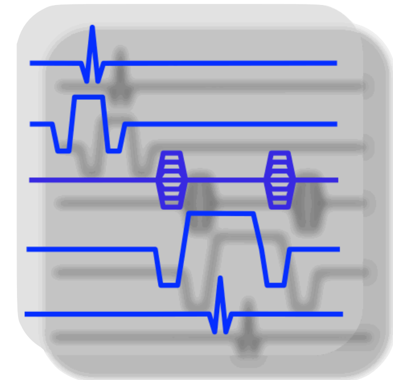


Principles of MRI

EE225E / BIO265

Chapter 07 Imaging Considerations

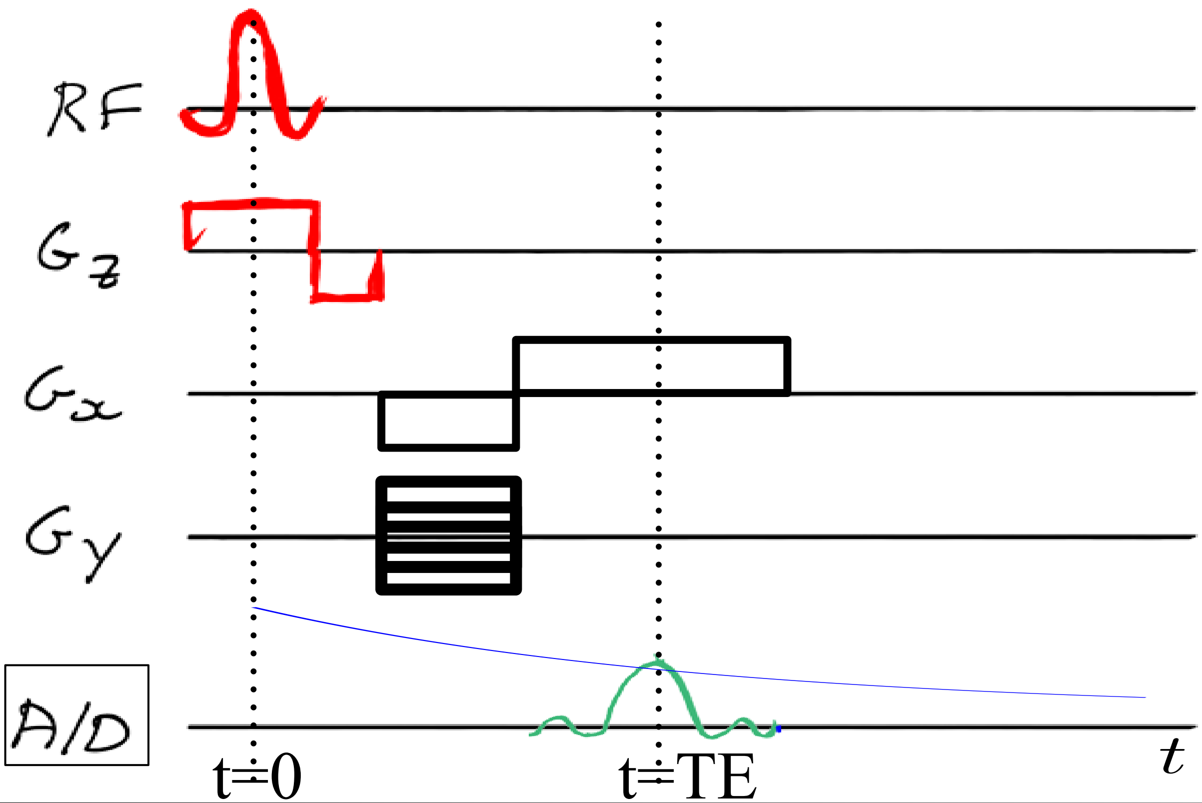
Next:

- Practical Issues in MRI
- T_2 decay
  - Map decay to k-space
  - result in artifacts
    - Image weighting
    - blurring in the readout
- Off-resonance

Effect of T2 Decay on Imaging

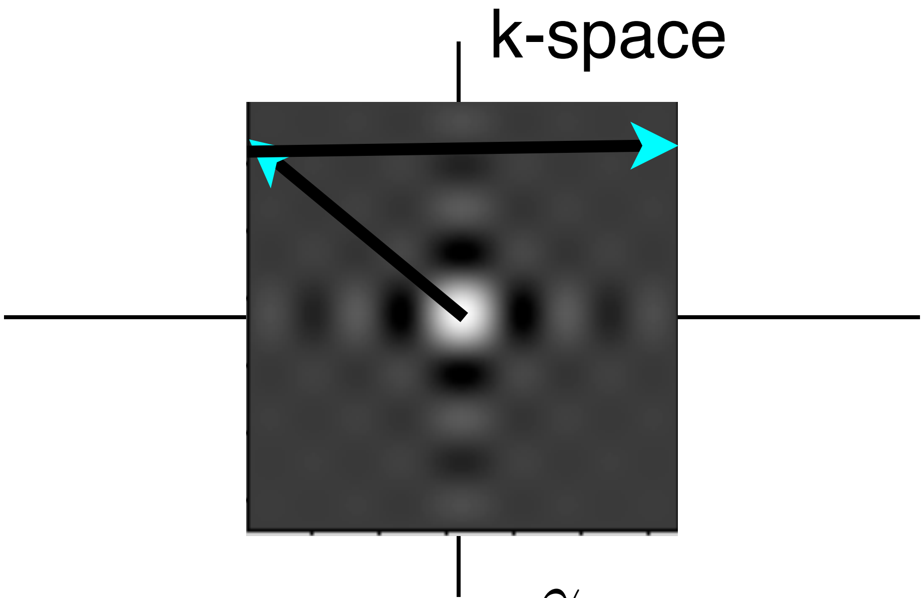
$$s(t) = \int_{\vec{R}} M_{xy}(\vec{r},0) e^{-\frac{t}{T_2}} e^{-i2\pi \vec{k}(t)\cdot\vec{r}} d\vec{r}$$

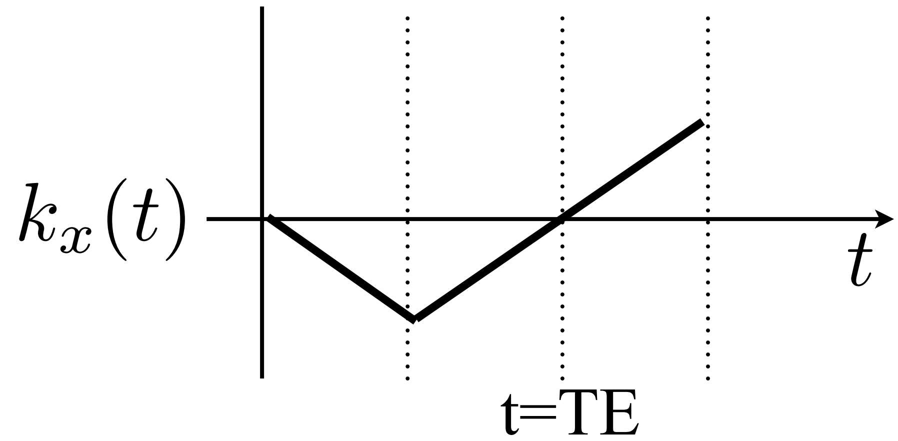
- Signal decays along k-space trajectory



Approximation:
Mxy created mid-RF
Decays with T_2 after

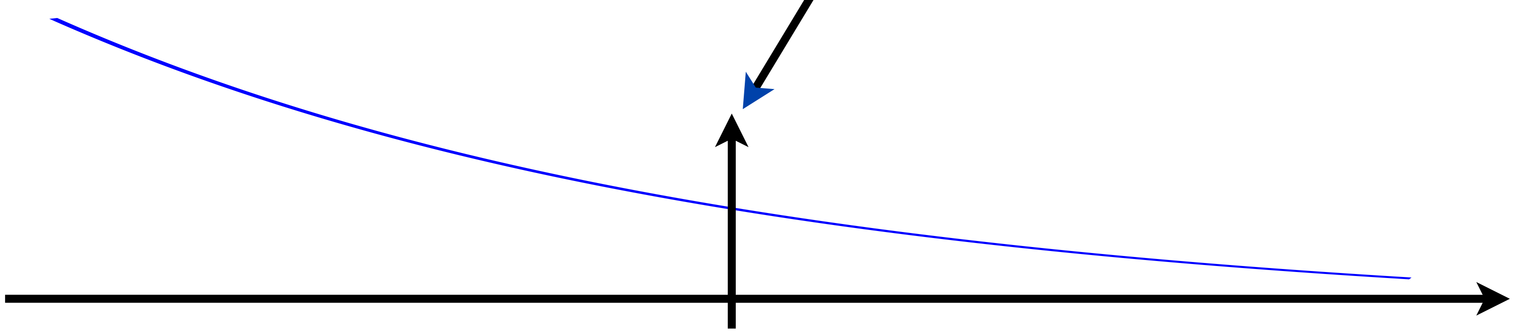
Effect of T2 Decay on Imaging





$$k_x = \frac{\gamma}{2\pi} G_x (t - TE) \;\Rightarrow\; t = \frac{k_x}{\frac{\gamma}{2\pi} G_x} + TE$$

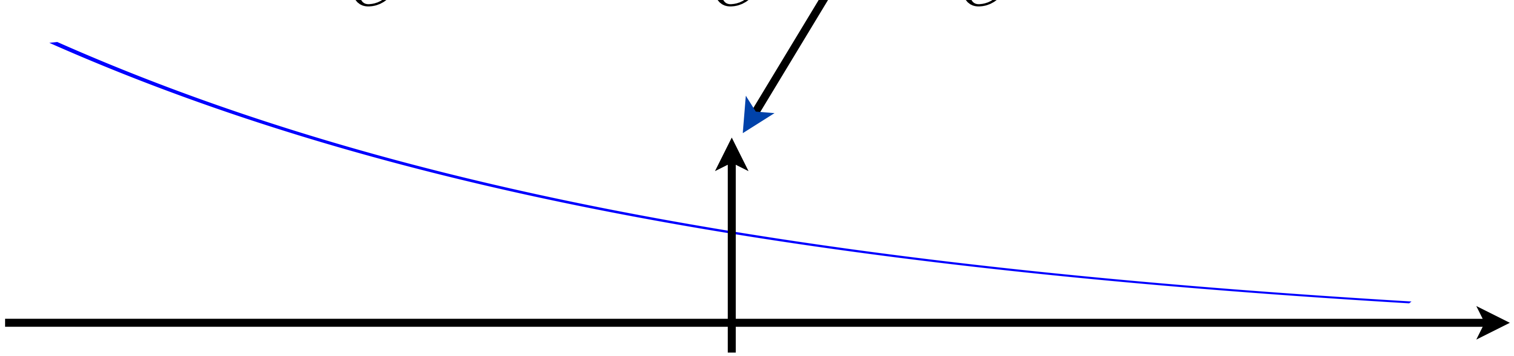
$$e^{-\frac{t}{T_2}} = e^{-\frac{TE}{T_2}} e^{-\frac{k_x}{\frac{\gamma}{2\pi} G_x T_2}}$$



Effect of T2 Decay on Imaging

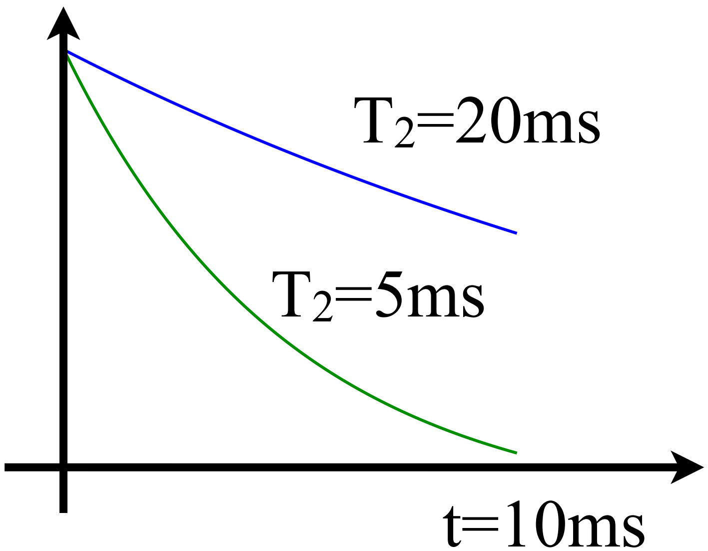
- Two Effects:
  - Signal Loss by $e^{-TE/T2}$ (T_2 Weighting)
  - Apodization by $e^{-\frac{k_x}{\frac{\gamma}{2\pi}G_x T_2}}$
    - Blurring in Image Domain (readout direction)
    - Usually minor effect
    - Reduced by increasing G_x

$$e^{-\frac{t}{T_2}} = e^{-\frac{TE}{T_2}} e^{-\frac{k_x}{\frac{\gamma}{2\pi}G_x T_2}}$$

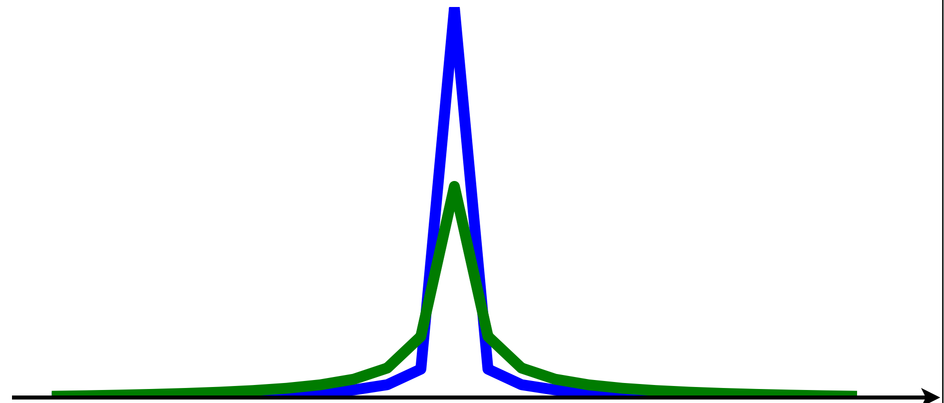


Point Spread Function

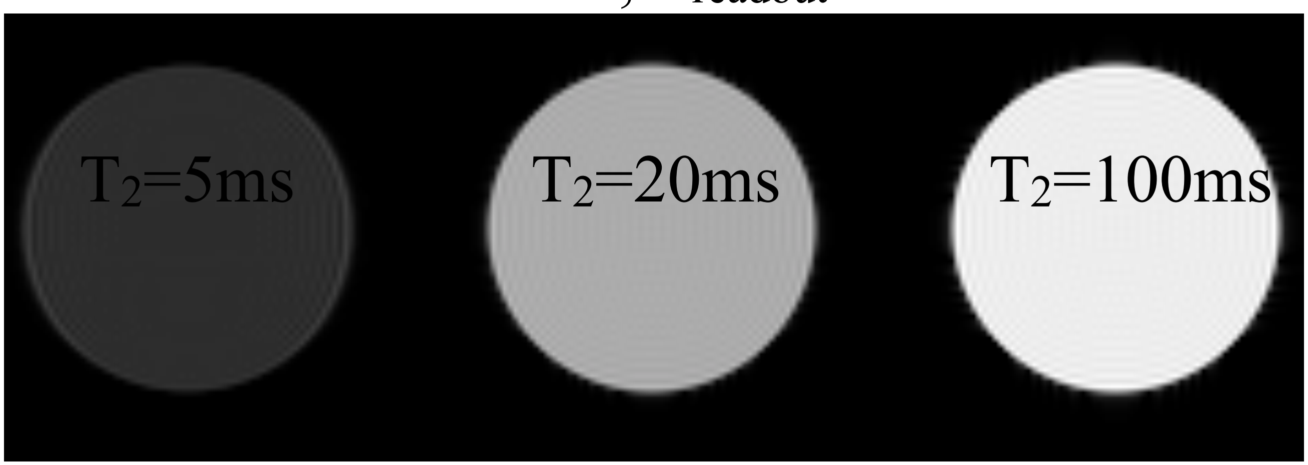
Decay



PSF



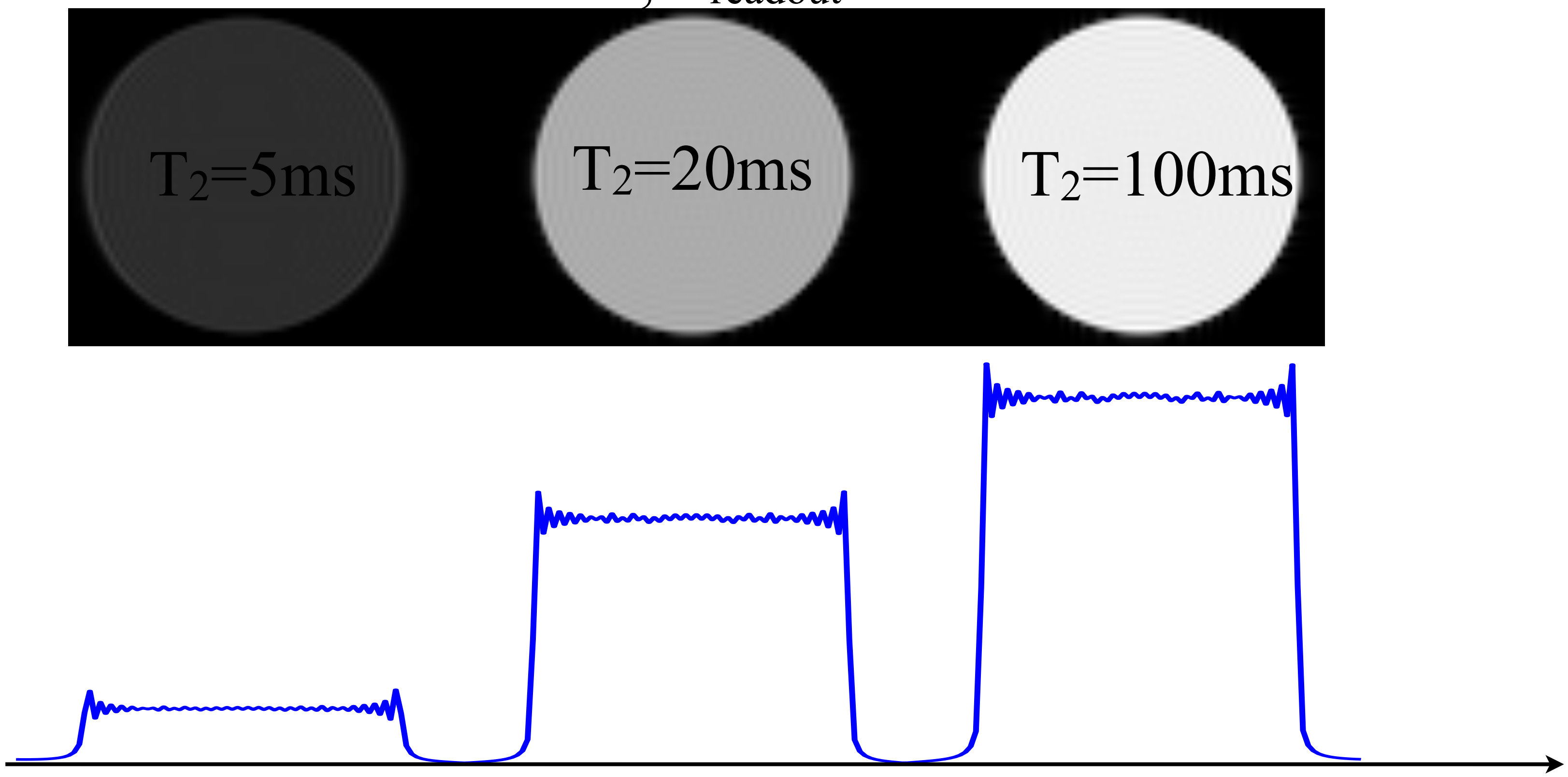
TE=10ms, $T_{readout}$=20ms



Effect of T2 Decay on Imaging

- Two effects:
  - Signal loss by $\exp(-TE/T_2)$ (T2 weighting)
  - Apodization - causes blurring in readout

TE=10ms, $T_{readout}$=20ms



Off - Resonance

- So far, assumed B_0 constant. But B_0 varies due to:
  - Main field inhomogeneity (~ 1ppm)
  - Object magnetic susceptibility
  - Chemical shift

Main Field Inhomogeneity

- Magnet is designed to be homogeneous over a (spherical) volume
- Typical numbers:
  - Bare magnet ~10-100 ppm
  - Shimmed magnet ~1 ppm
    @3T 1ppm is 127Hz
- Generally, main magnet inhomogeneity is <u>not</u> a limitation

Object Susceptibility

- Most biological objects perturb the field

$$\Delta B_{z,\mathrm{tissue}} \approx \chi B_{0,\mathrm{freespace}}$$

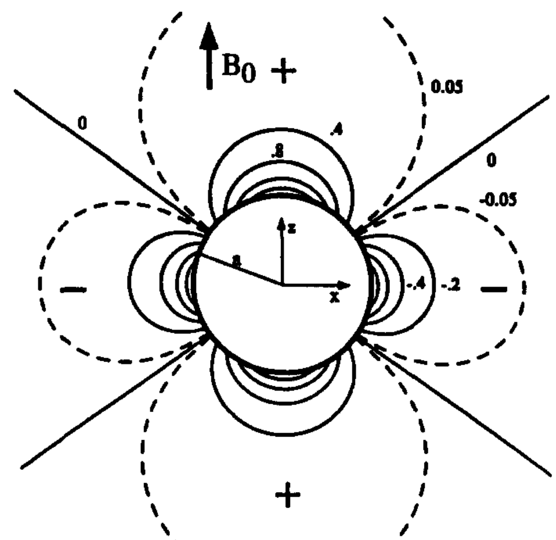
- χ is the magnetic susceptibility
- Larmor frequency lower in tissue than air

  χ_{water} = -9.05ppm w.r.t free-space

  χ_{air} = 0.36 ppm w.r.t free-space

for a sphere:

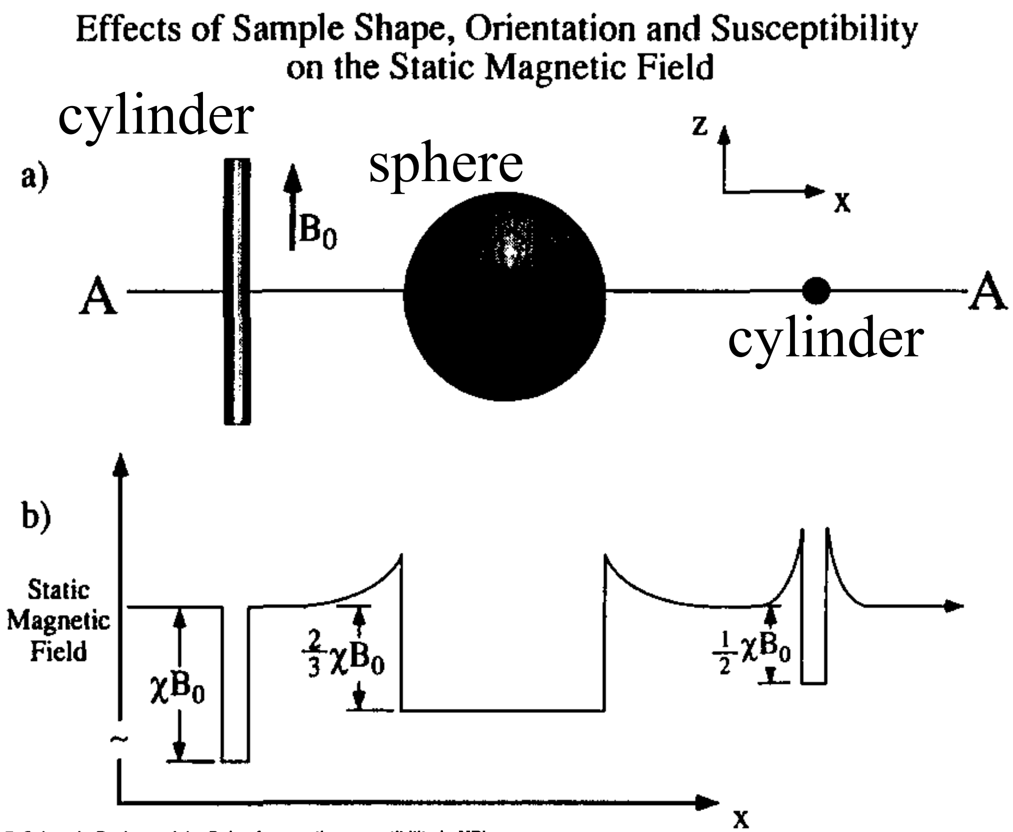
$$\Delta B_z = \frac{\Delta\chi B_0}{3}\left(\frac{a}{r}\right)^3 (3\cos^2\theta - 1)$$



