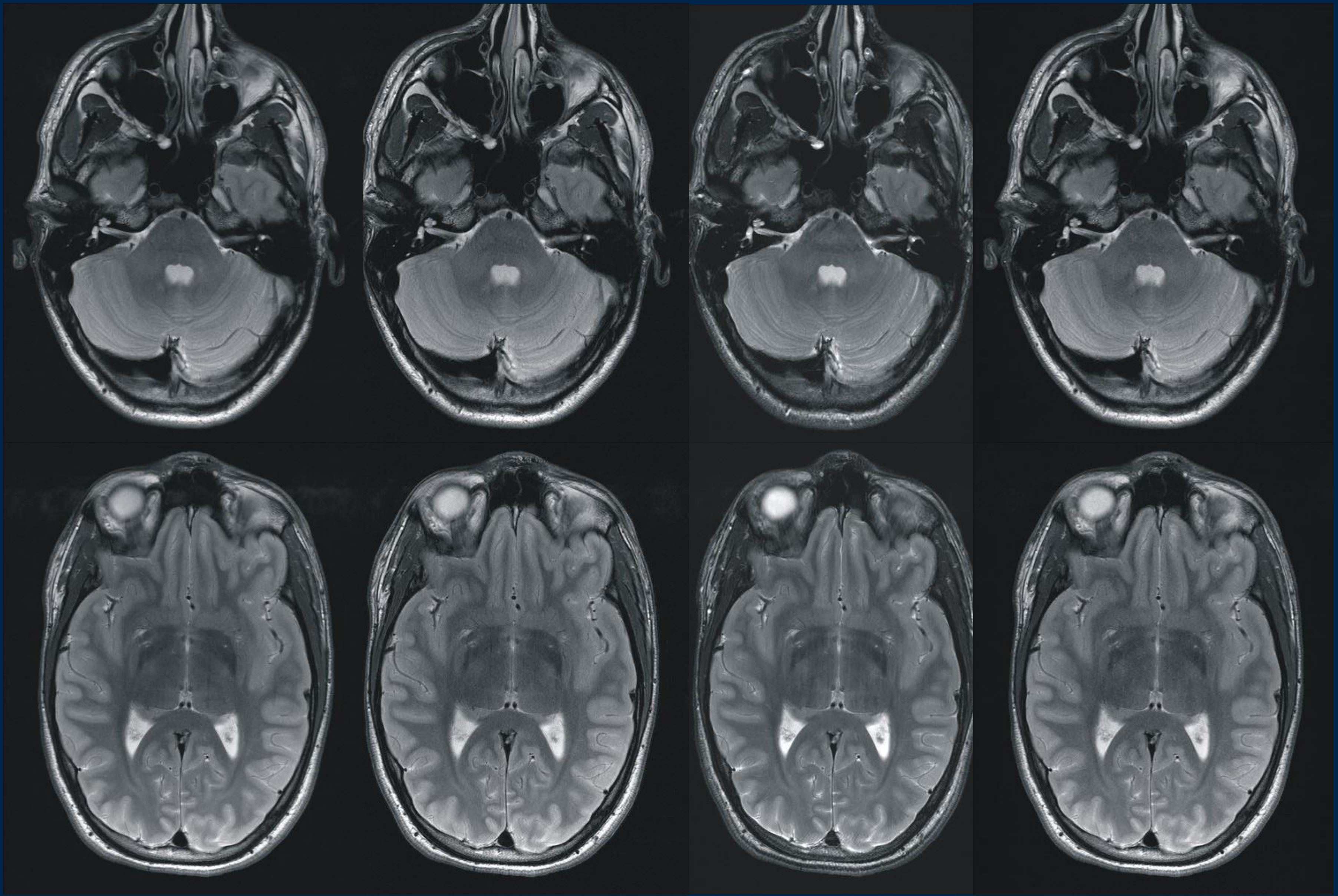
TSE 180°
TE 104 ms
SAR 100%

TRAPS
sym.Gauss
TE 104 ms
SAR 34 %

TRAPS
sym.Exp.
TE 104 ms
SAR 26 %

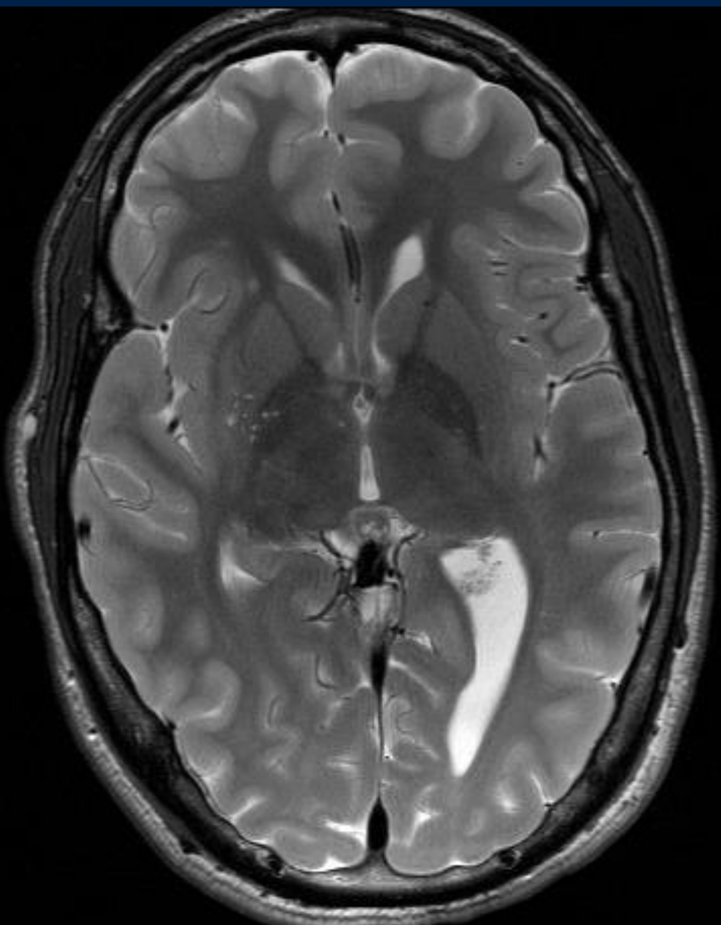
TRAPS
TE 104 ms
SAR 20 %

TRAPS | HF 5/8 (1) | GRAPPA (2/26) HF 5/8, (2) | GRAPPA (2/26) (2)

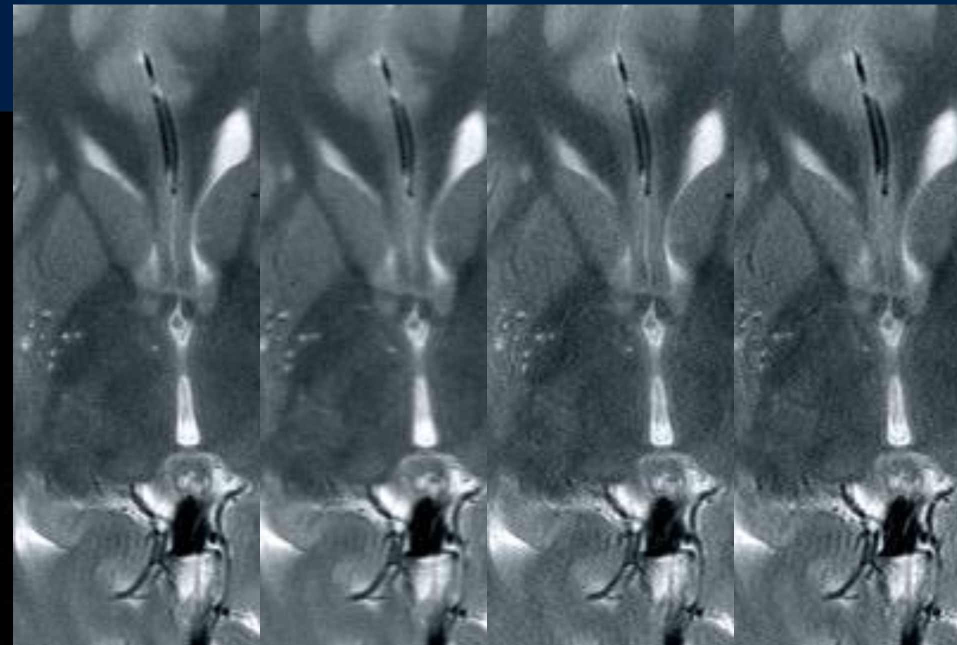


SNR 100 | 84 | 134 | 161

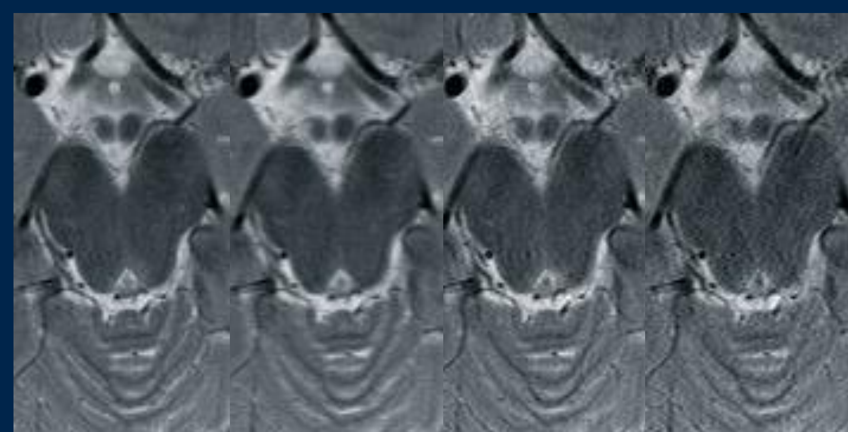
Image salience
hyperTSE with red.acq.



3T, ETL 25, TE/TR 90/4000,
SLTH 3 mm, FOV 25.6, 512x512



100 75 67 32 %



Take Home Messages

- a pulse is a pulse is a pulse…
  take care of unwanted signals

- periodic sequences drastically reduce the compexity of echo formation pathways.

- The EPG allows to calculate signal intensities for arbitrary pulse sequences and to develop optimized flip angle schemes.

- Use proper flip angles and phases for your RF pulses.

- TSE (FSE, RARE,…) with low refocusing flip angles improves SNR and the PSF and reduces SAR.