John F. Schenck: Review article: Role of magnetic susceptibility in MRI

Object Susceptibility

- Complex behavior at boundaries.
  - Depends on $\Delta\chi$ and geometry
  - Typical $\Delta B0 \pm 3$ ppm $(-12 < \chi < -6)$

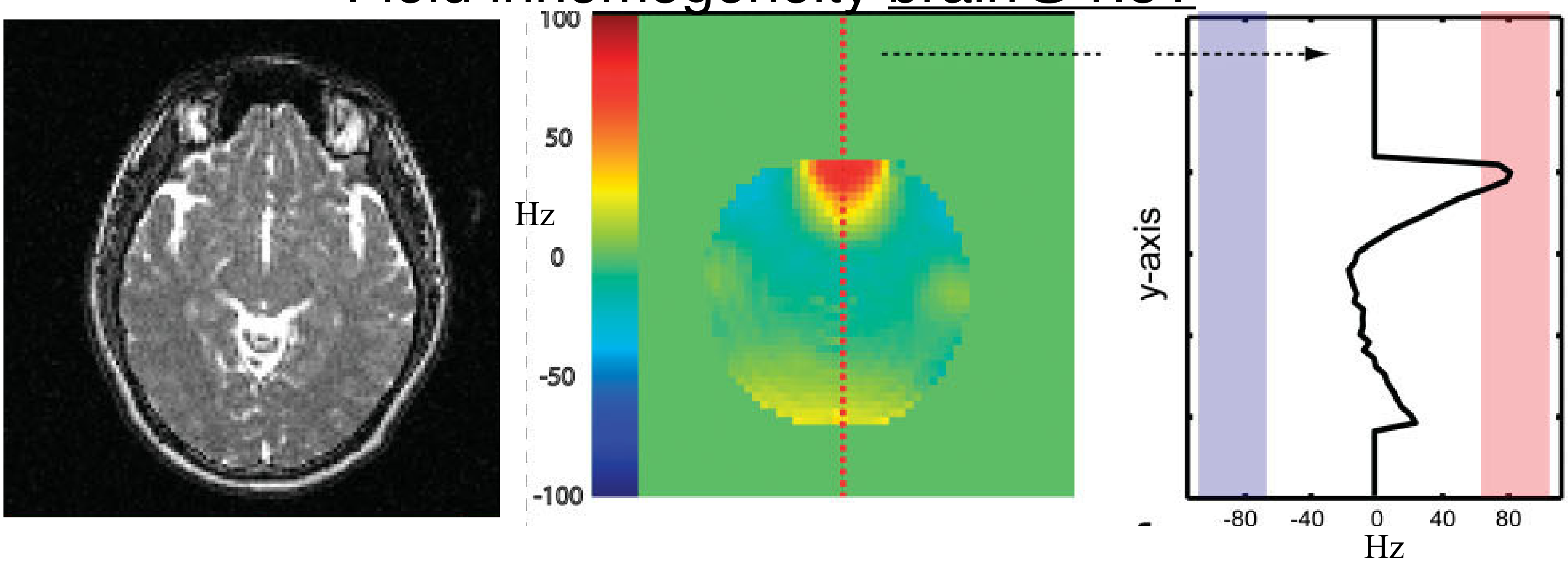


John F. Schenck: Review article: Role of magnetic susceptibility in MRI

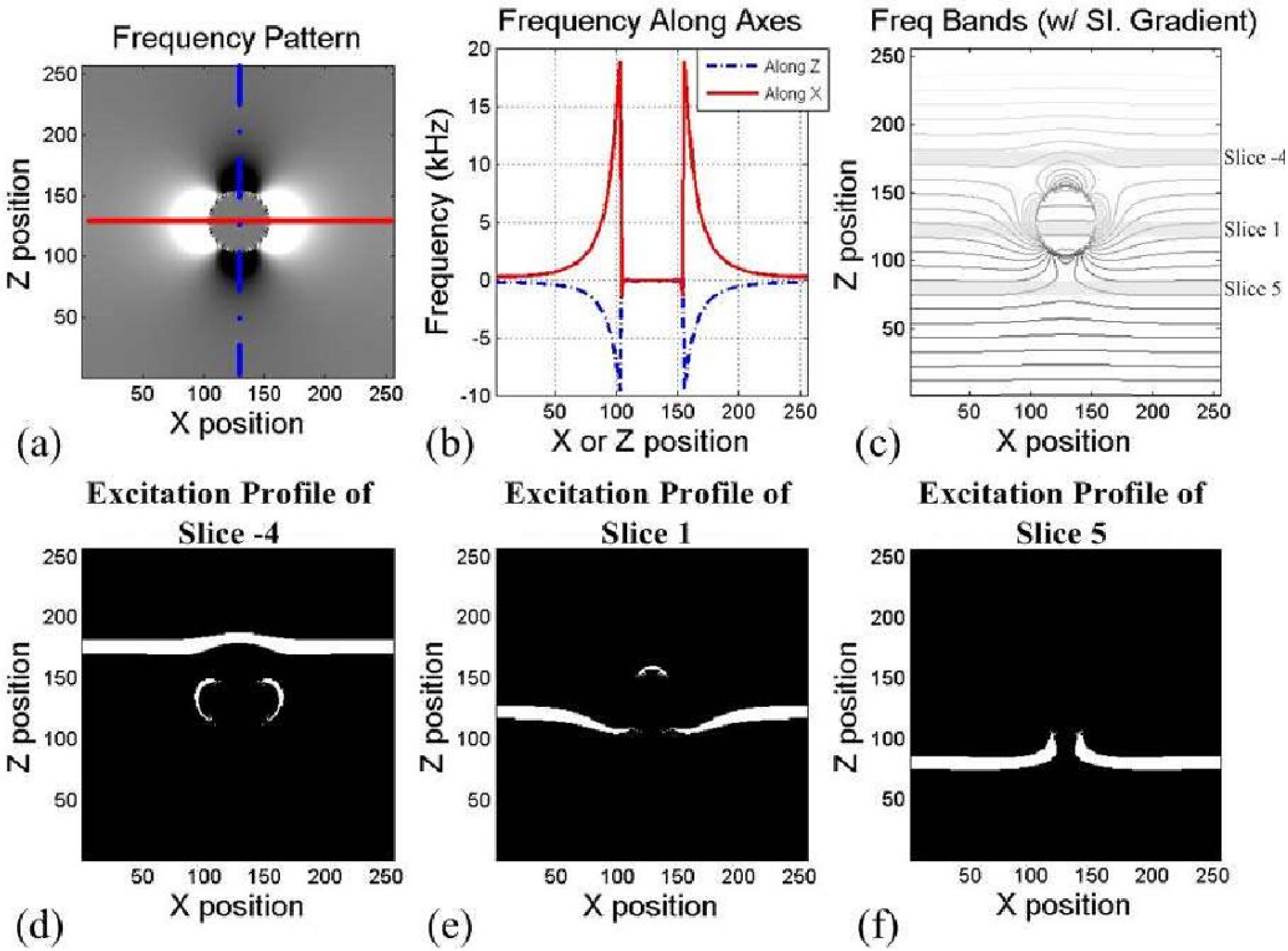
Macroscopic Effect

- Problem areas:
  - Brain above sinuses, auditory canals
  - Heart surrounded by lungs
  - Abdomen

Field inhomogeneity brain@1.5T



Macroscopic Effects - Metal Artifacts



Magn Reson Med. 2009 July ; 62(1): 66–76. doi:10.1002/mrm.21967.

Macroscopic Effects - Metal Artifacts

metal artifact

corrected (SEMAC)

- χ_{titanium} =182

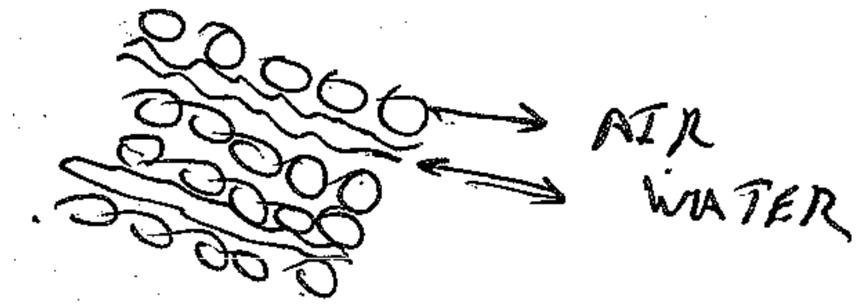
could be a project...

- $\chi_{\text{stainless steal}}$ (nonmagnetic) = 3520-6700

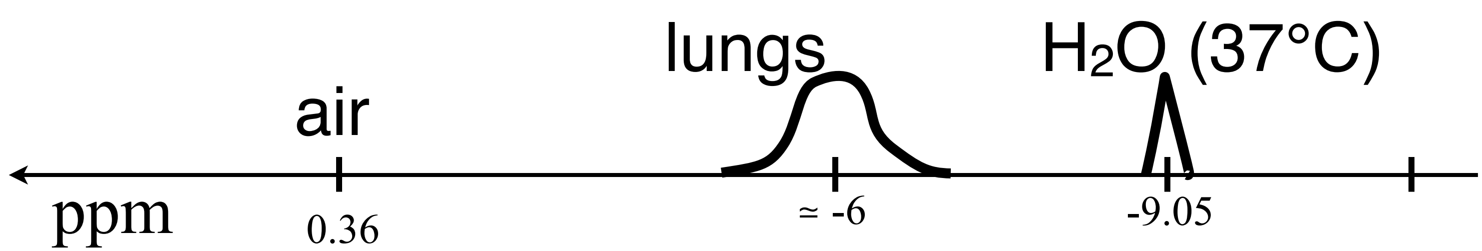
Magn Reson Med. 2009 July ; 62(1): 66–76. doi:10.1002/mrm.21967.

Microscopic Effects

- Lungs:
  - Approx: 1/6 tissue, 5/6 air



- Result:
  - Distribution of field/frequencies



  - Tells a lot about microstructure of tissue

Blood

- $^+$Water $\chi=-9.05$
- $^+$Hemoglobin molecule (deoxy) $\chi=0.15$
- $^+$Red Blood cells (deoxy) $\chi=-6.52$
- *Deoxy blood $\chi=-8.77$
- *Oxy blood $\chi=-9.05$

*Magnetic Resonance in Medicine 68:863–867 (2012)

+ **John F. Schenck: Review article: Role of magnetic susceptibility in MRI**

Chemical Shift

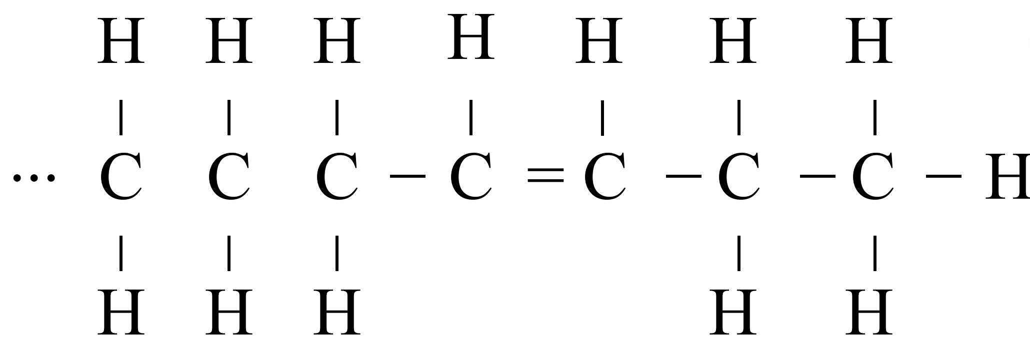
- Protons in complex molecules are "shimmed" by adjacent spins and electrons

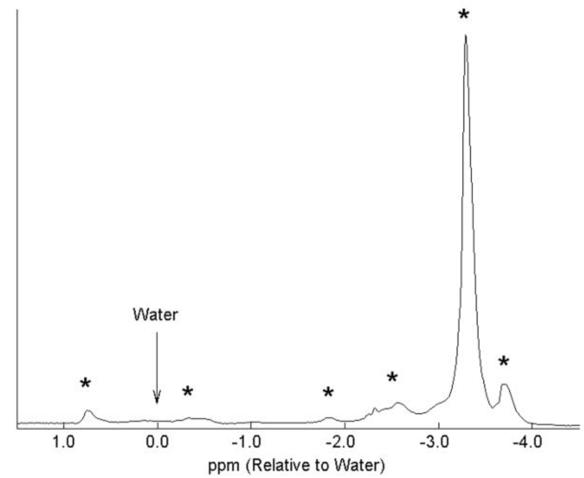
$$B_{\mathrm{cs}} = B_0(1 - \sigma)$$

- σ is a shielding constant - depends on molecular structure
- Example: Lipids

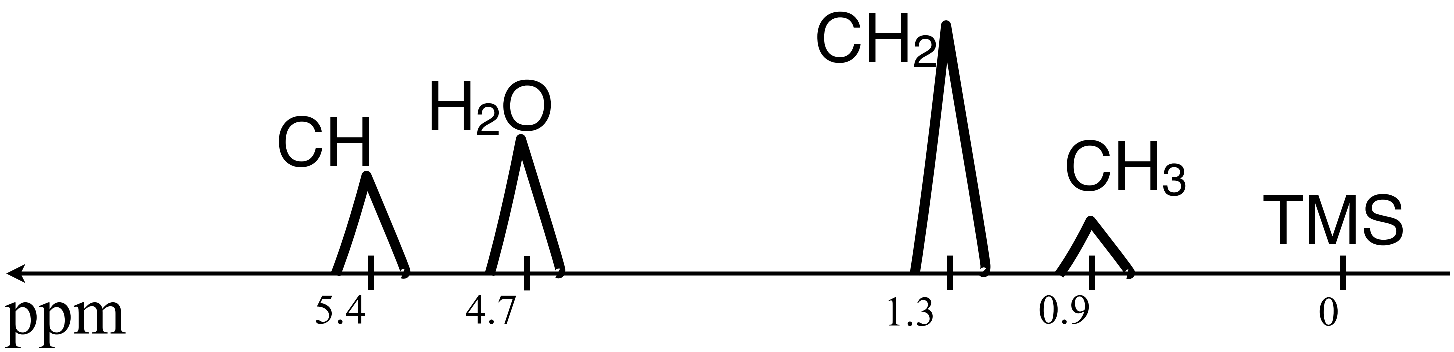
Chemical Shift

- Example: Lipids





J Magn Reson Imaging. 2009 June; 29(6): 1332–1339.



Lipids from CH2 is 3.4ppm below water

@3T ≈ 440 Hz

Heterogeneous Tissue

- Tissue is a combination of
  - Chemical shift
  - Susceptibility
  - Geometry
- Results are complex
  - Interesting cases:
    - Blood (fMRI)
    - Lungs
    - Trabecular bone
    - Iron in brain / liver

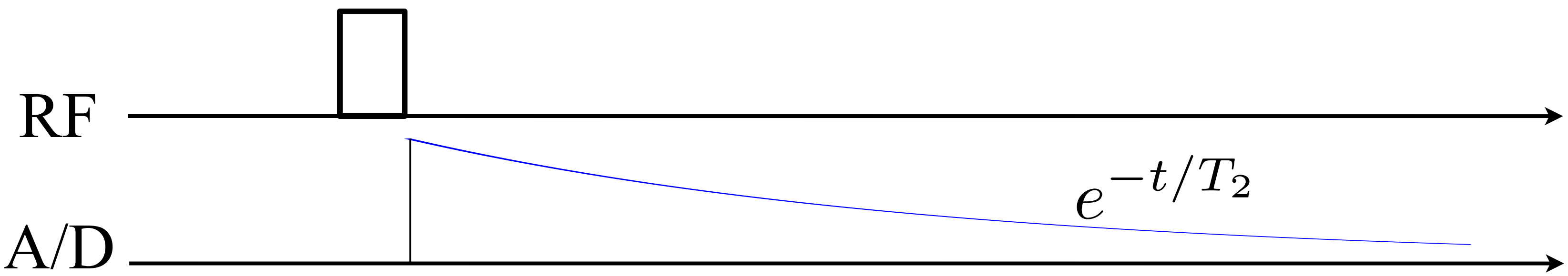
Effect on Imaging

- Magnitude
- Phase
- Geometric
- Blurring

- All depend on spatial scale we look at, and acquisition strategy

Off Resonance Effect on FID

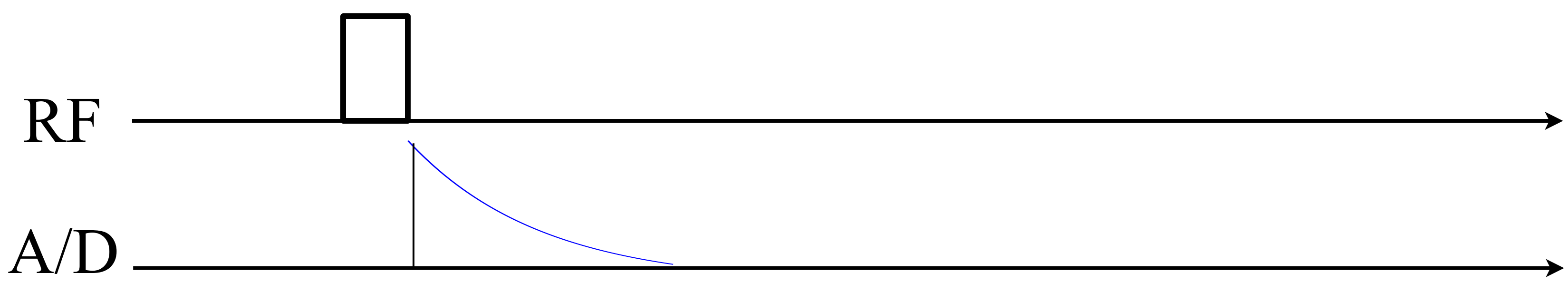
- Simple spectroscopy experiment
  - On resonance



Signal decays with T_2

Off Resonance Effect on FID

- Simple spectroscopy experiment
  - With Susceptibility variation, FID is:



Why?

Off Resonance Effect on FID

- The field is:

$$B(\vec{r}) \;=\; \underbrace{B_0}_{\text{uniform}} \;+\; \underbrace{E(\vec{r})}_{\text{error-field}}$$

- Error is spatial and spectral
- In the rotating frame w_0

$$\begin{aligned}\vec{B} &= E(\vec{r})\hat{k} \\ \omega_E(\vec{r}) &= \gamma E(\vec{r}) \\ f_E(\vec{r}) &= \frac{\gamma}{2\pi} E(\vec{r})\end{aligned}$$

Off Resonance Effect on FID

$$m_{x,y}(\vec{r},t) = m_{xy}(\vec{r},0)e^{-i\omega_E(\vec{r})t}e^{-\frac{t}{T2(\vec{r})}}$$

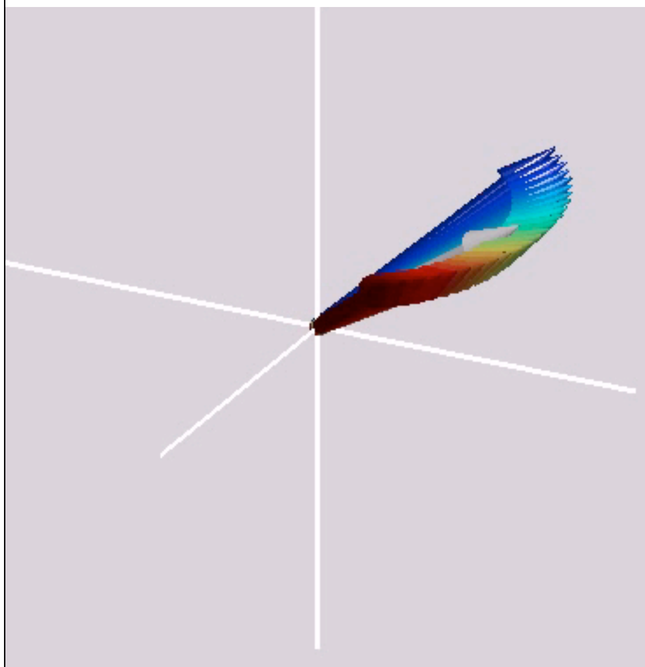
- Received signal is:

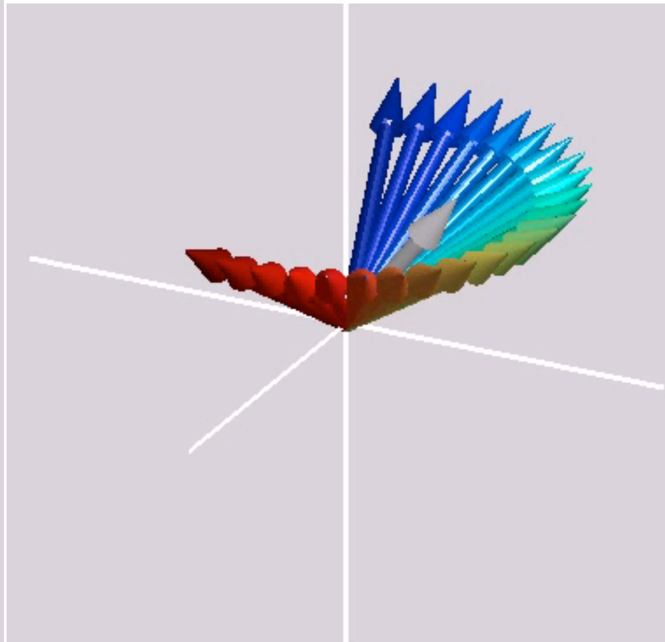
$$s(t) = \int_{\vec{R}} m_{xy}(\vec{r},0)e^{-i\omega_E(\vec{r})t}e^{-\frac{t}{T2(\vec{r})}}d\vec{r}$$

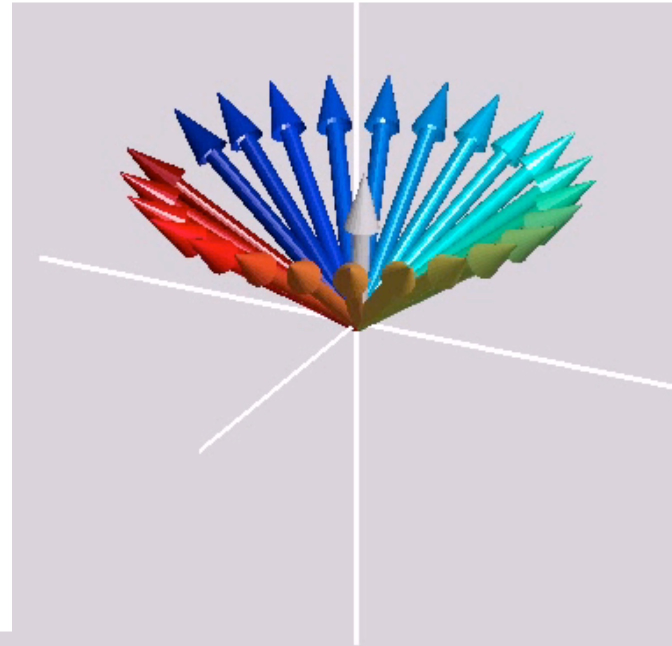
magnetization dephasing relaxation

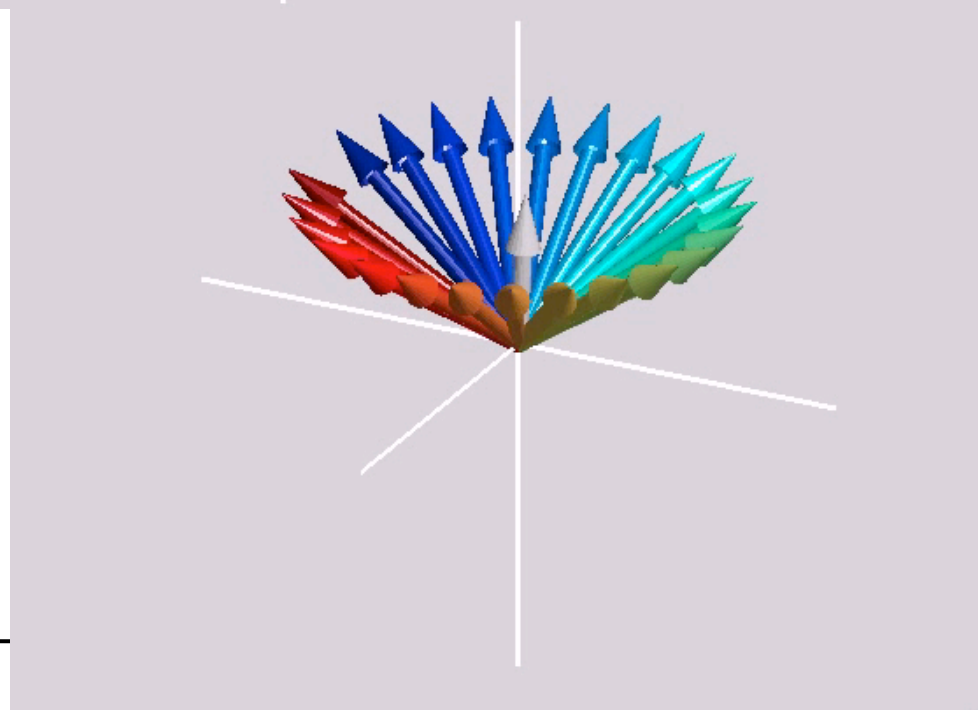
  - with time, phase dispersion causes signal cancellation and loss.

Off - Resonance Effects on FID

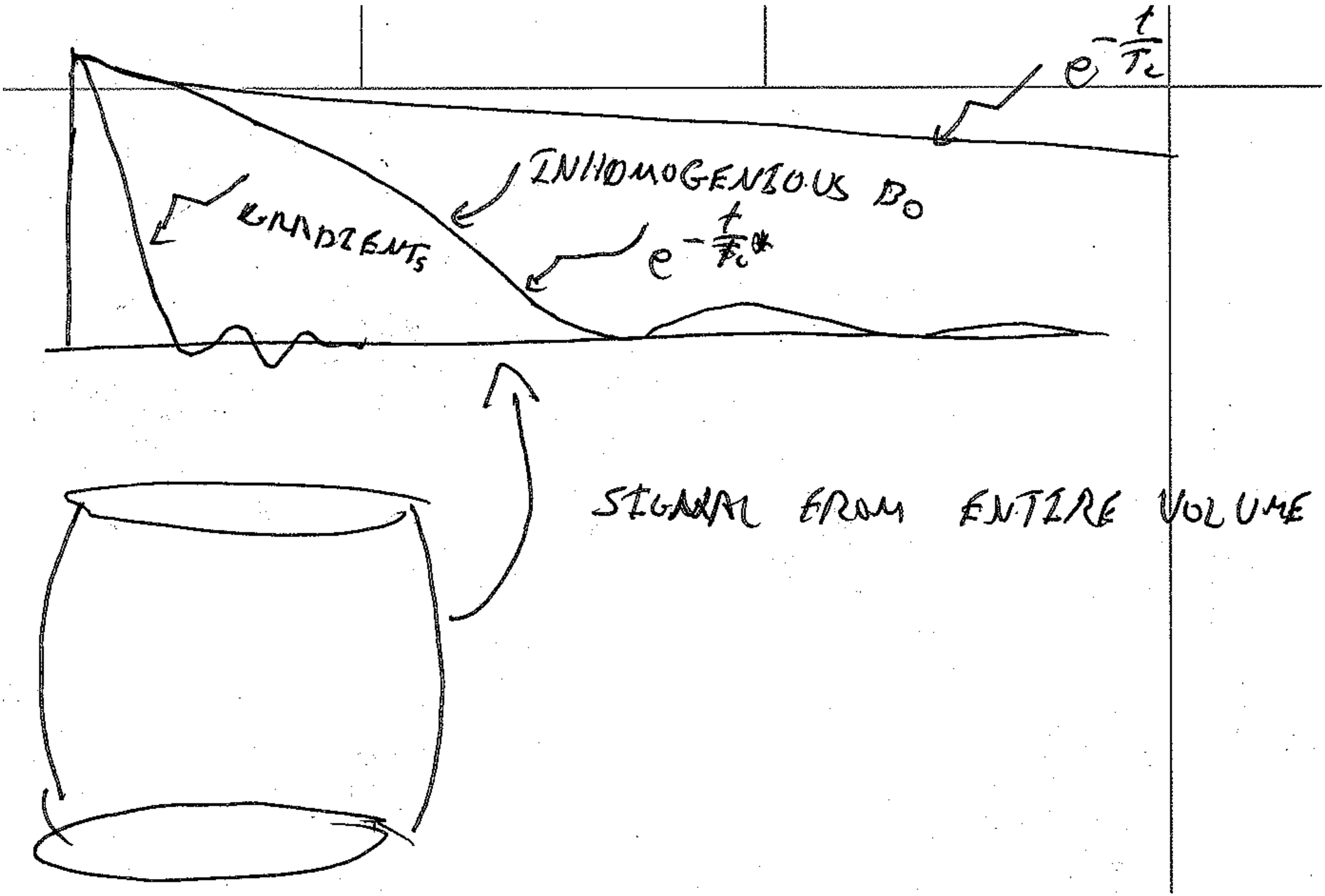








Off Resonance Effects on FID



Off Resonance Effects on FID

GRADIENTS ARE VERY STRONG INHOMOGENEITY!

INHOMOGENEITY → SIGNAL LOSS KNOWN AS T_2^*

APPROXIMATE AS EXPONENTIAL

$$s(t)\Big|_{voxel} = \left[\int_{voxel} m_{xy}(r,0)\, e^{-i\omega_E(\vec{r})t}\, e^{-t/T_2(r)}\, d\vec{r}\right]$$

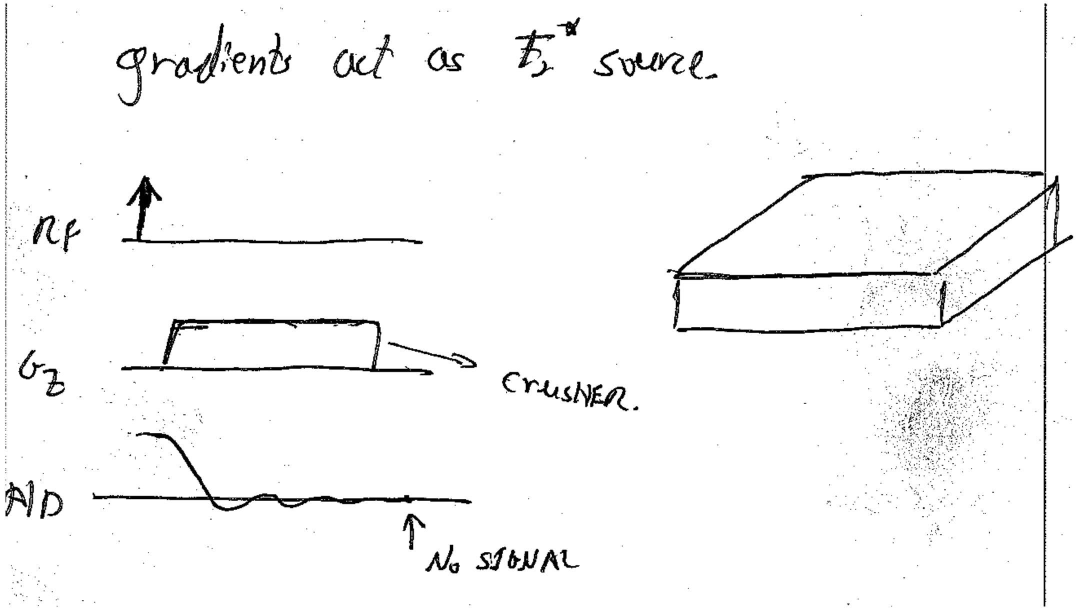
$$\simeq \left[\int_{voxel} m_{xy}(r,0)\, d\vec{r}\right] e^{-\frac{t}{T_2^*(r)}}$$

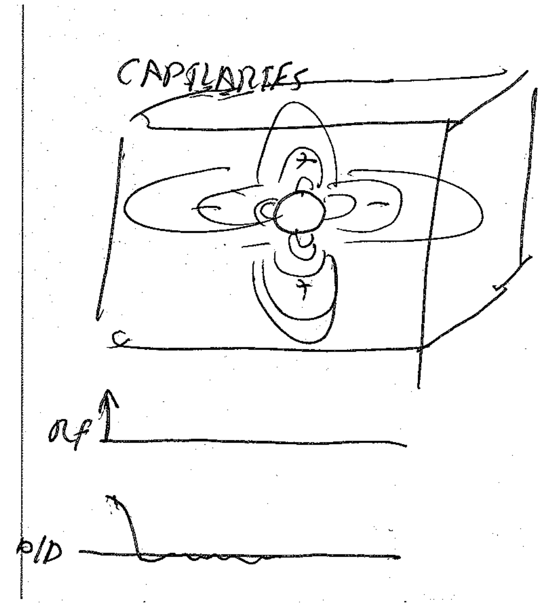
$$\frac{1}{T_2^*} = \underbrace{\frac{1}{T_2}}_{\text{RELAX}} + \underbrace{\frac{1}{T_2'}}_{\text{DEPHASE}}$$

$$R_2^* = R_2 + R_2'$$

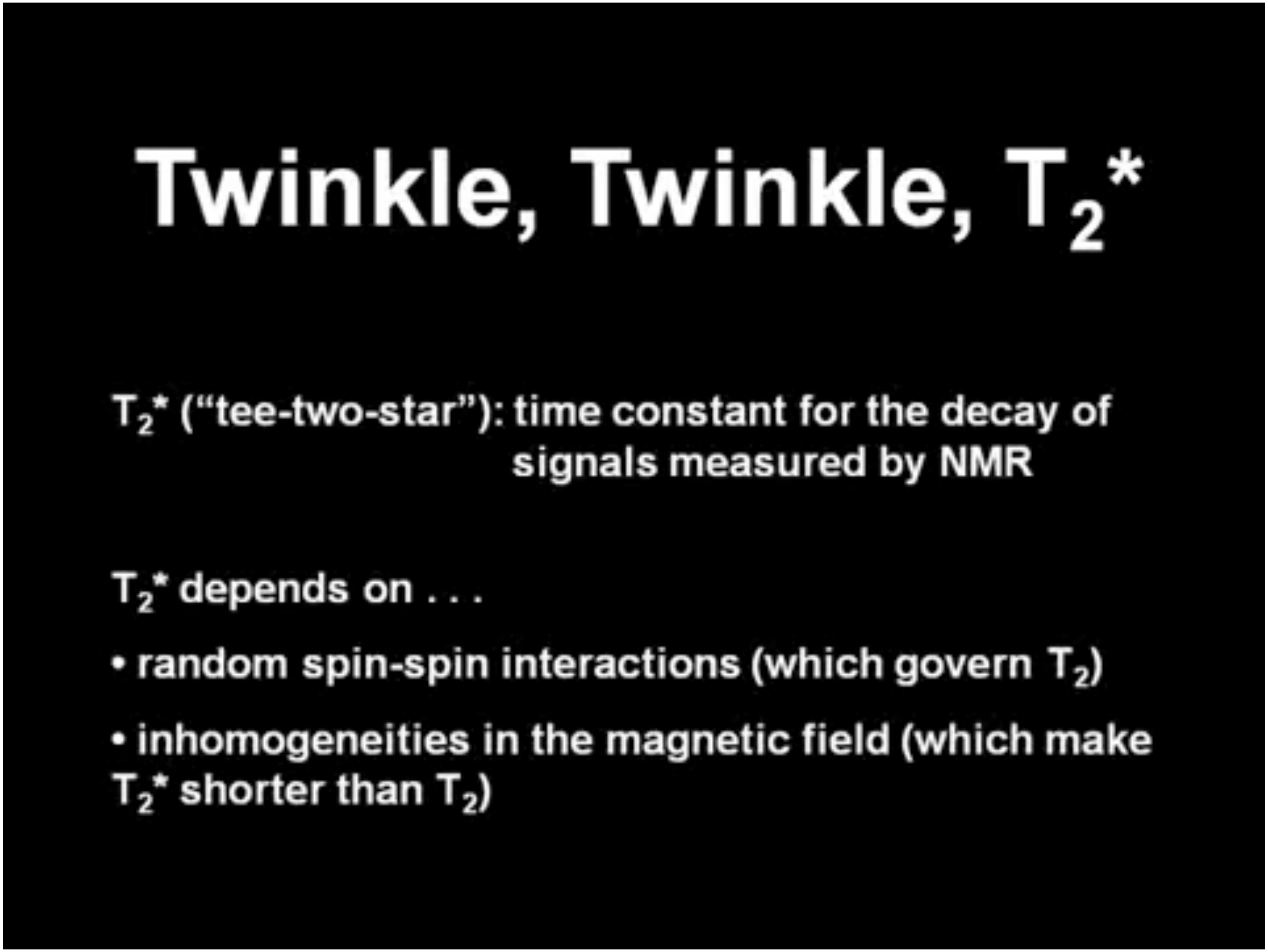
Off Resonance Effects on FID

- T2*: Not a good model for Large-Scale variations (dephasing near sinuses)
- T2*: Is a good model for small scale distributed variations (dephasing near capilaries)

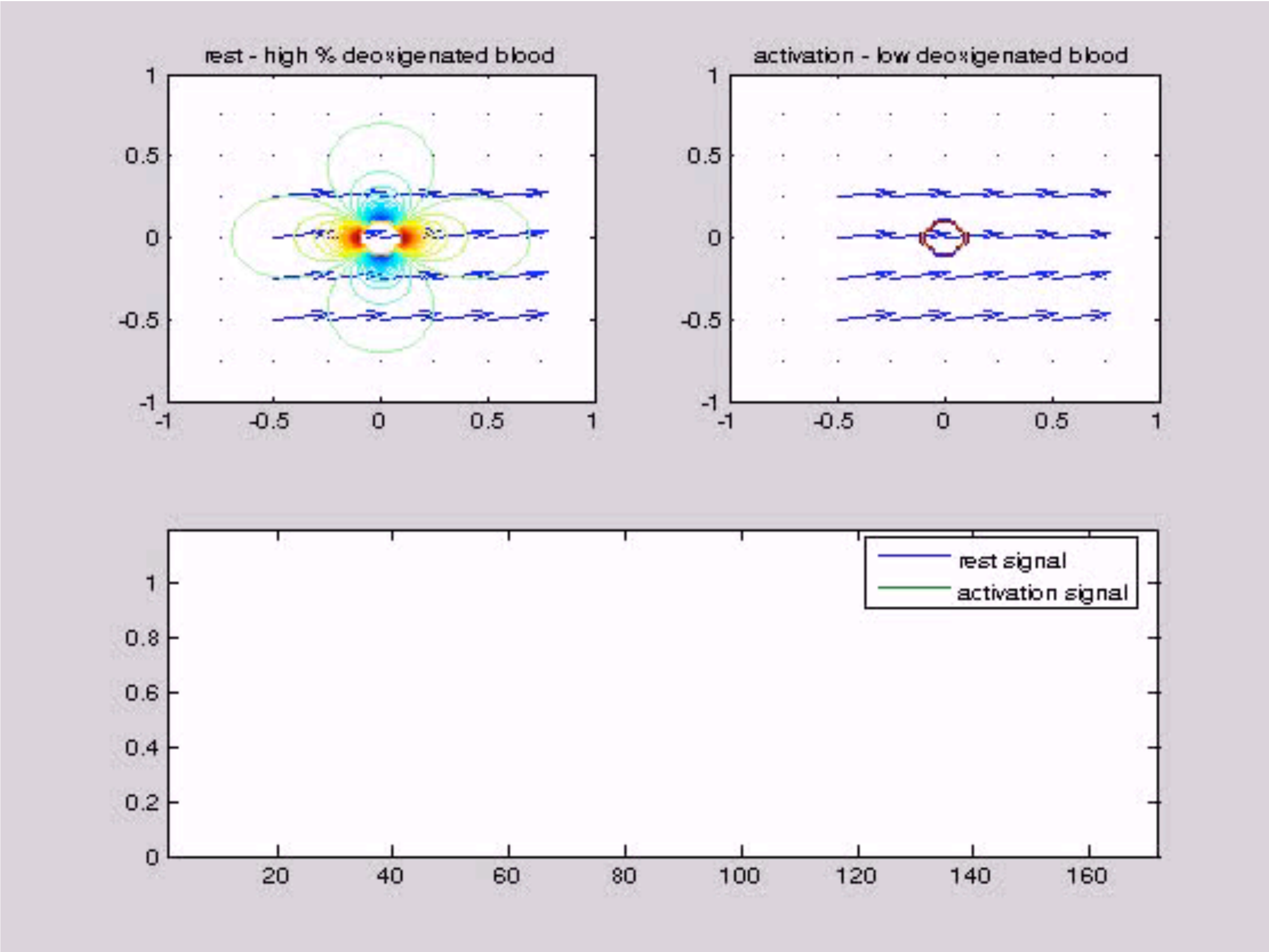




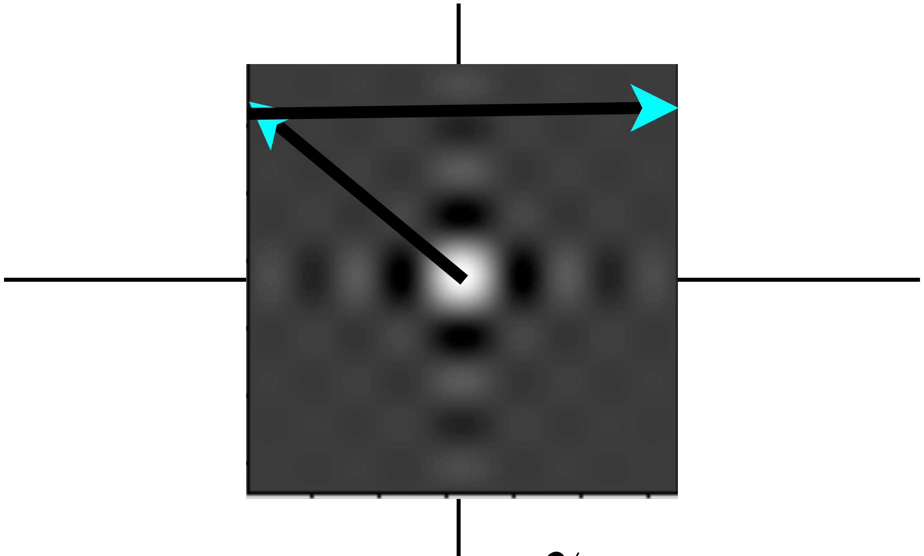
Twinkle Twinkle T2*

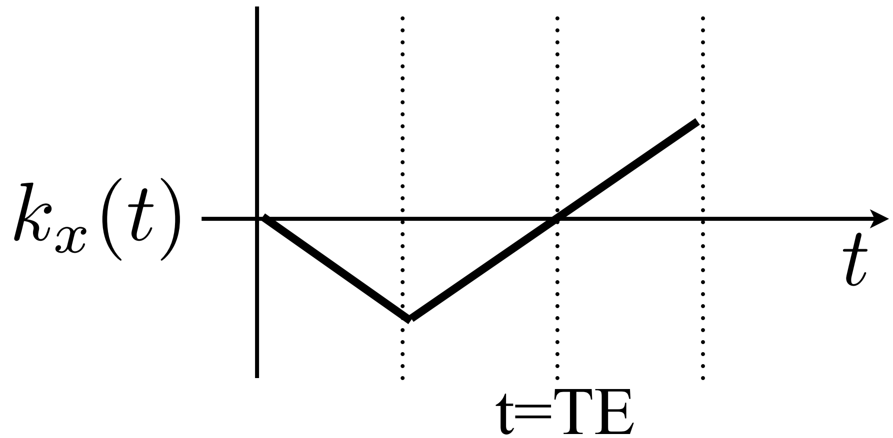


Example fMRI



Off -Resonance Effects on Imaging





$$k_x = \frac{\gamma}{2\pi} G_x (t - TE) \Rightarrow t = \frac{k_x}{\frac{\gamma}{2\pi} G_x} + TE$$

The x-verse magnetization is:

$$m_{xy}(\vec{r}, t) = m_{xy}(\vec{r}, 0) e^{-i\omega_E(\vec{r})t} e^{-\frac{t}{T_2(\vec{r})}} e^{-i2\pi k_x(t)x} d\vec{r}$$

Off -Resonance Effects on Imaging

neglecting T_2 and substituting for t:

$$m_{xy}(\vec{r},t) = m_{xy}(\vec{r},0)e^{-i\omega_E(\vec{r})\left(\frac{k_x(t)}{\frac{\gamma}{2\pi}G_x}+TE\right)}e^{-i2\pi k_x(t)x}d\vec{r}$$

Or,

$$m_{xy}(\vec{r},t) = m_{xy}(\vec{r},0)e^{-i\omega_E(\vec{r})TE}e^{-i2\pi k_x(t)\left(x+\frac{\omega_E(\vec{r})}{\gamma G_x}\right)}d\vec{r}$$

phase/dephasing displacement

Off -Resonance Effects on Imaging

$$m_{xy}(\vec{r},t) = m_{xy}(\vec{r},0)e^{-i\omega_E(\vec{r})TE}e^{-i2\pi k_x(t)\left(x+\frac{\omega_E(\vec{r})}{\gamma G_x}\right)}d\vec{r}$$

phase/dephasing displacement

An on-resonance spin at position:

$$x' = x + \frac{\omega_E(\vec{r})}{\gamma G_x}$$

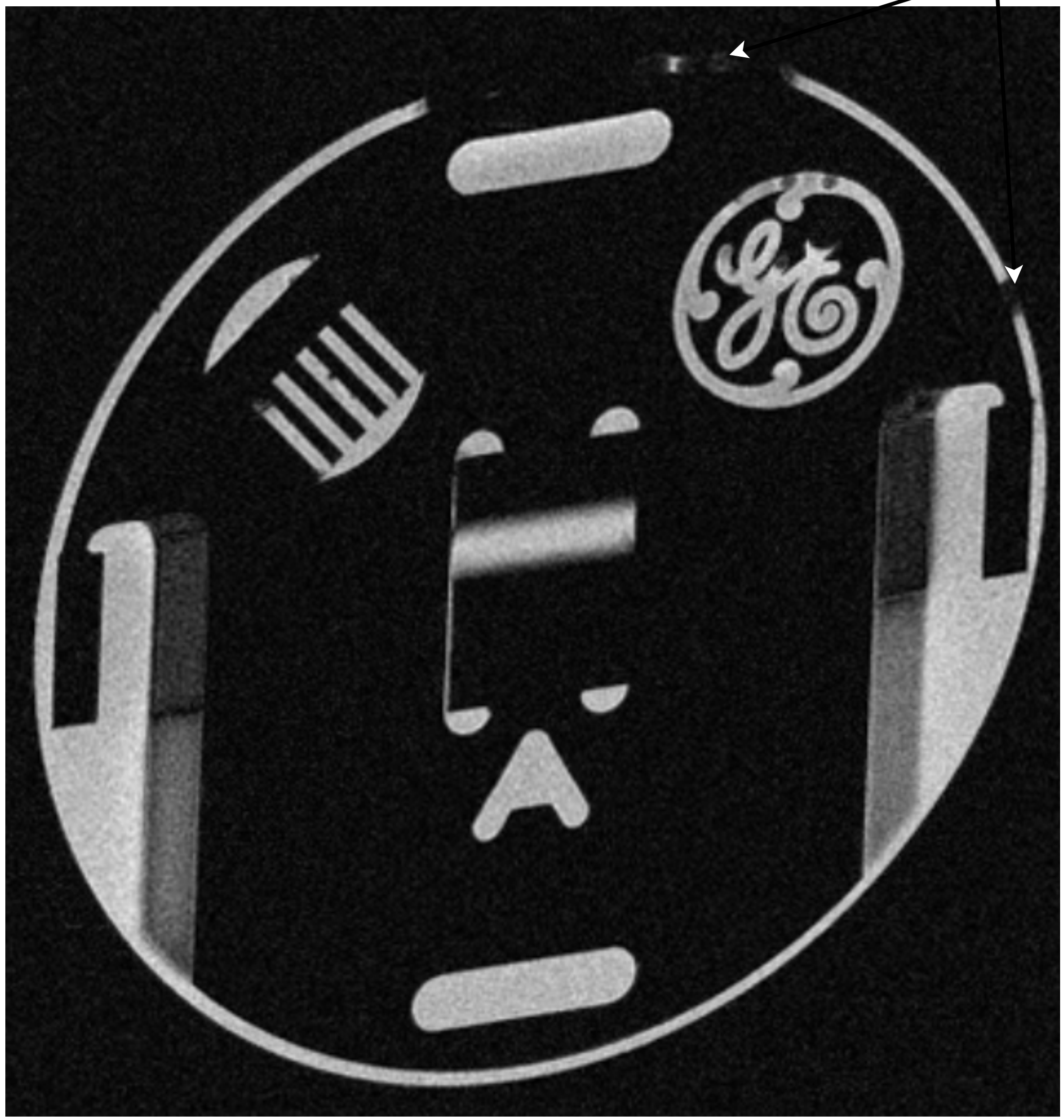
Produces the same signal as a spin at x, with off-resonance!

Examples:

signal loss

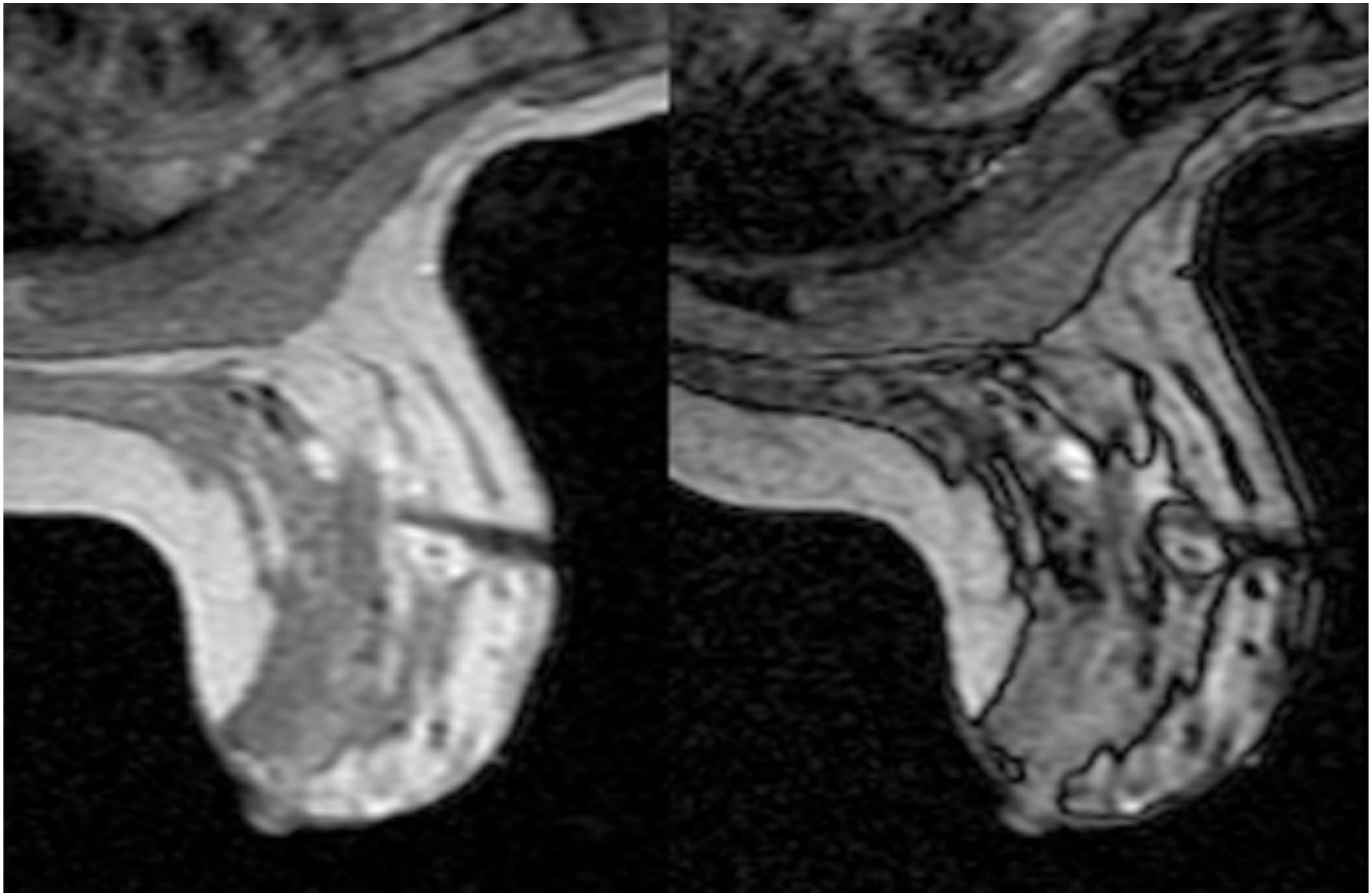
shape

readout
direction?



Examples: Phase vs Echo Time

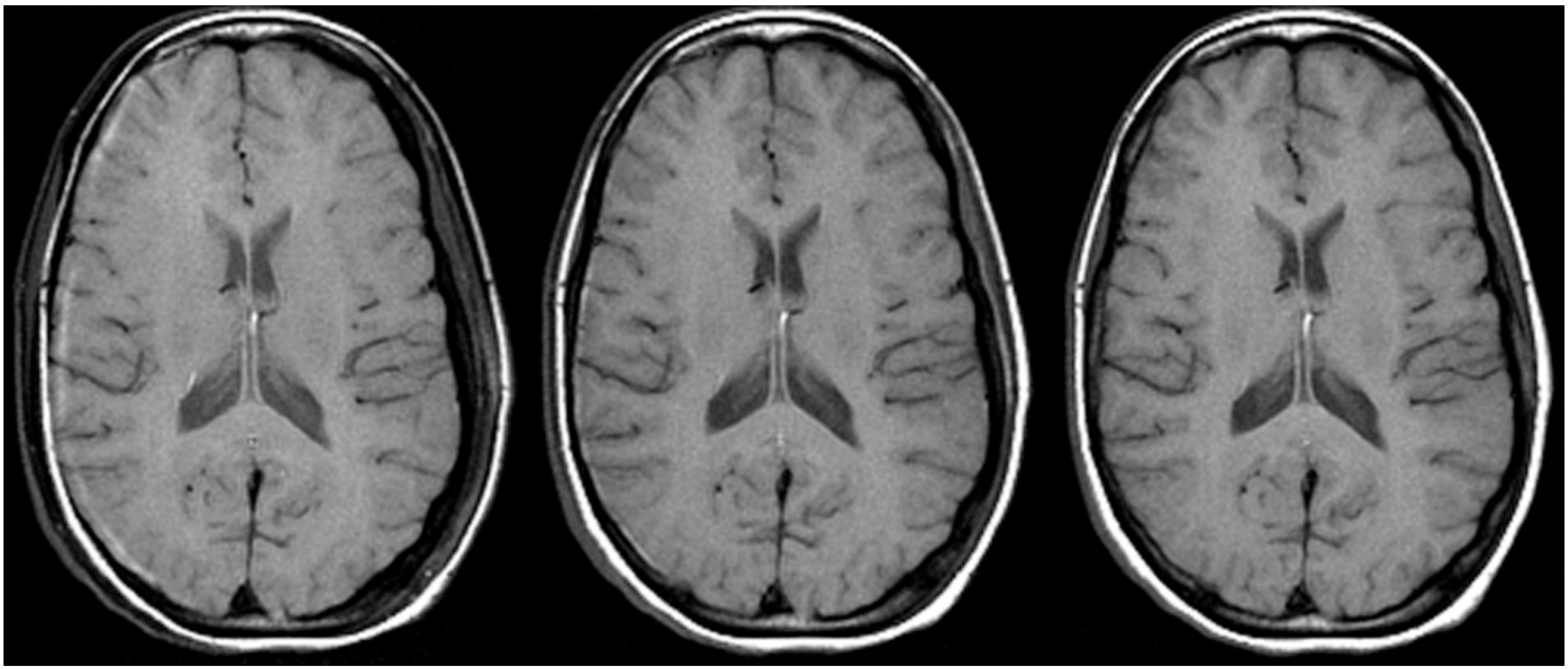
water and lipids in phase   water and lipids out-of-phase



Example: Chemical Shift

$$x' = x + \frac{\omega_E(\vec{r})}{\gamma G_x}$$

Increasing G_x reduces chemical shift artifact



Example:

Let,

$$\frac{\gamma}{2\pi}G_x = 1 \text{ KHz/cm}$$

$$E(\vec{r}) = 3 \text{ ppm}$$

$$\omega_E(\vec{r}) = 2\pi \cdot 200 \text{ Hz}$$

$$\Delta x = x' - x = \frac{\omega_E(\vec{r})}{\gamma G_x} = \frac{\cancel{2\pi} \cdot 200 \text{ Hz}}{\cancel{2\pi} \cdot 1 \text{ KHz/cm}} = 0.2\text{cm}$$

At: $\delta_x = 1 \text{ mm}$ this is a shift of two pixels!

Effects in Spin-Warp

- Off-Resonance
  - –Modest spatial distortions (few pixels)
  - –Relatively benign artifacts
  - –Reduce artifacts with large Gx
- Chemical-Shift
  - – Fat shift of -220Hz @ 1.5T
  - – Fat image is displaced from Water
  - – In practice F/W shift limited to ~2pixels

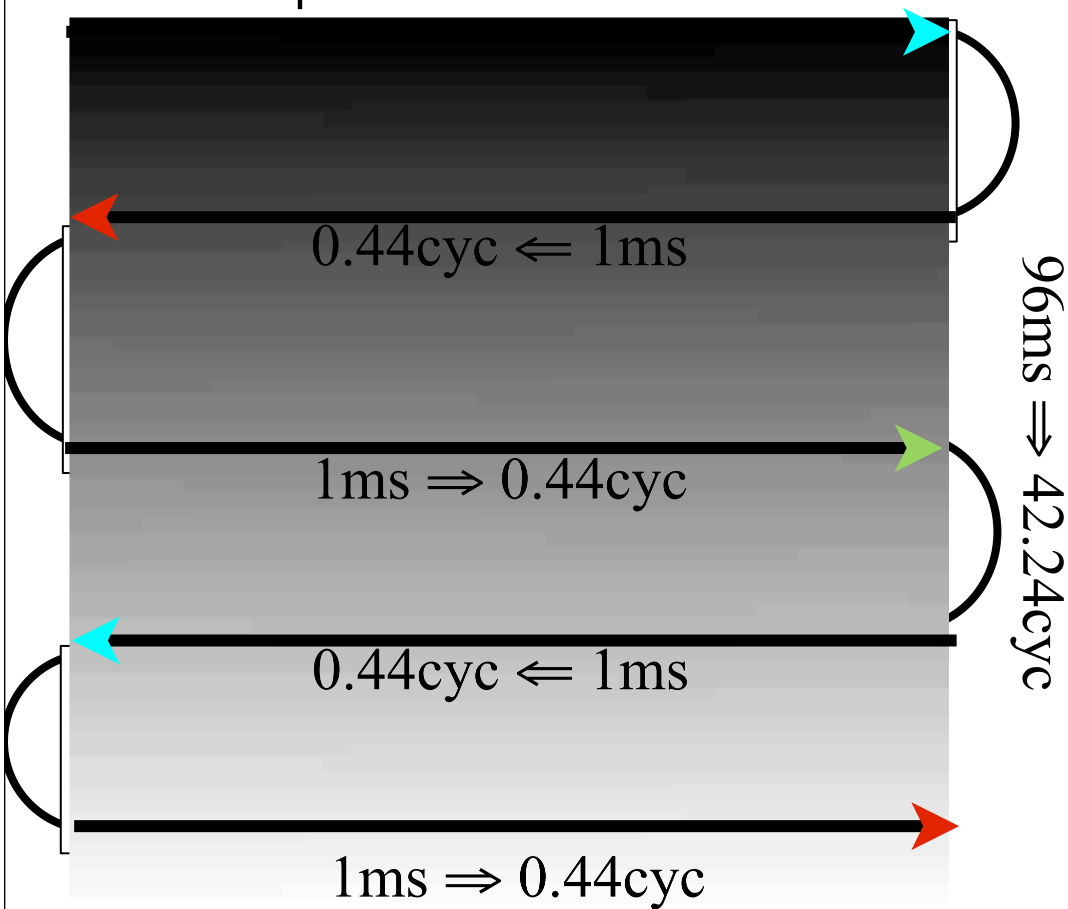
2 pixels shift are two cycles of linear phase across k-space

$$\frac{2\ \text{cyc}}{220\ \text{Hz}} \approx 9.1\ \text{ms}$$

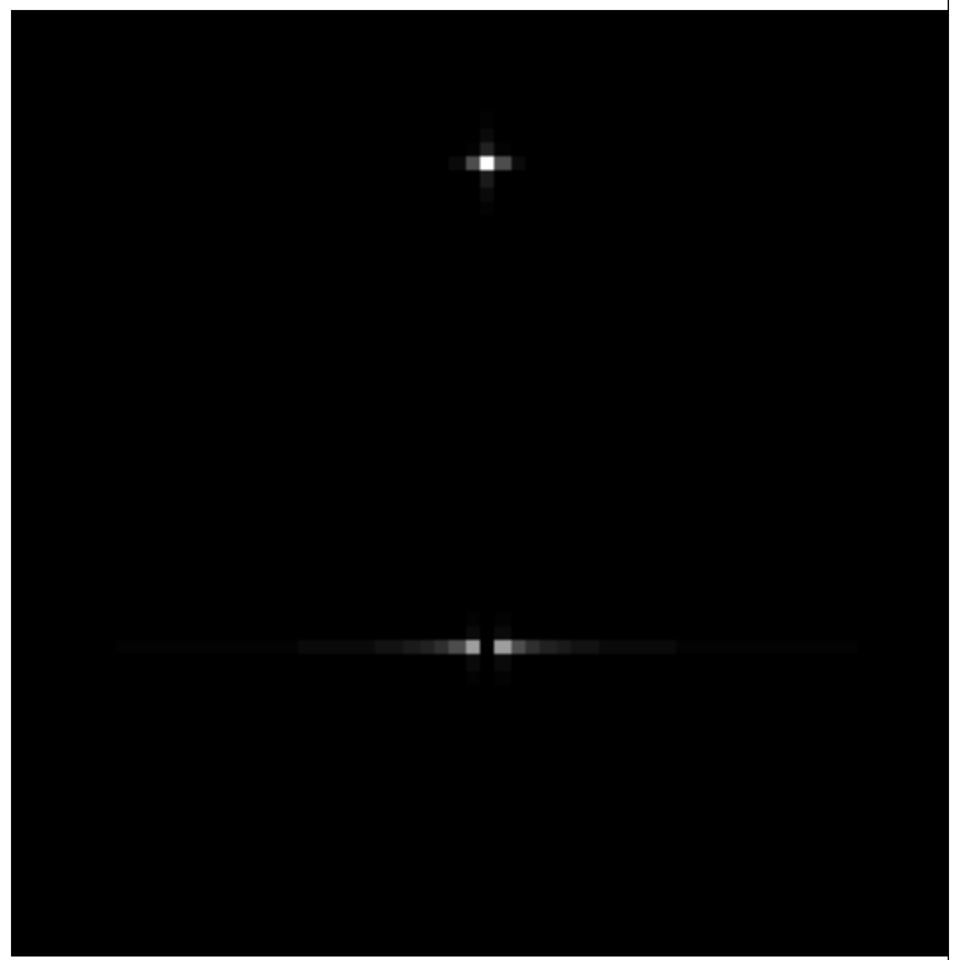
Off-Resonance in EPI

Example: Lipids

phase accumulation

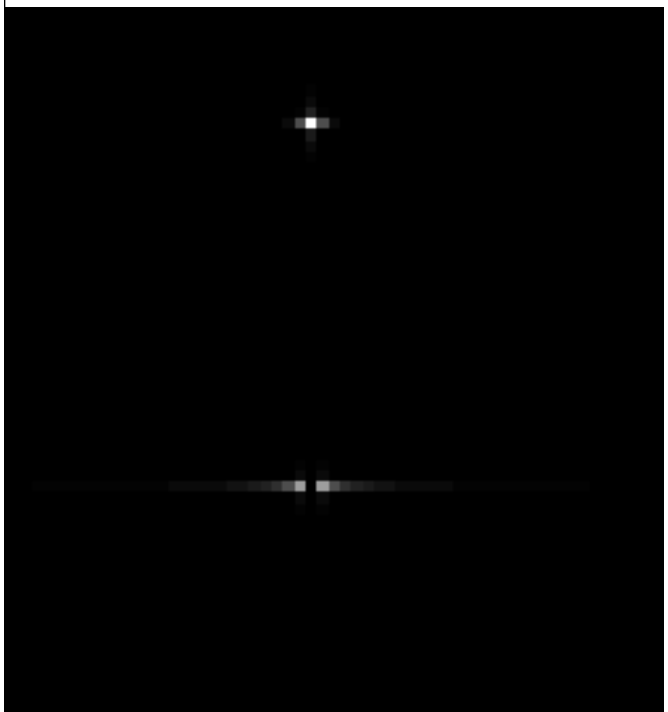


point-spread function

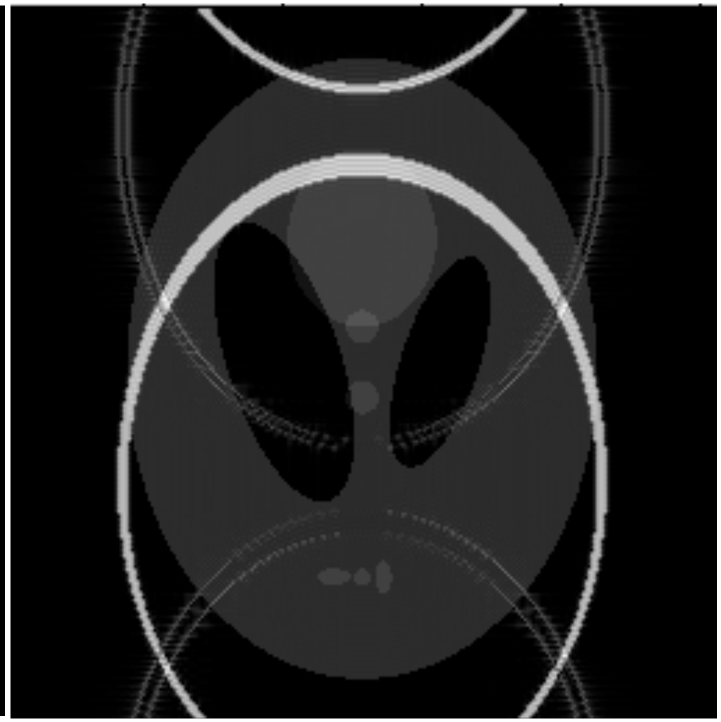


Off-Resonance in EPI

point-spread function



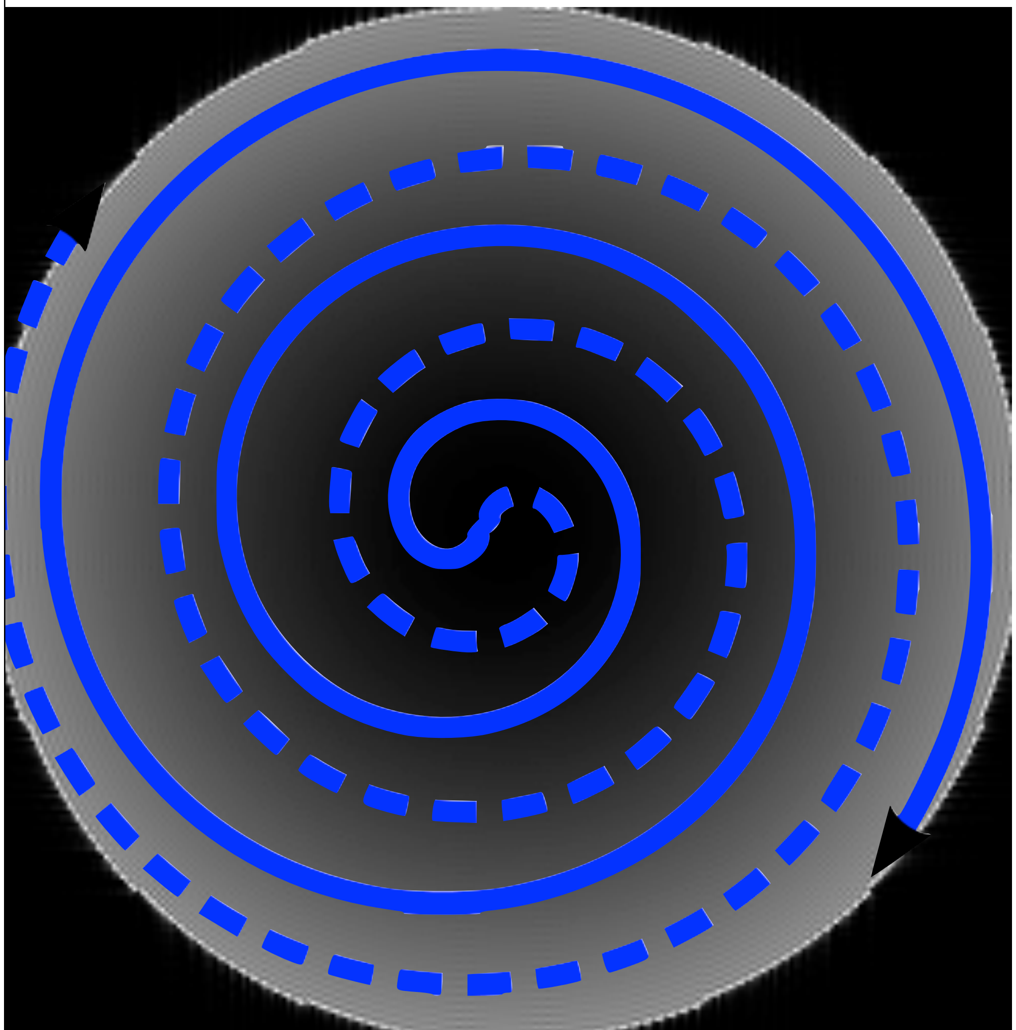
simulation



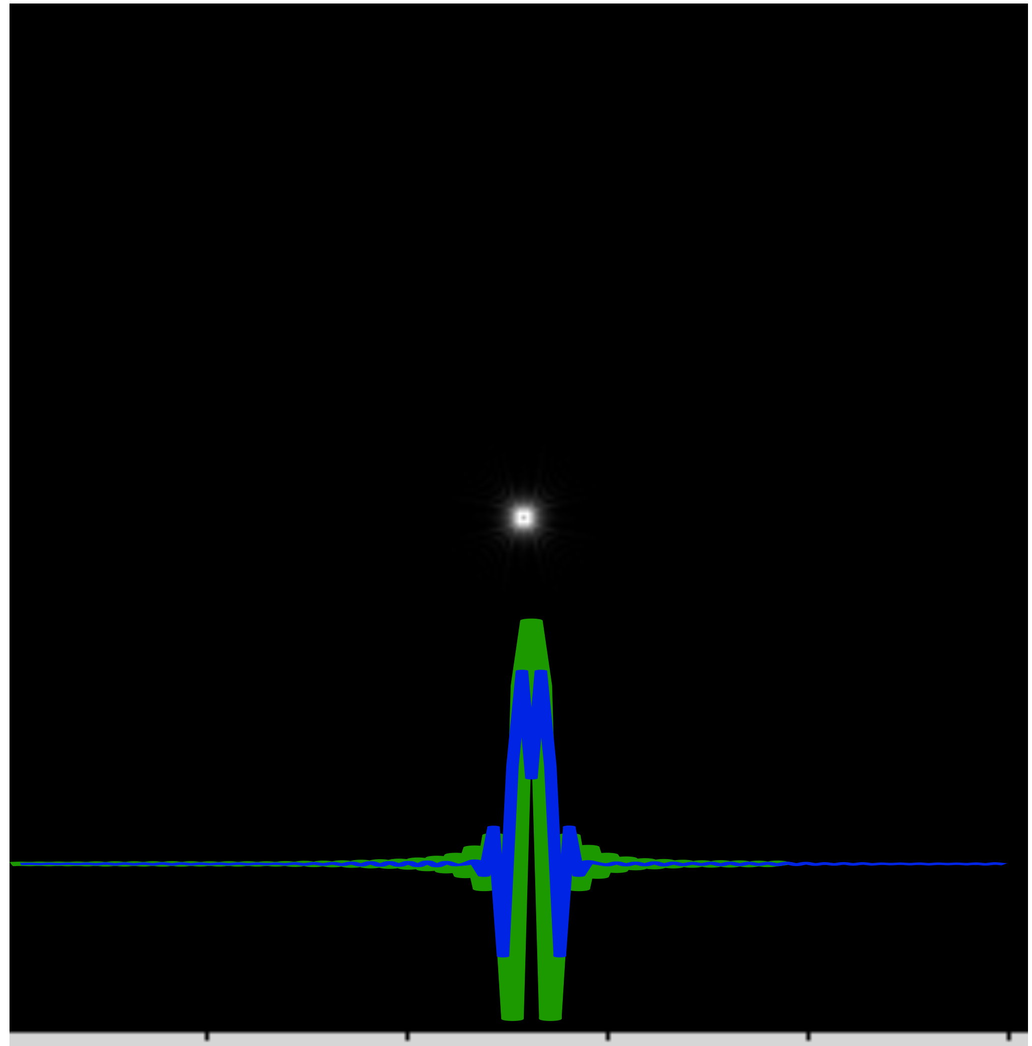
Leg

Off-Resonance in Spiral

phase accumulation



point-spread function

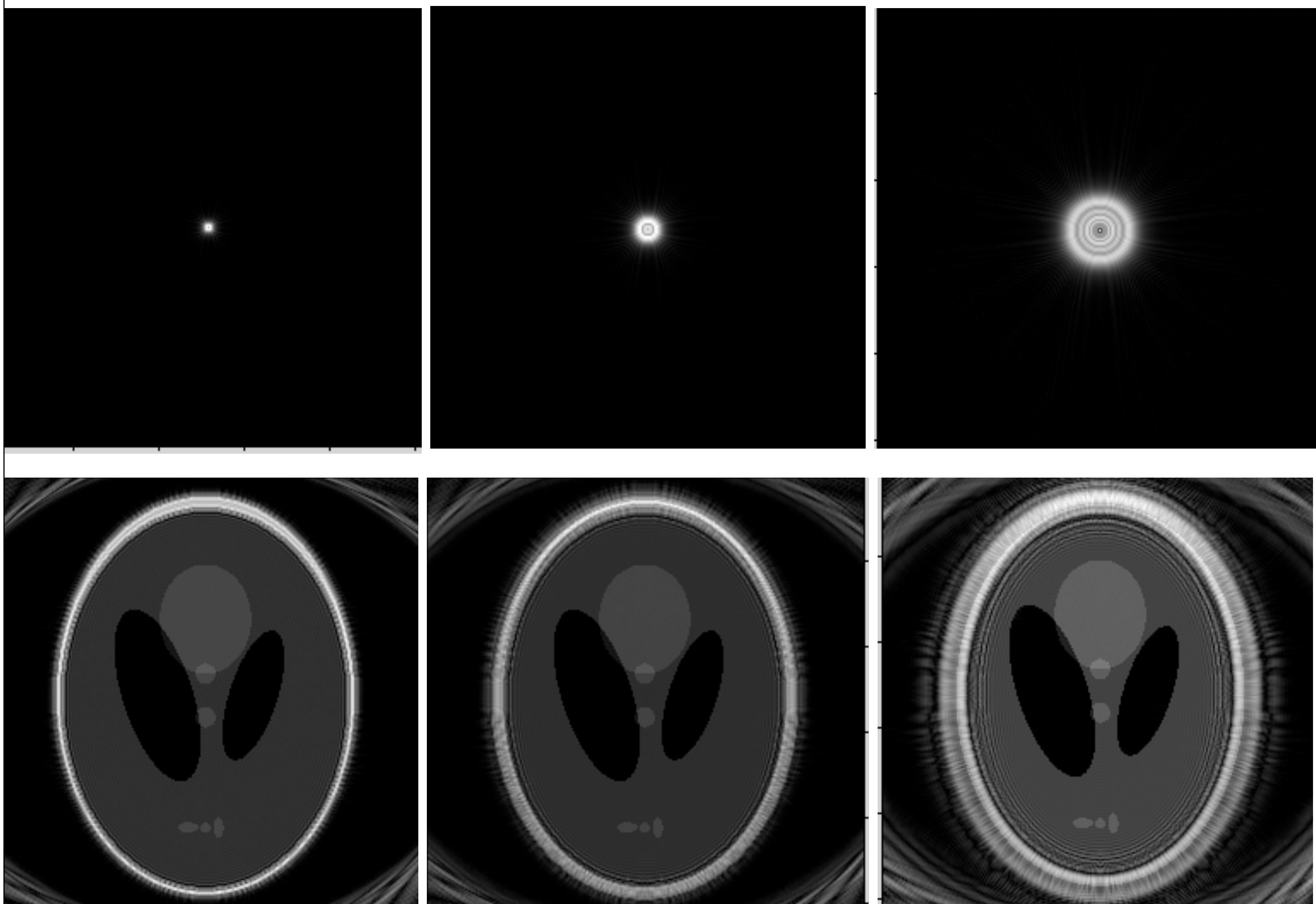


$$2\text{ ms} \Rightarrow 0.88\text{cyc}$$

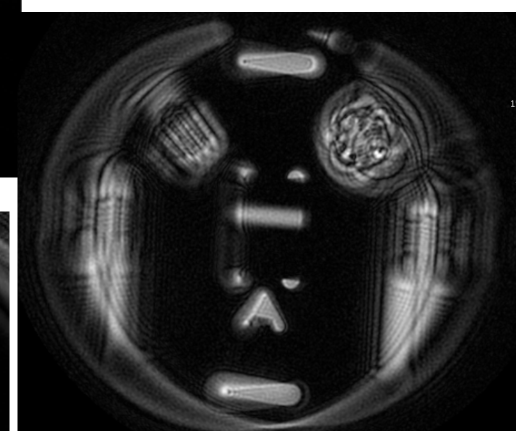
Off-Resonance in Spiral

Readout time @3T:

2ms 5ms 13ms

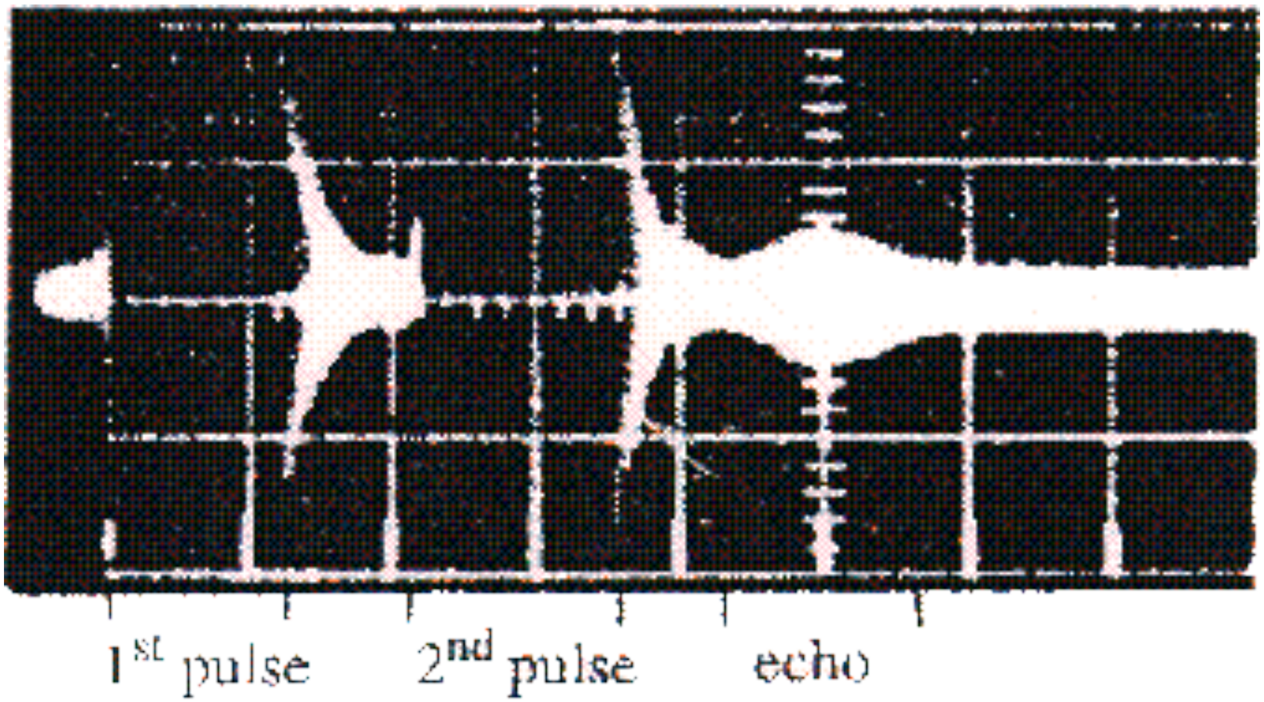


Spiral scan
with linear off-resonance



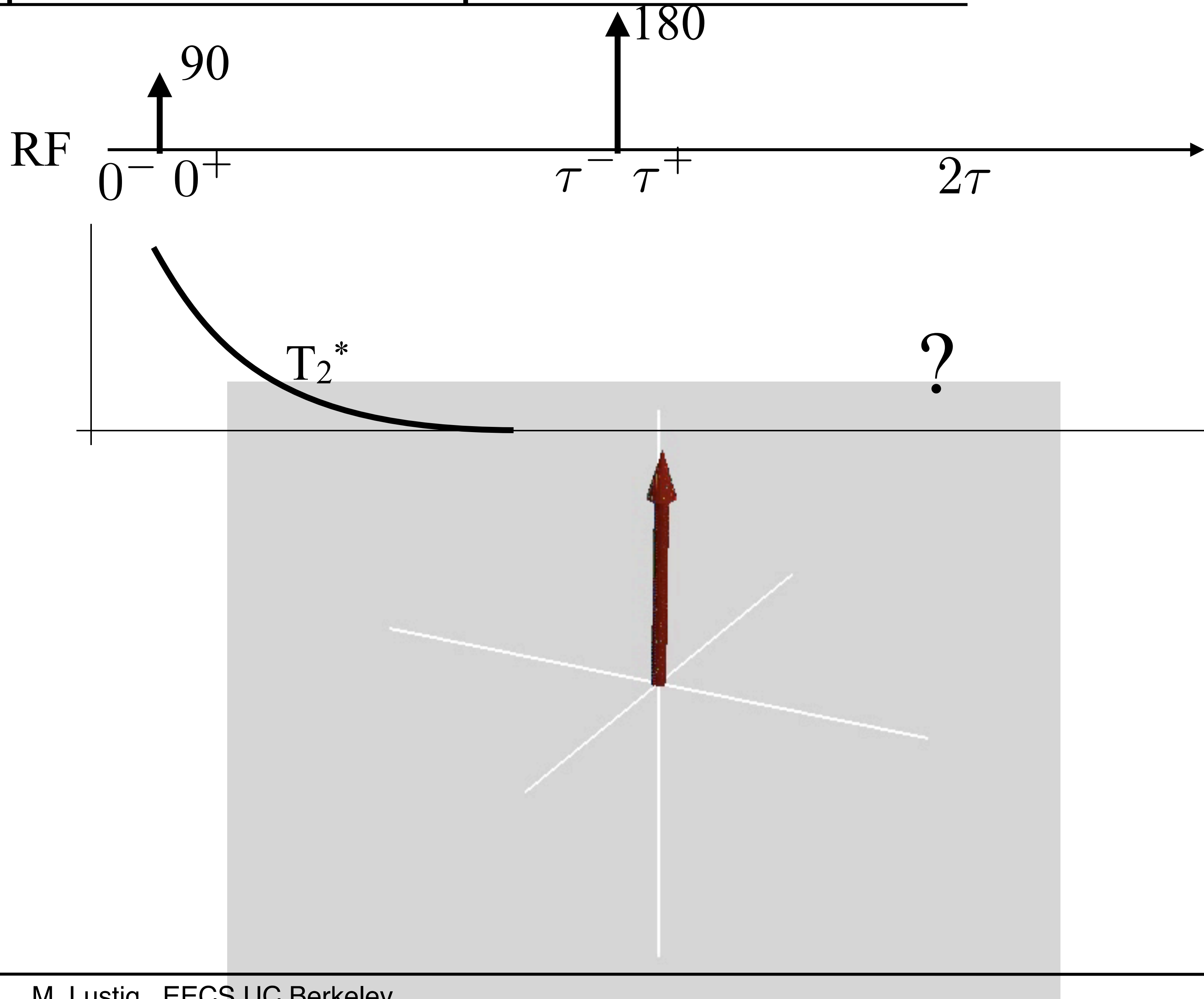
Echoes

- Early in NMR people noticed the following odd behavior (Hann, 1950)

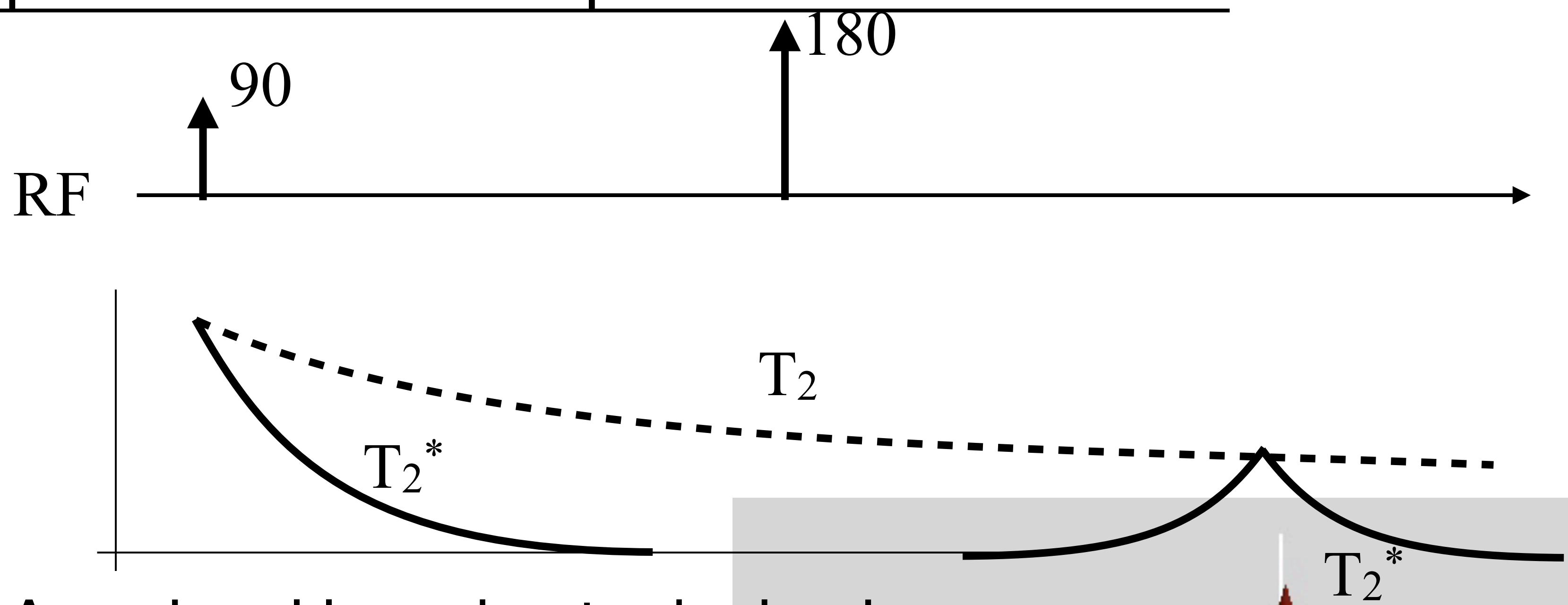


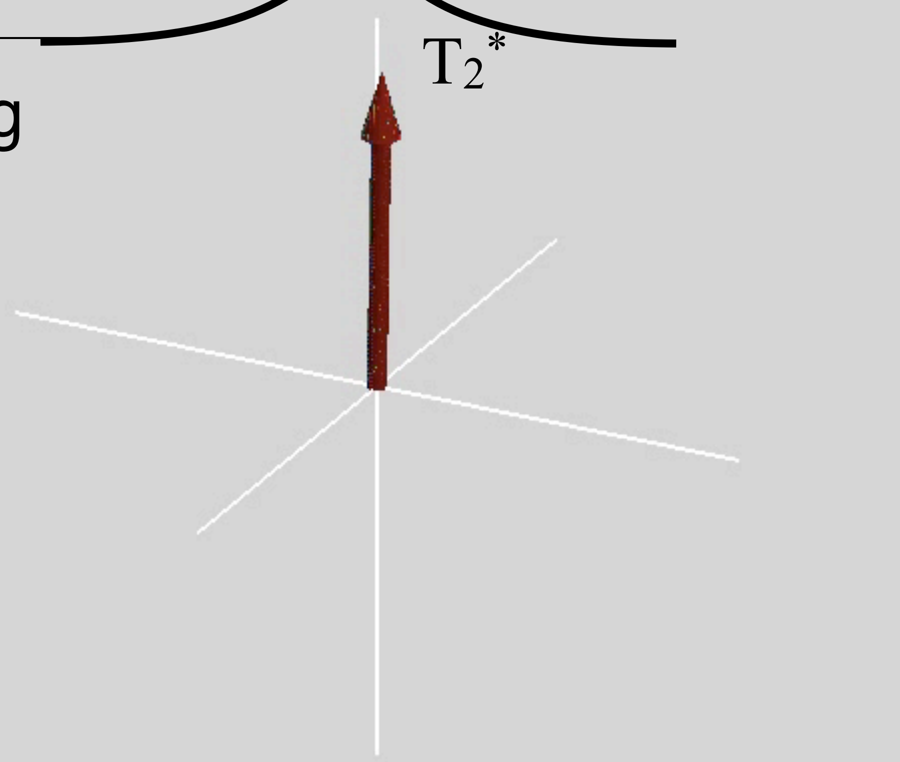
Two 90° excitations, separated by T cause large signal to form at 2T,   Why?

Spin Echo Pulse Sequence



Spin Echo Pulse Sequence





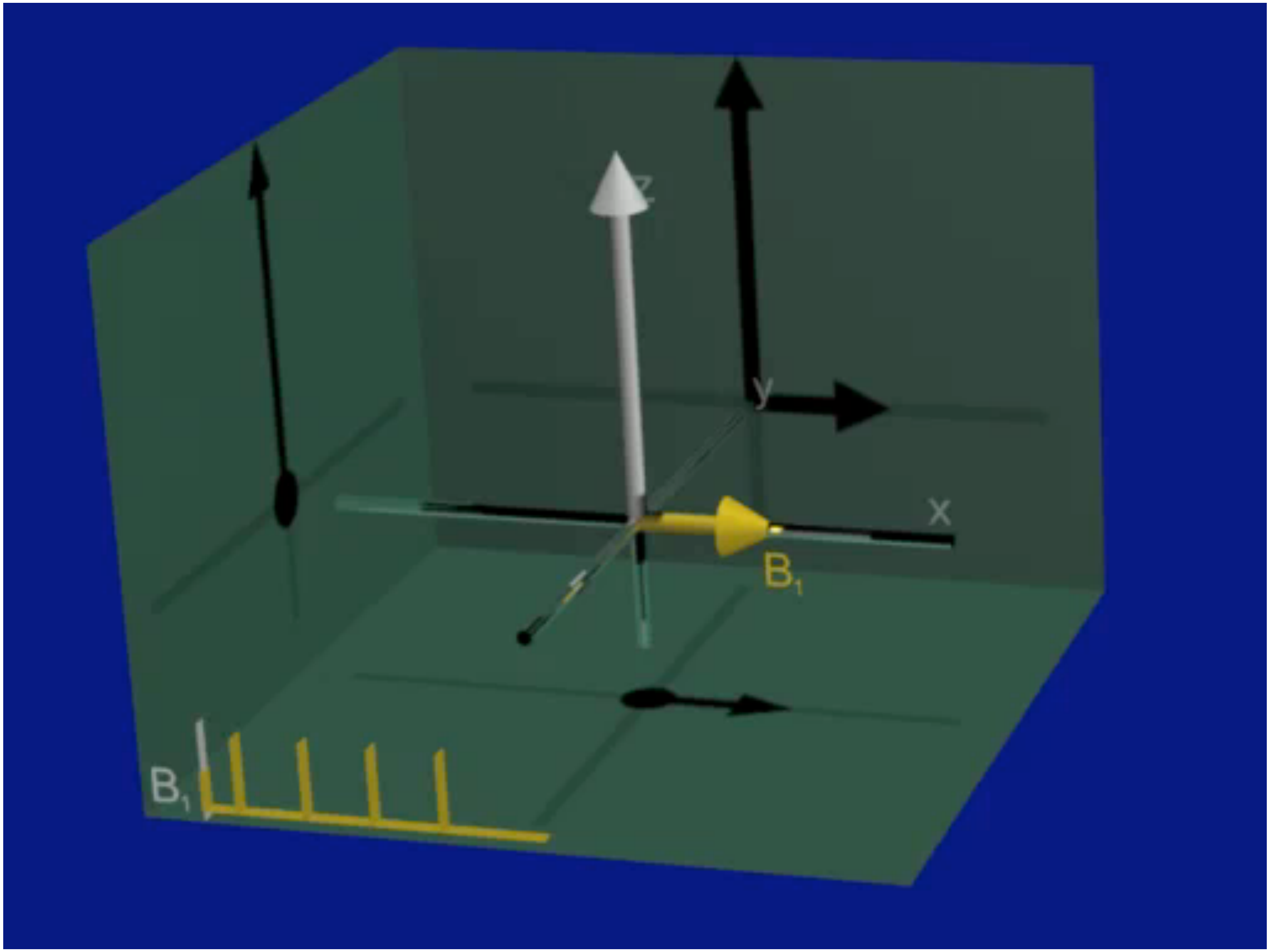
Any signal loss due to dephasing is recovered at the spin-echo

If wE(r,t) changes over time, refocusing is not perfect

Provides probe to measure molecular motion

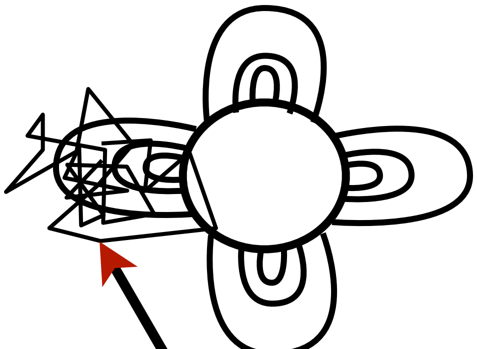
Multi-Spin Echo - CPMG

- `

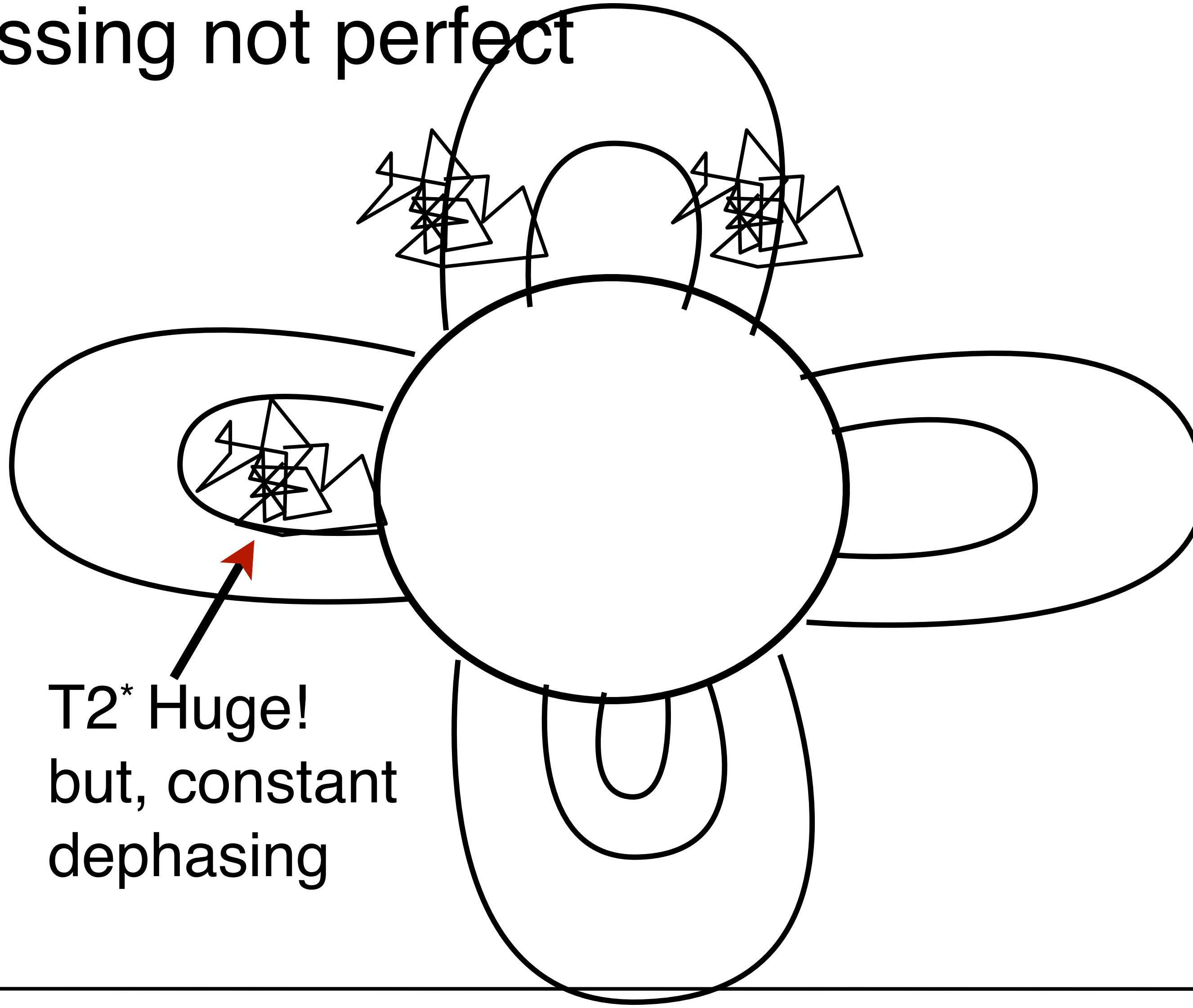


Non uniform dephasing

- Any signal due to dephasing $\omega_E(r)t$ is refocussed
- If $\omega_E(r,t)$ refocussing not perfect

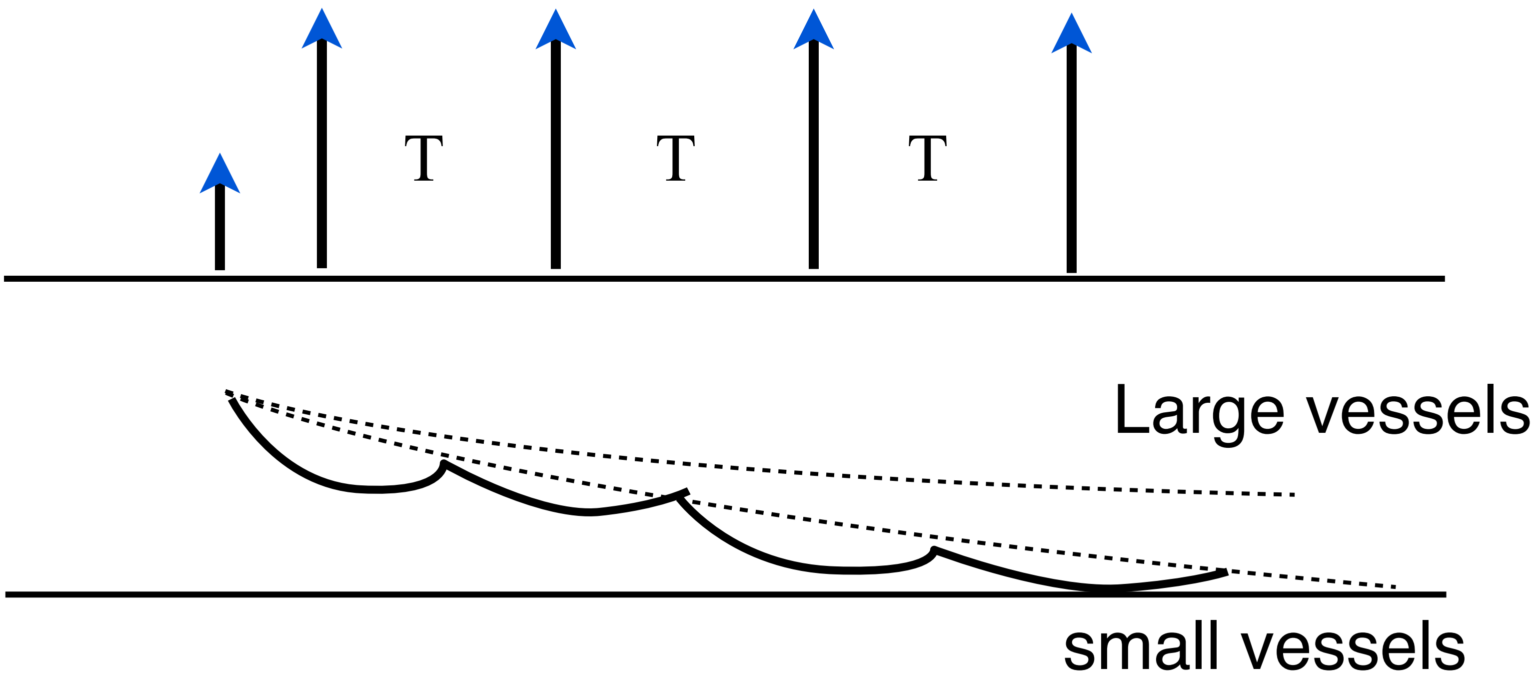


time-varying dephasing shows as T_2



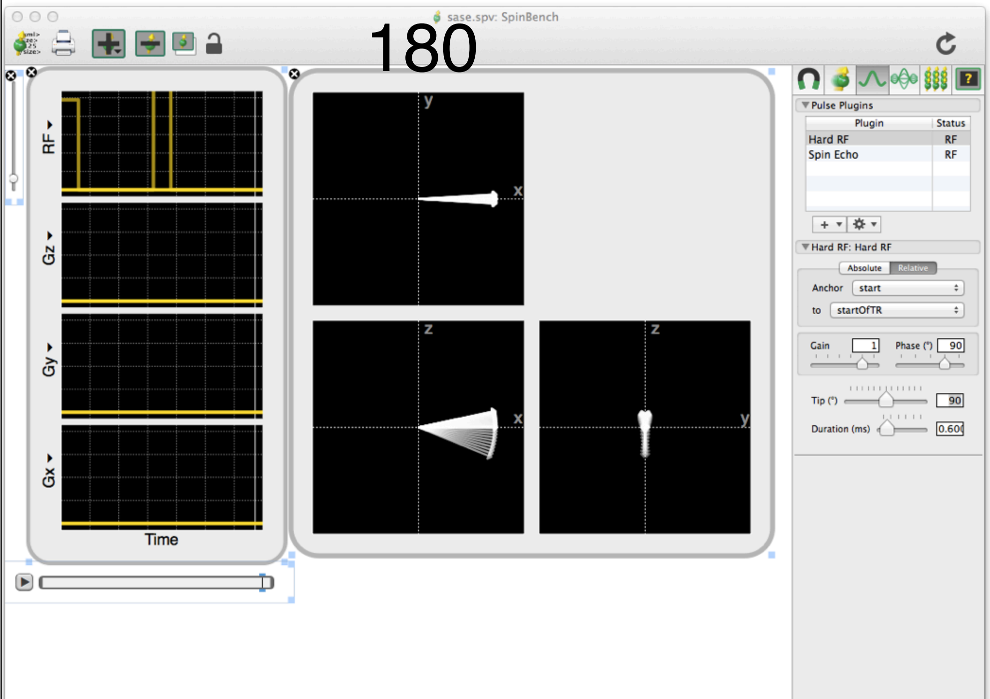
$T2^*$ Huge! but, constant dephasing

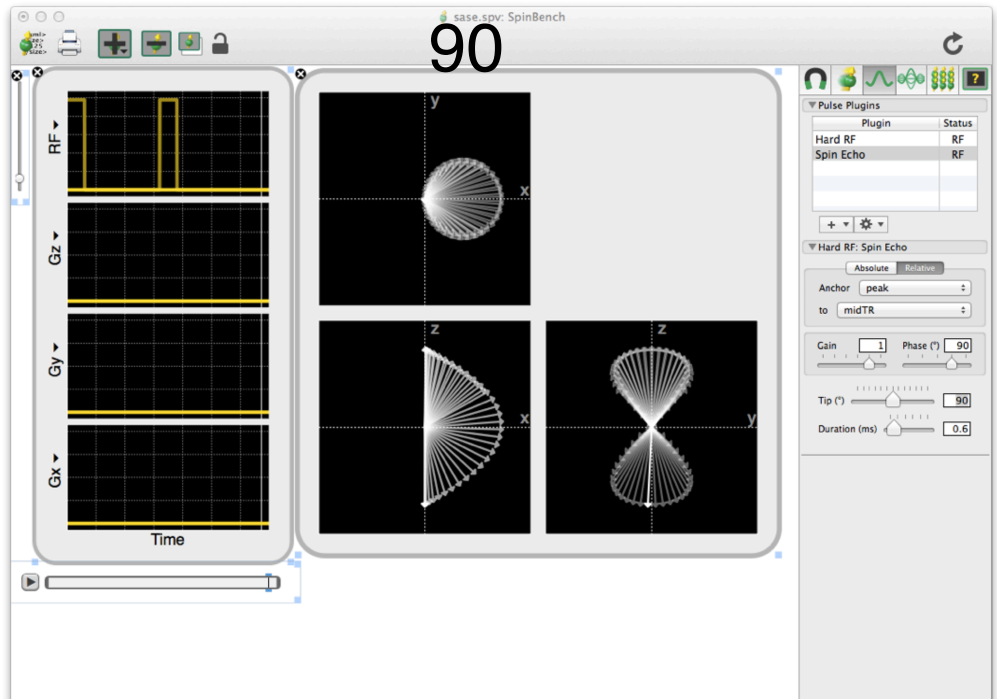
T2(T)



Low Flip Angle Spin Echoes

- Any pulse can produce a spin-echo
  - 180 maximally refocuses magnetization
  - Lower refocusing power with lower flip angle
  - 90 refocusses 1/2 (see homework)

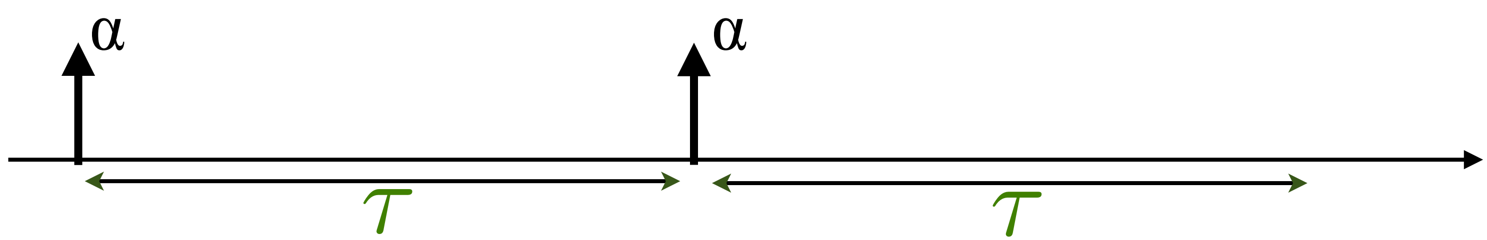




Low Flip Angle Spin Echoes

- Refocusing RF result can be decomposed to several components:
  - Pass through
  - Refocused
  - Parasitic excitation
  - Magnetization stored in Mz

Low Flip Angle Spin Echoes



$$M = R_z(\omega_E \tau) R_x(\alpha) R_z(\omega_E \tau) R_x(\alpha) M_0$$

For 90 degrees:

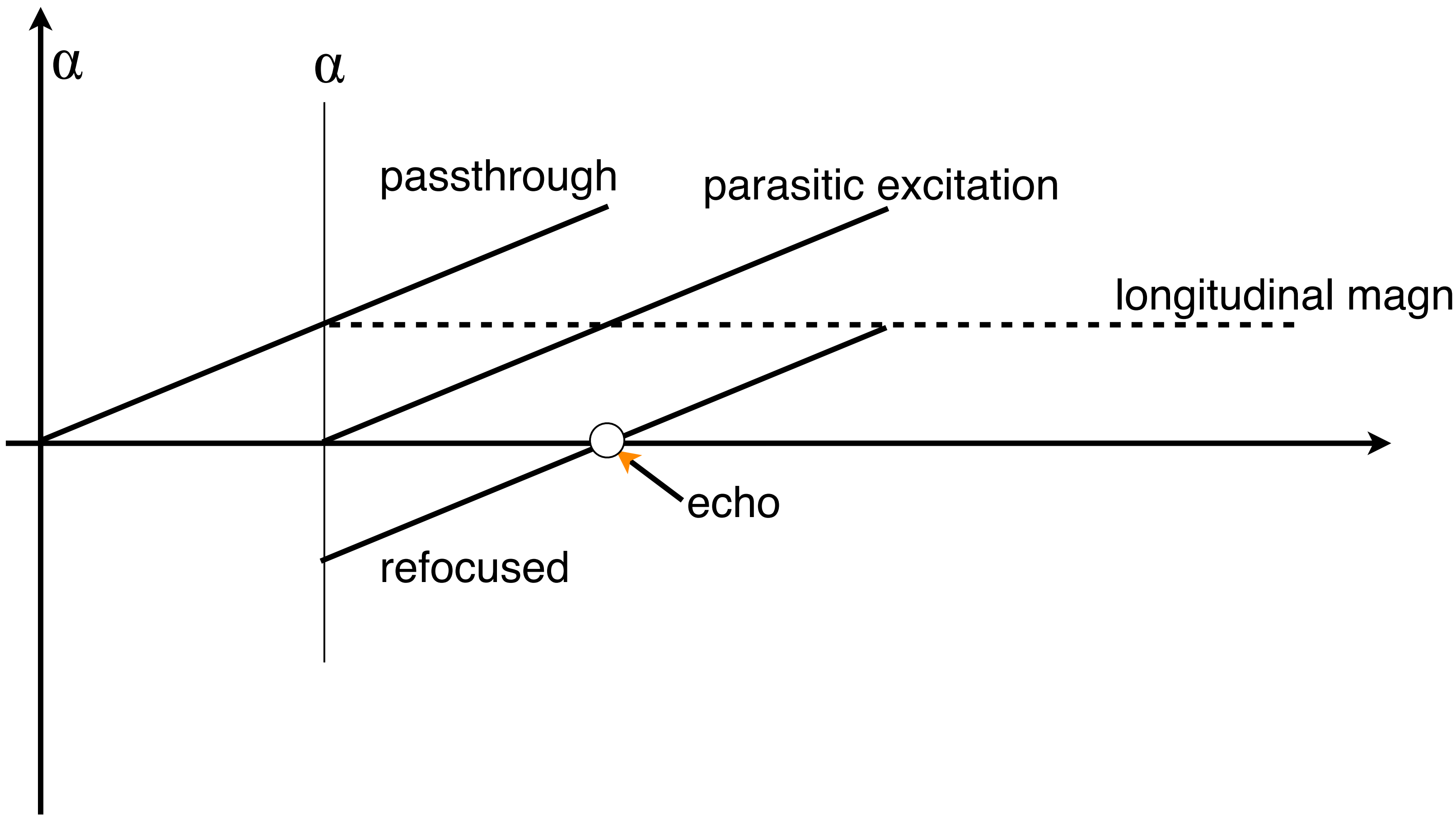
$$M_{xy} = \frac{1}{2}\sin(\omega_E 2\tau) M_0 - i\sin^2(\omega_E \tau) M_0$$

In general.... I think

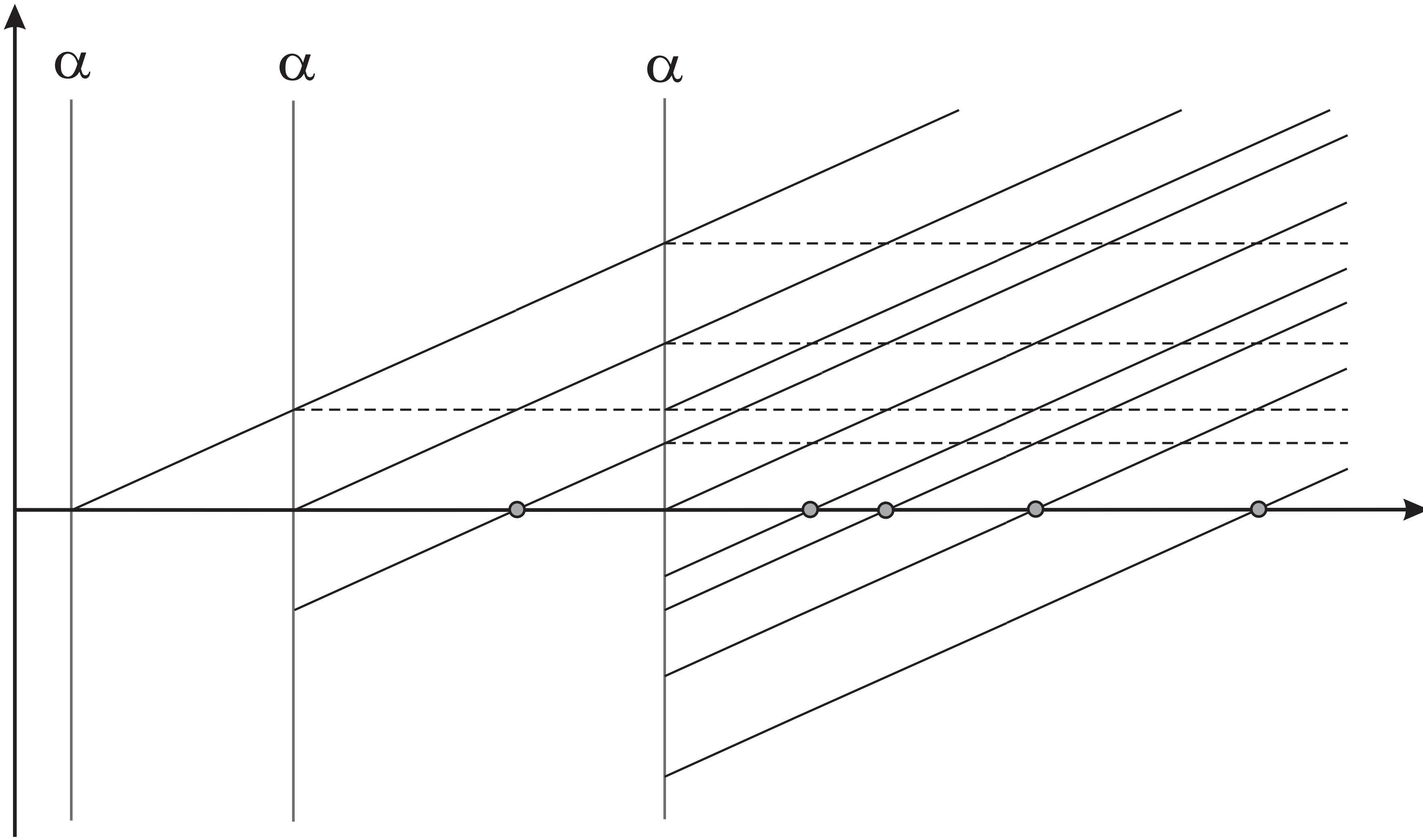
$$M_{xy} = \underbrace{A_1\cos(2\omega_E\tau) + A_2\sin(2\omega_E\tau)}_{\text{passthrough}} + \underbrace{B_1\cos^2(\omega_E\tau) + B_2\sin^2(\omega_E\tau)}_{\text{refocused}} + \underbrace{C_1\cos(\omega_E\tau) + C_2\sin(\omega_E\tau)}_{\text{parasitic}}$$

Phase Graphs

- Useful to find echo formations



Phase Graphs



* from document by Matthias Weigel

Extended Phase Graphs

- Each component has different magnitude and phase
- Echo consist of contribution from many pathways
- Can track to calculate magnitude & Phase of echo (Beyond scope... see document by Matthias Weigel)

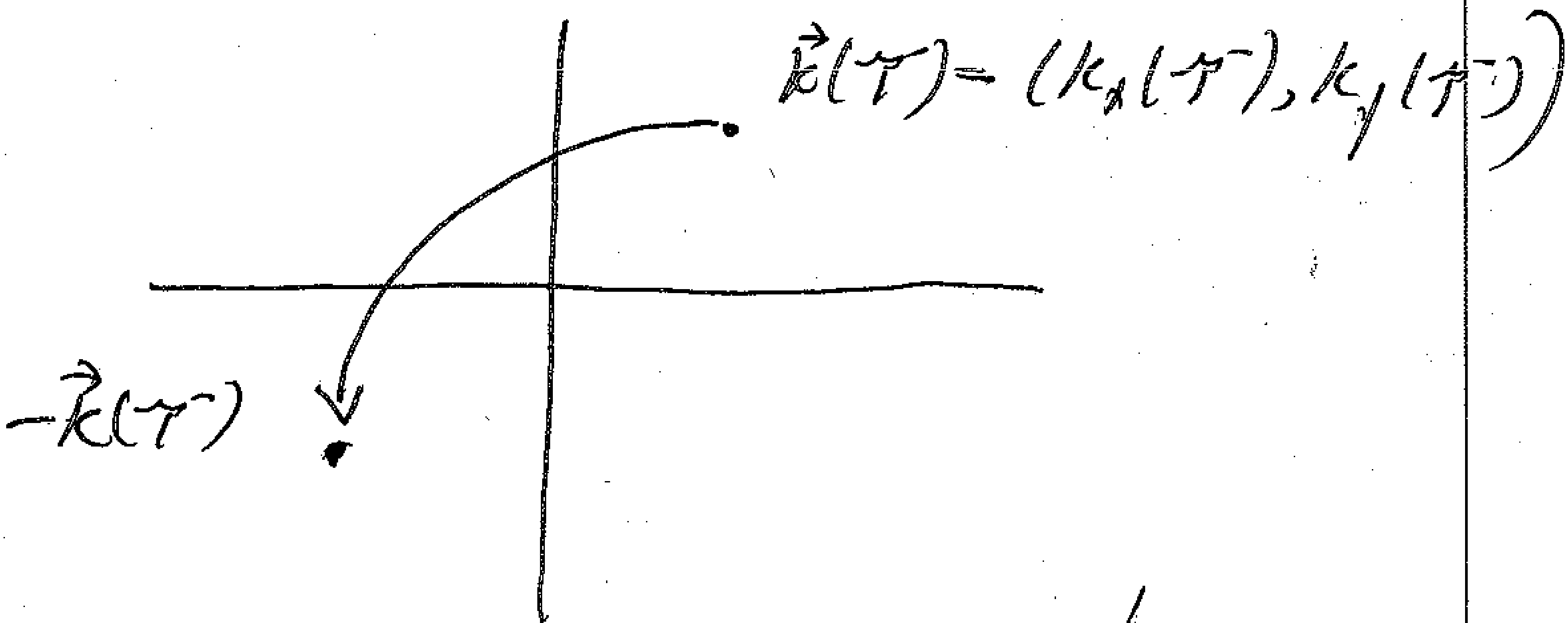
Spin Echo Imaging

- Spin echo negates phase -- Conjugation
- How to incorporate in pulse sequence?

$$M_{xy}(\vec{r},t) = M_{xy}(\vec{r},0)e^{-i2\pi(k_x(t)x+k_y(t)y)}$$

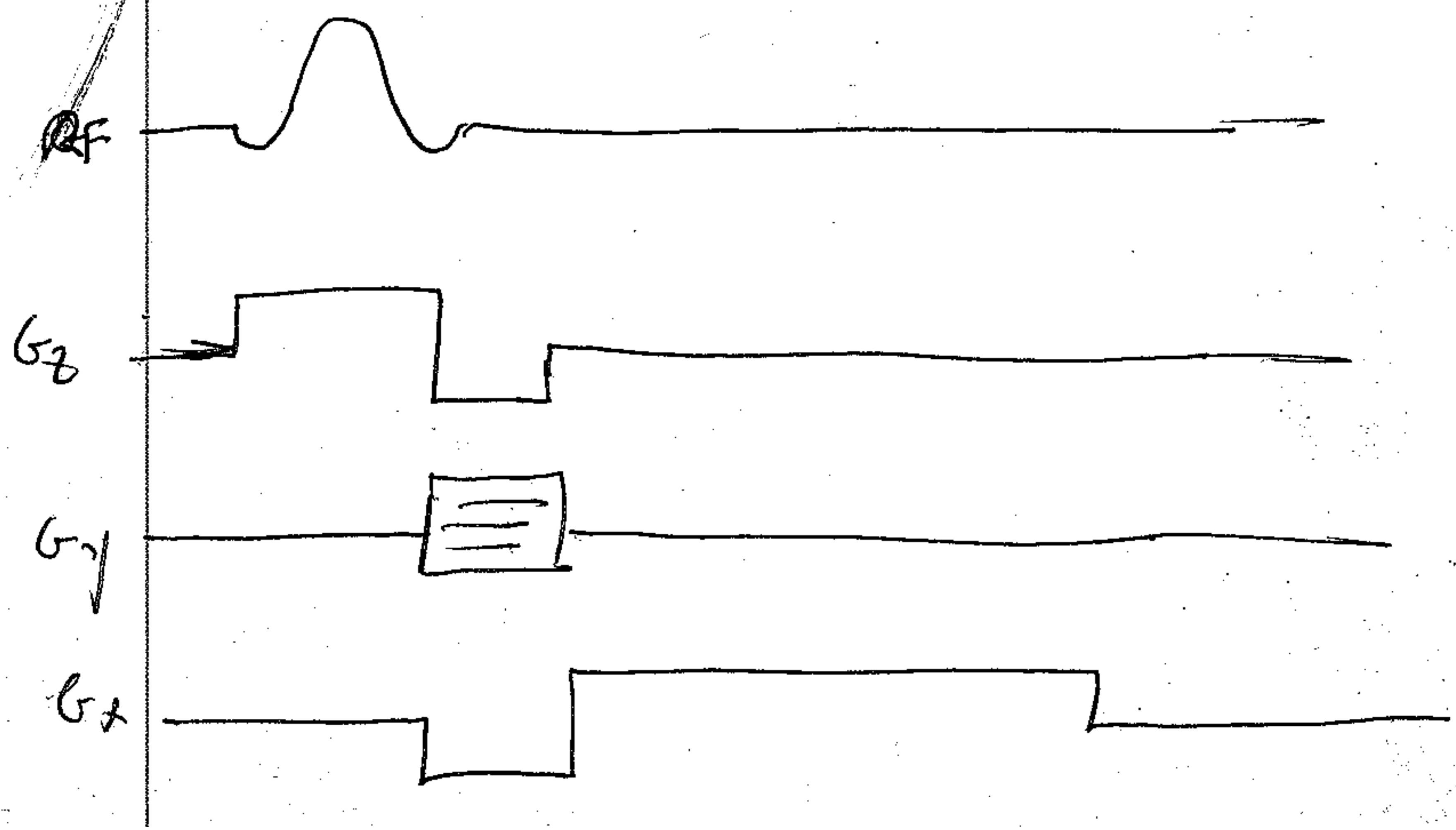
Spin Echo Imaging

- Spin echo negates phase -- Conjugation
- How to incorporate in pulse sequence?



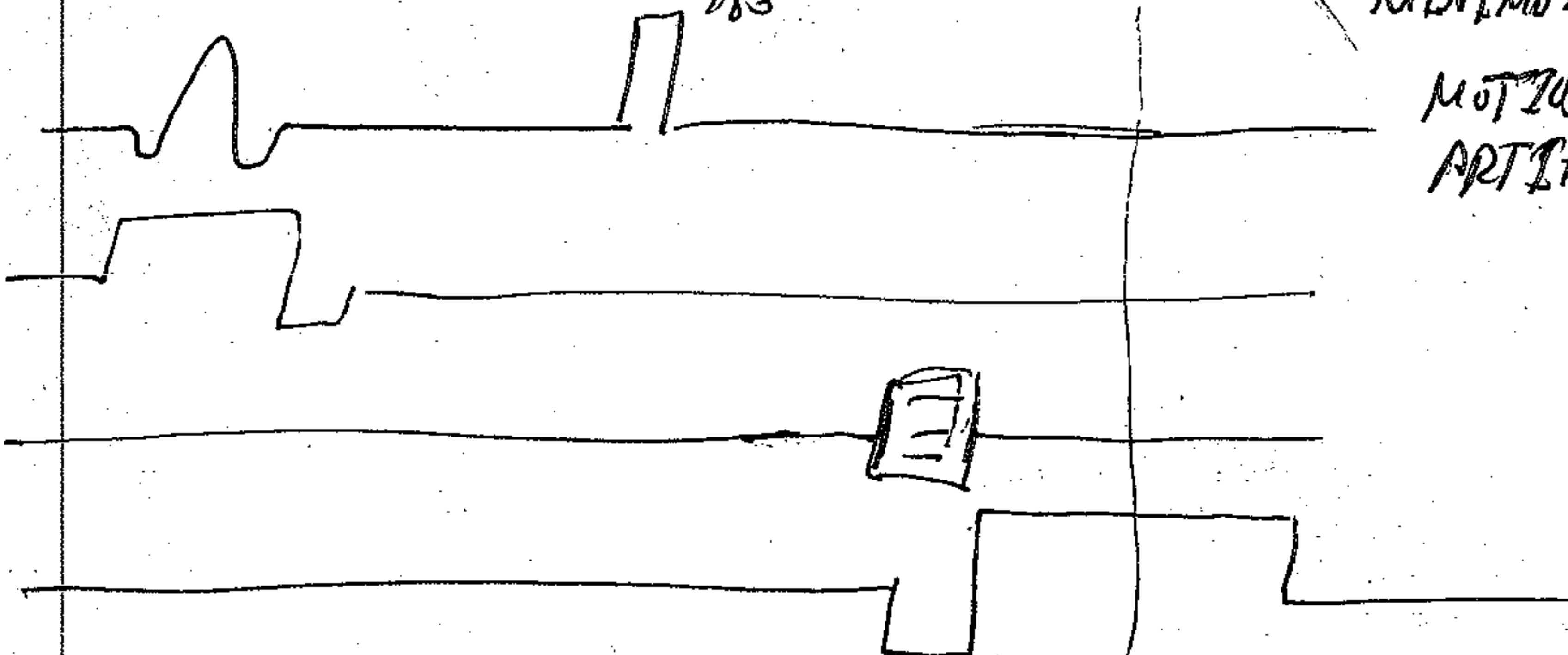
K-SPACE GOES TO CONJUGATE POSITION!

REGULAR 2DFT GRADIENT ECHO!



NEGATE GRADIENT LEFT OF 180

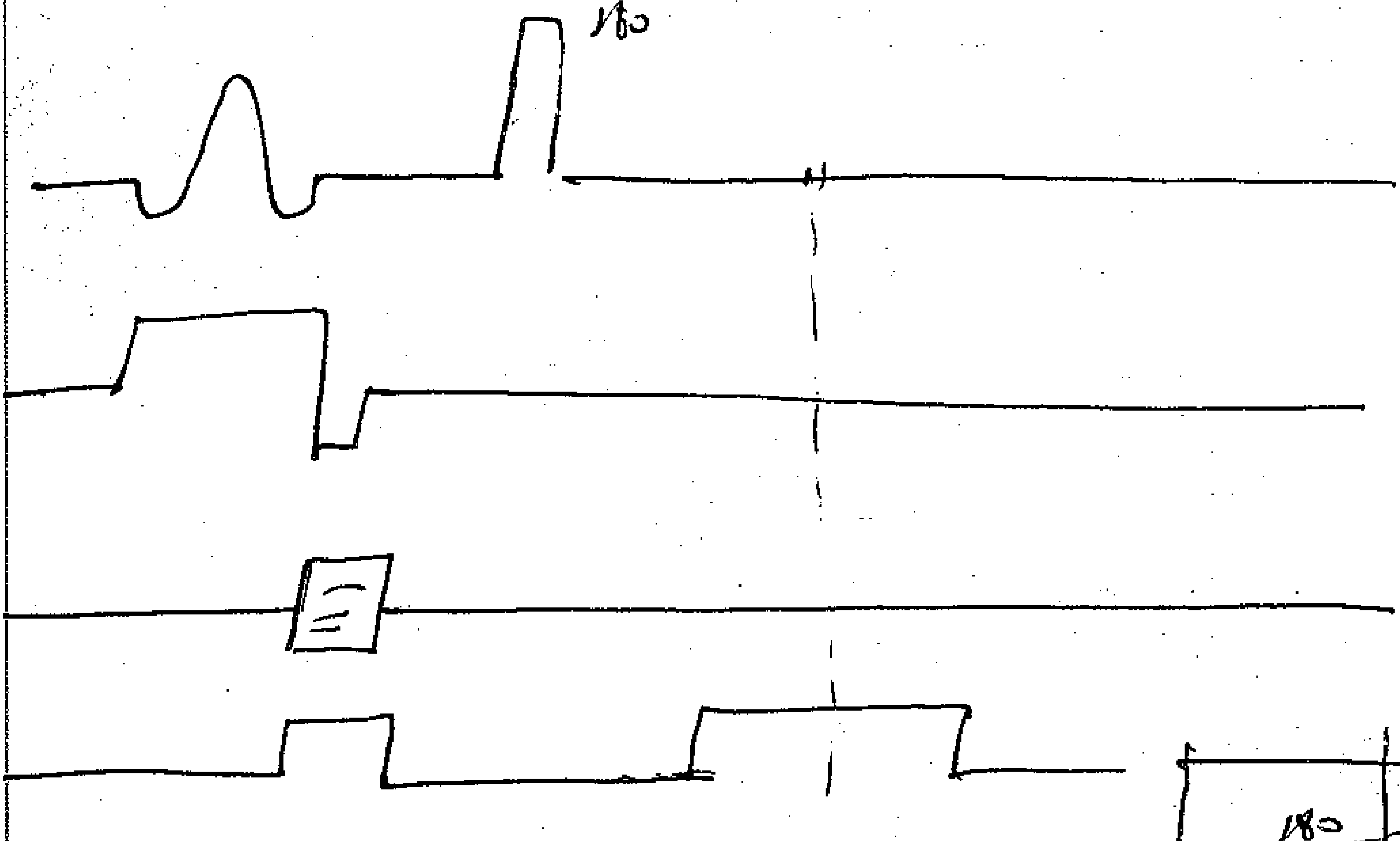
TRIVIAL ~~[illegible]~~ ADAPTATION:



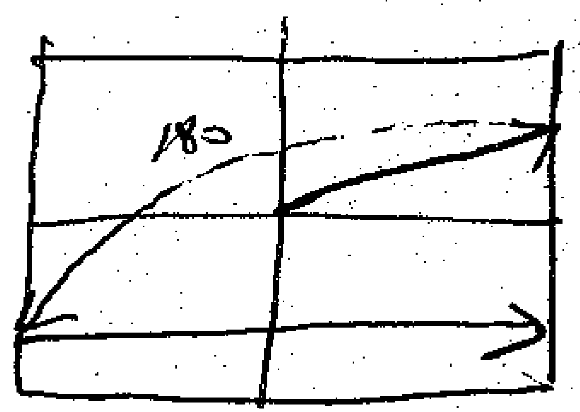
MINIMUM MOTION ARTIFACTS.

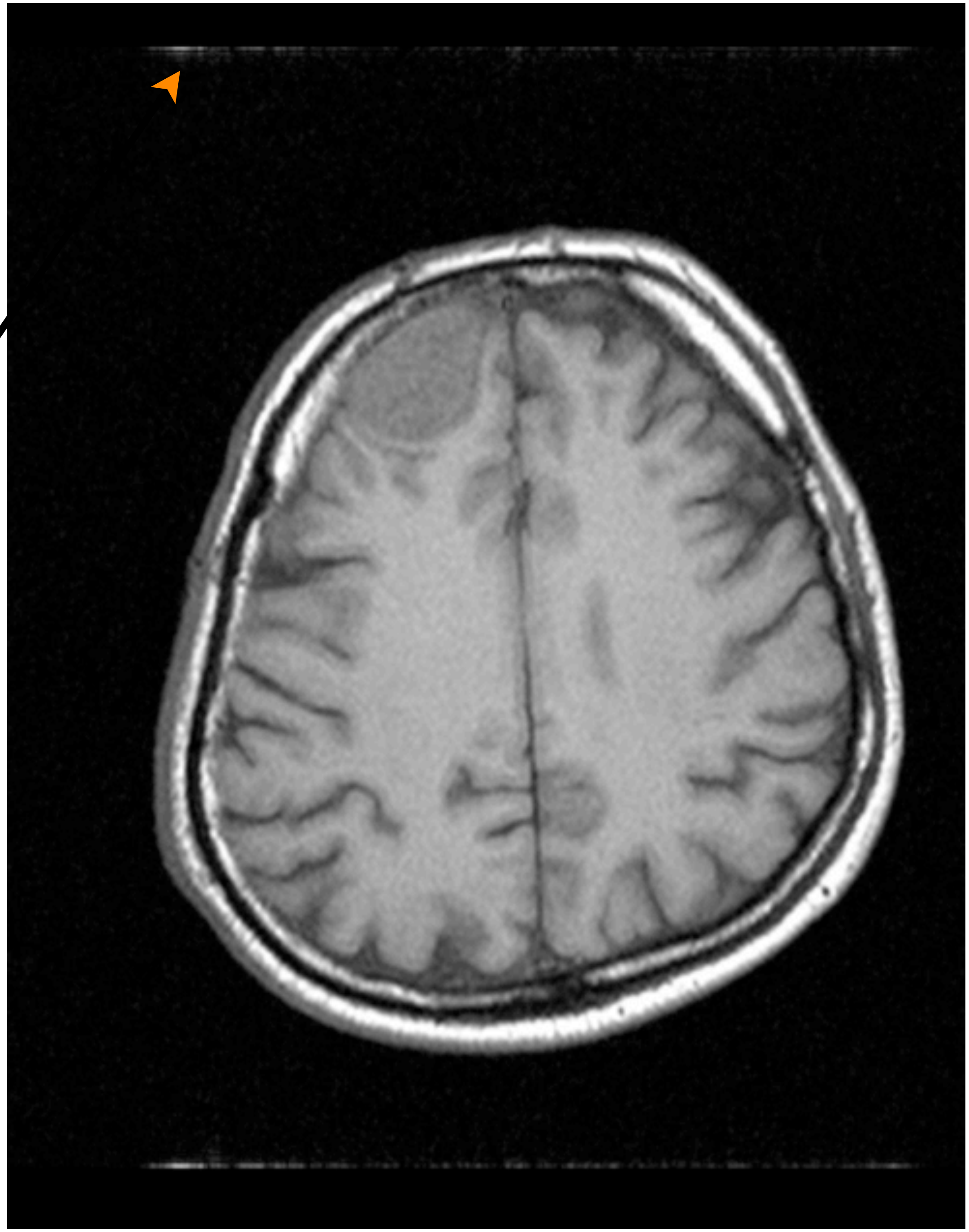
WANT GRADIENT ECHO TO HAPPEN WITH SPIN-ECHO.

SHORTEST ECHO TIME



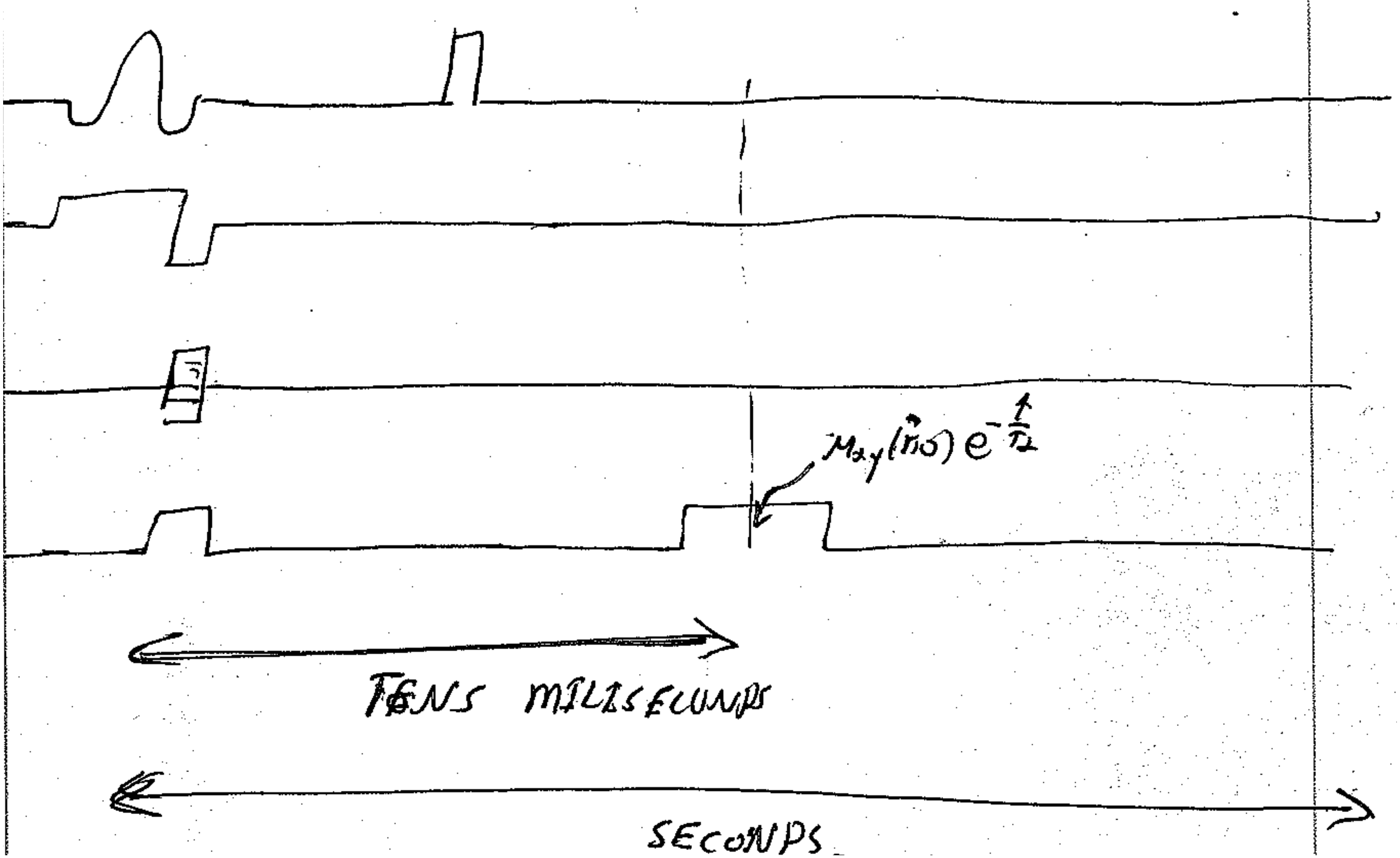
imperfect 180 causes parasitic
which is not phase encoded (HW)



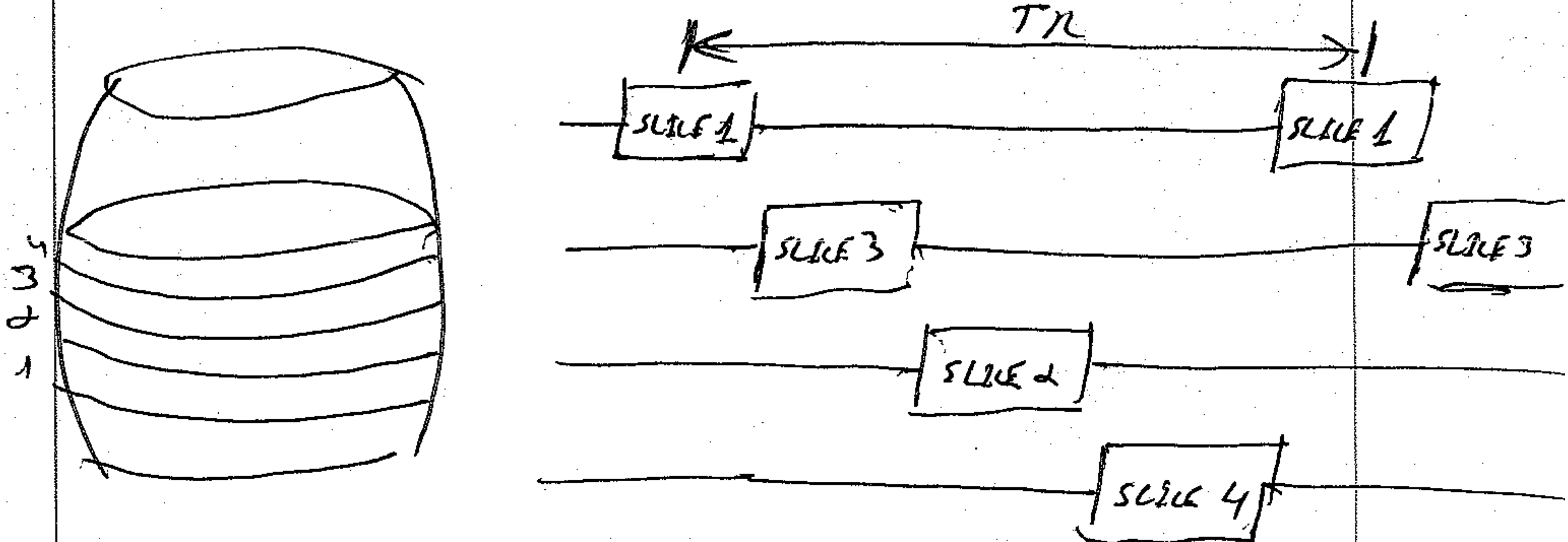


MULTI-SLICE

SIMPLE T_2-WEIGHTED SPIN-ECHO.

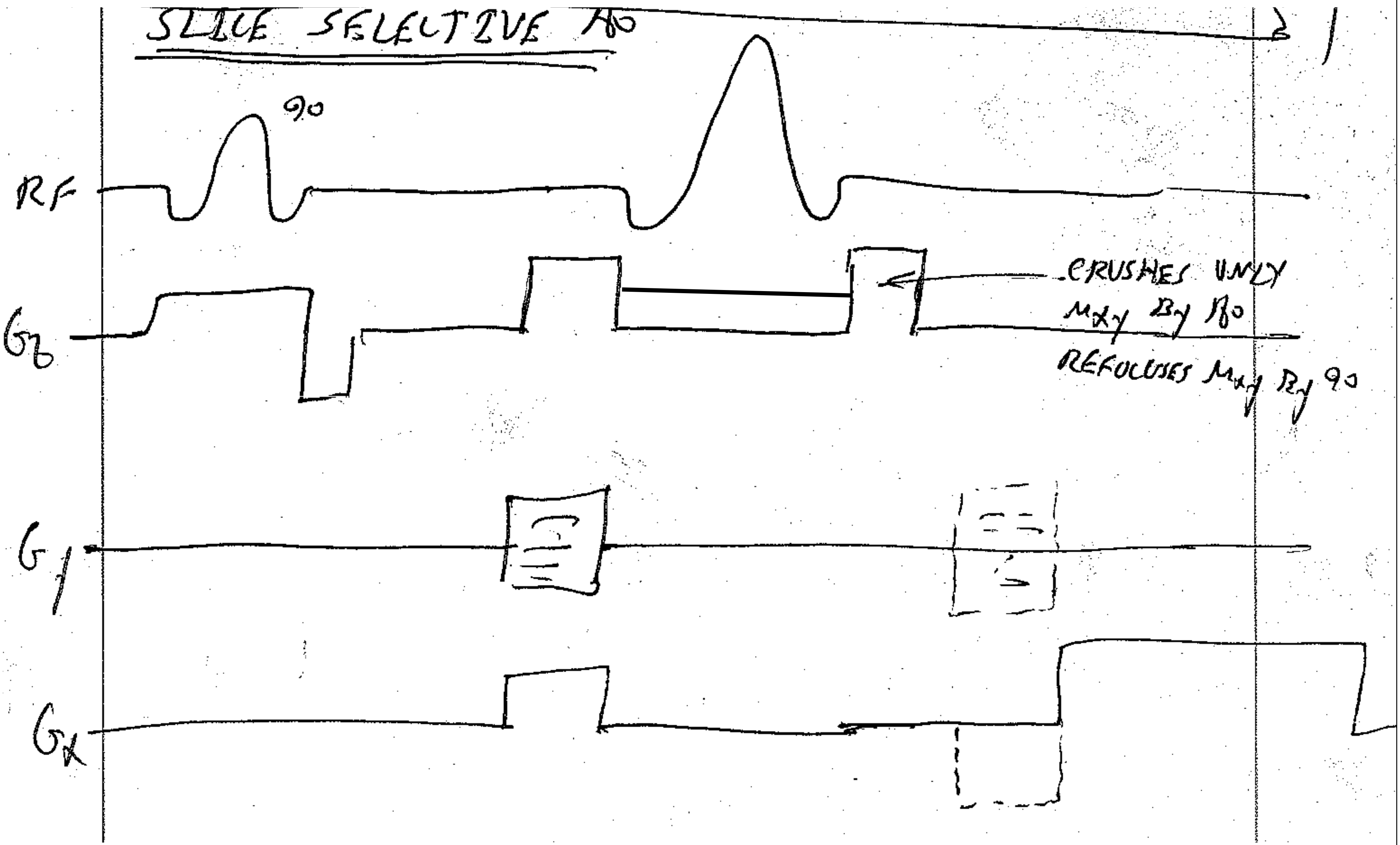


INEFFICIENT! ADD MULTISLICE MAKE 180 SELECTIVE



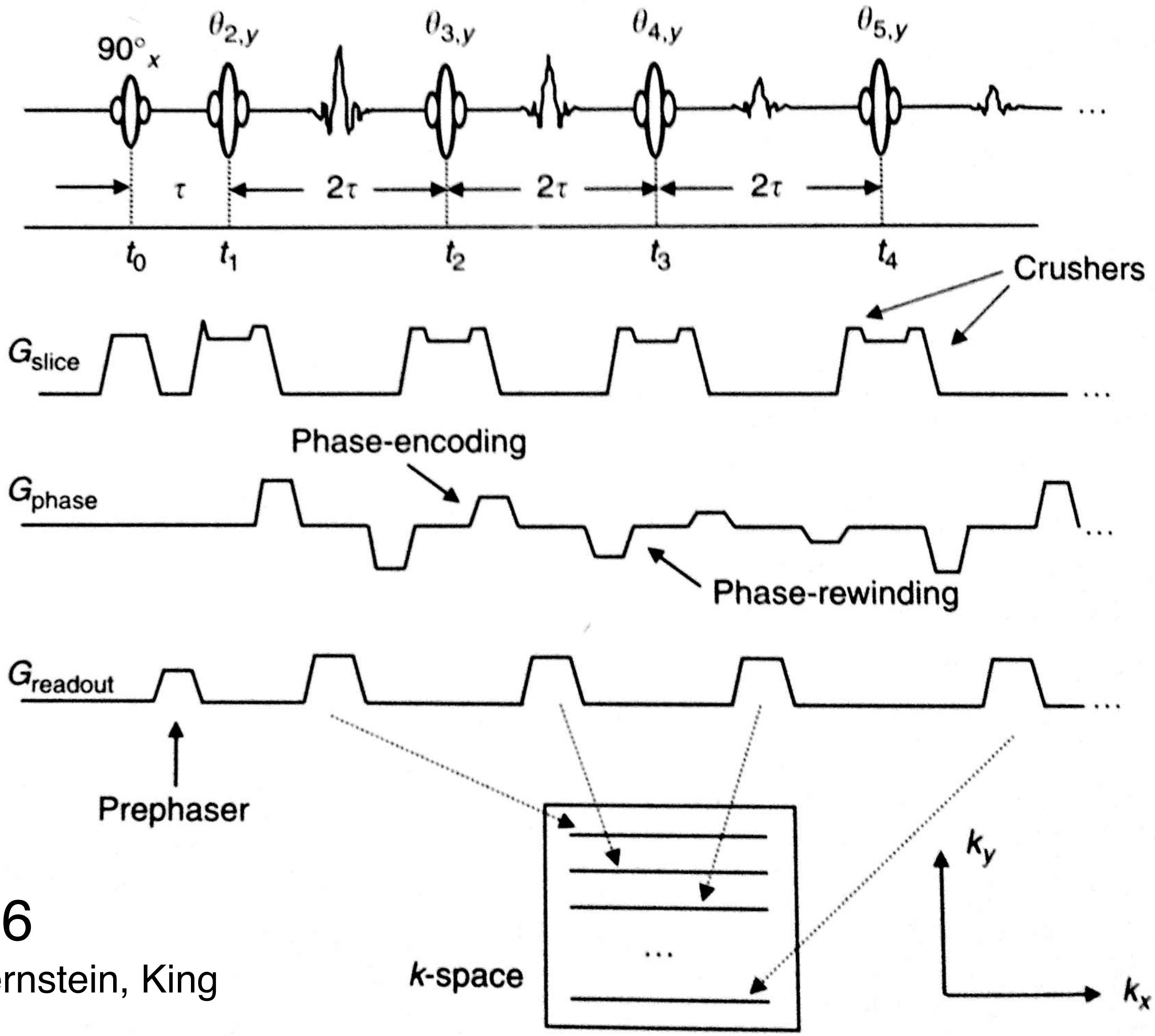
WHEN IMAGING ONE SLICE, OTHER RECOVER!

VERY EFFICIENT ALWAYS AQUIRING DATA.



what's the phase graph for all pathways?

Fast/Turbo Spin-Echo (RARE)



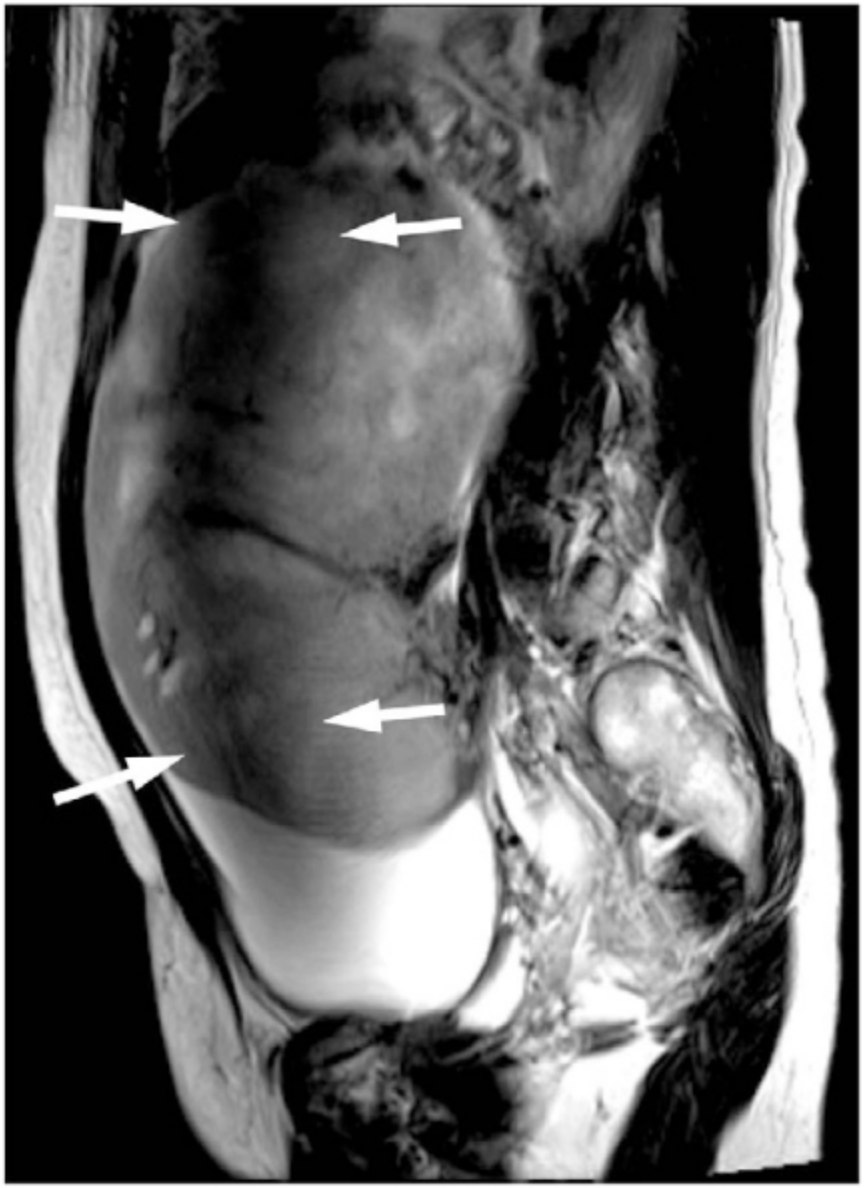
Hennig '86

figure from Bernstein, King and Zhou

Other non-idealities

- RF Inhomogeneity
  - Affects Excitation
    - Spatially varying flip-angle
    - Spatially varying phase
    - Can cause problem for fat saturation
  - Worse @ high field (wave effects)
  - Affects receive

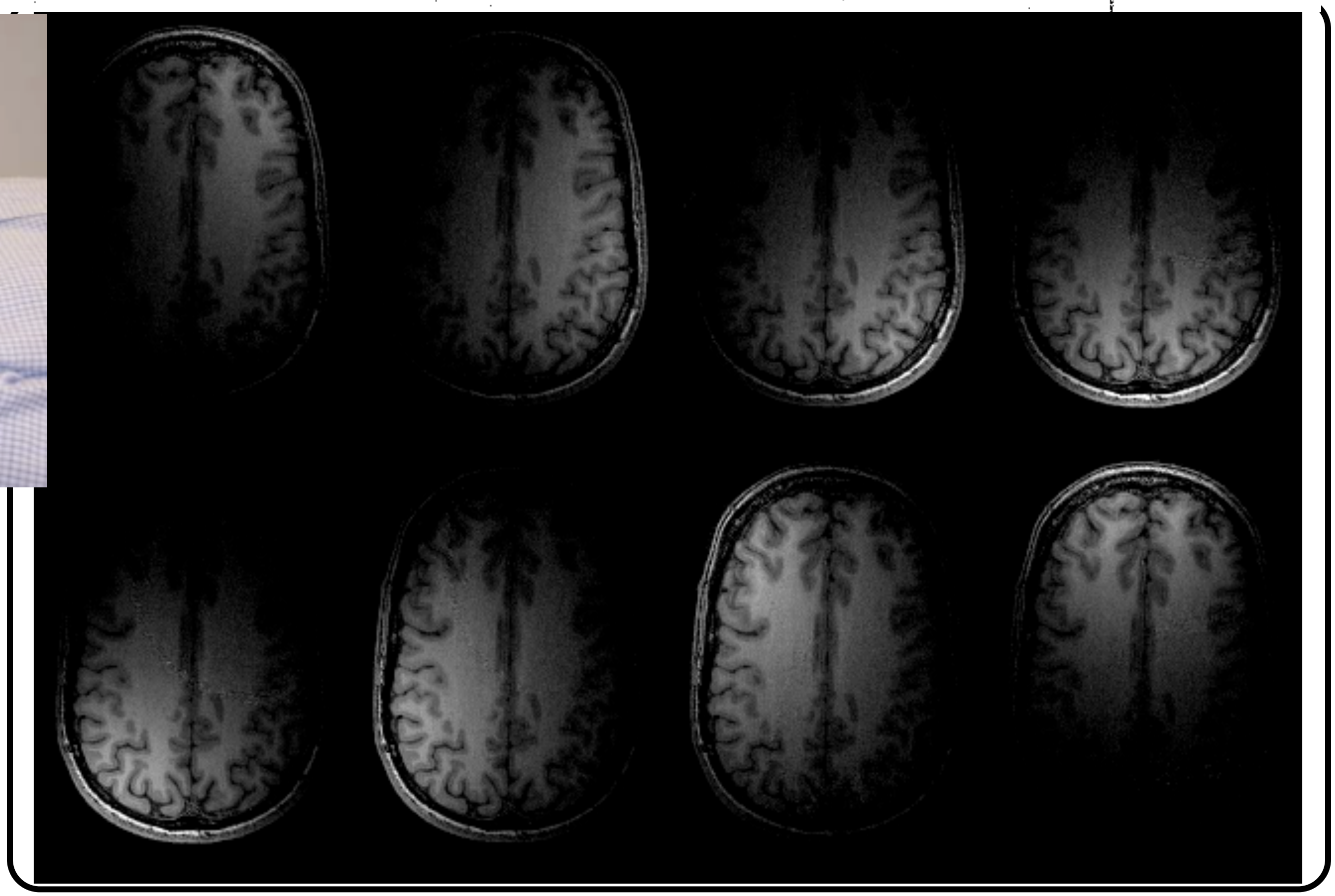
RF excitation inhomogeneity



AFFECTS RECEIVE:

(-) VARYING COMPLEX SENSITIVITY

$$s(t) = \iint_r c(\vec{r}_{x,y})\, m(\vec{r}_{x,y})\, e^{-i2\pi(\vec{k}\cdot\vec{r})}\, dr$$



CAN BE A GOOD THING: SENSITIVITY ENCODING.

$$s_1(t) = \int_R m(\vec{r},0)\, c_1(\vec{r})\, e^{-i2\pi(\vec{k}\cdot\vec{r})}\, d\vec{r}$$

$$s_2(t) = \int_R m(\vec{r},0)\, c_2(\vec{r})\, e^{-i2\pi(\vec{k}\cdot r)}\, d\vec{r}$$

TO RECONSTRUCT mC_1 & mC_2 need n encodings

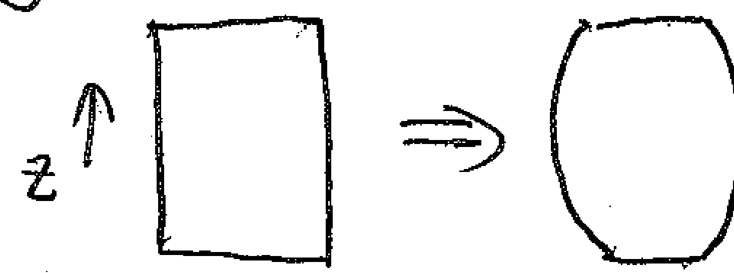
BUT TO RECONSTRUCT m need (maybe) $\frac{n}{2}$ encodings.

More later!

Gradient non-idealities

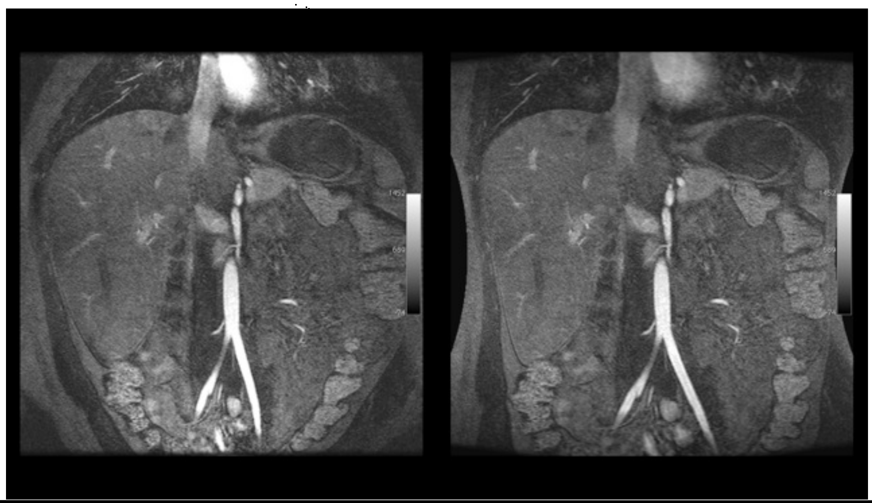
GRADIENTS

(–) Non Linearity – GRADIENT ROLLES OFF



← FOV ↑ RES ↓

EASY TO CORRECT BY INTERPOLATION



Concomitant Gradient (Maxwell Terms)

(-) CONCOMITANT GRADIENTS

IDEAL GRADIENTS VIOLATE MAXWELL EQN.

FOR CYLINDRICAL COILS USED IN MRI

$$B = \underset{\substack{\uparrow \\ \text{main}}}{B_0} + \underbrace{G_x x + G_y y + G_z z}_{\text{gradients}} + \frac{1}{2B_0}\left[\frac{G_z^2}{4}(x^2+y^2) + (G_x^2+G_y^2)z^2 - G_xG_z xz - G_yG_z yz\right]$$

EXAMPLE! AT $z = 20\,\text{cm}$ $G_x = 40\ \text{mT/m}$ $B_0 = 1.5\,\text{T}$

Concomitant Gradient (Maxwell Terms)

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EXAMPLE! AT $z = 20\,\text{cm}$ $G_x = 40\ \text{mT/m}$ $B_0 = 1.5\,T$

$$\boxed{\frac{G_x^2 z^2}{2B_0} = \frac{(40\cdot 10^{-3}\cdot 0.2)^2}{2\cdot 1.5} = 2.13\cdot 10^{-5}\,T = 14.2\ \text{PPM}}$$

$G = 10\ \text{mT/m} \Rightarrow 0.889\ \text{ppm}$

$B_0 = 0.7T \Rightarrow 65.3\ \text{ppm}!$

Concomitant Gradients

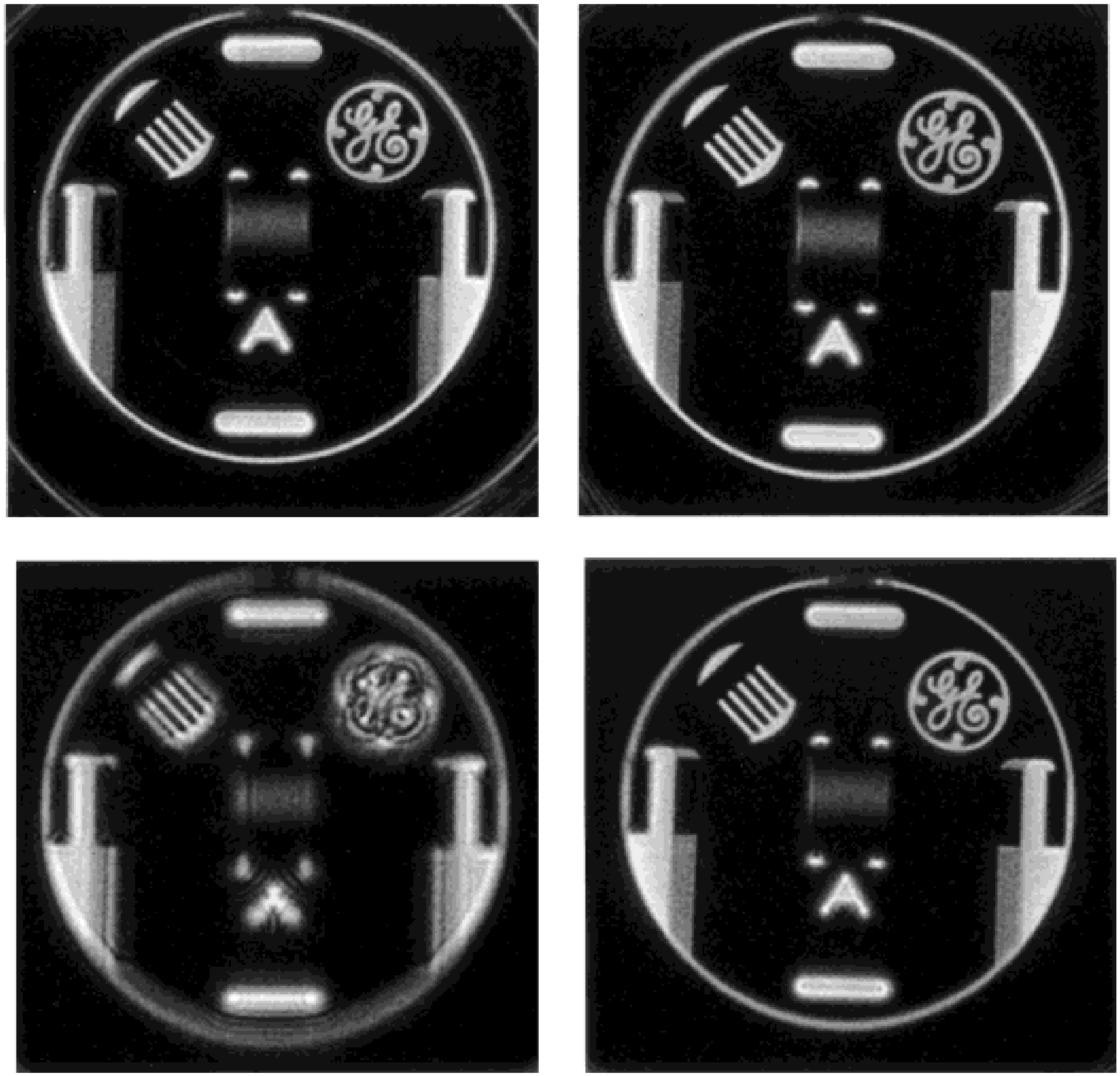
king et. al, MRM 41:103-112(1999)

$$\frac{G_x^2 z^2}{2B_0}$$

$g_m = 2.1$ G/cm $\quad$ $g_m = 0.524$ G/cm

z=0 cm

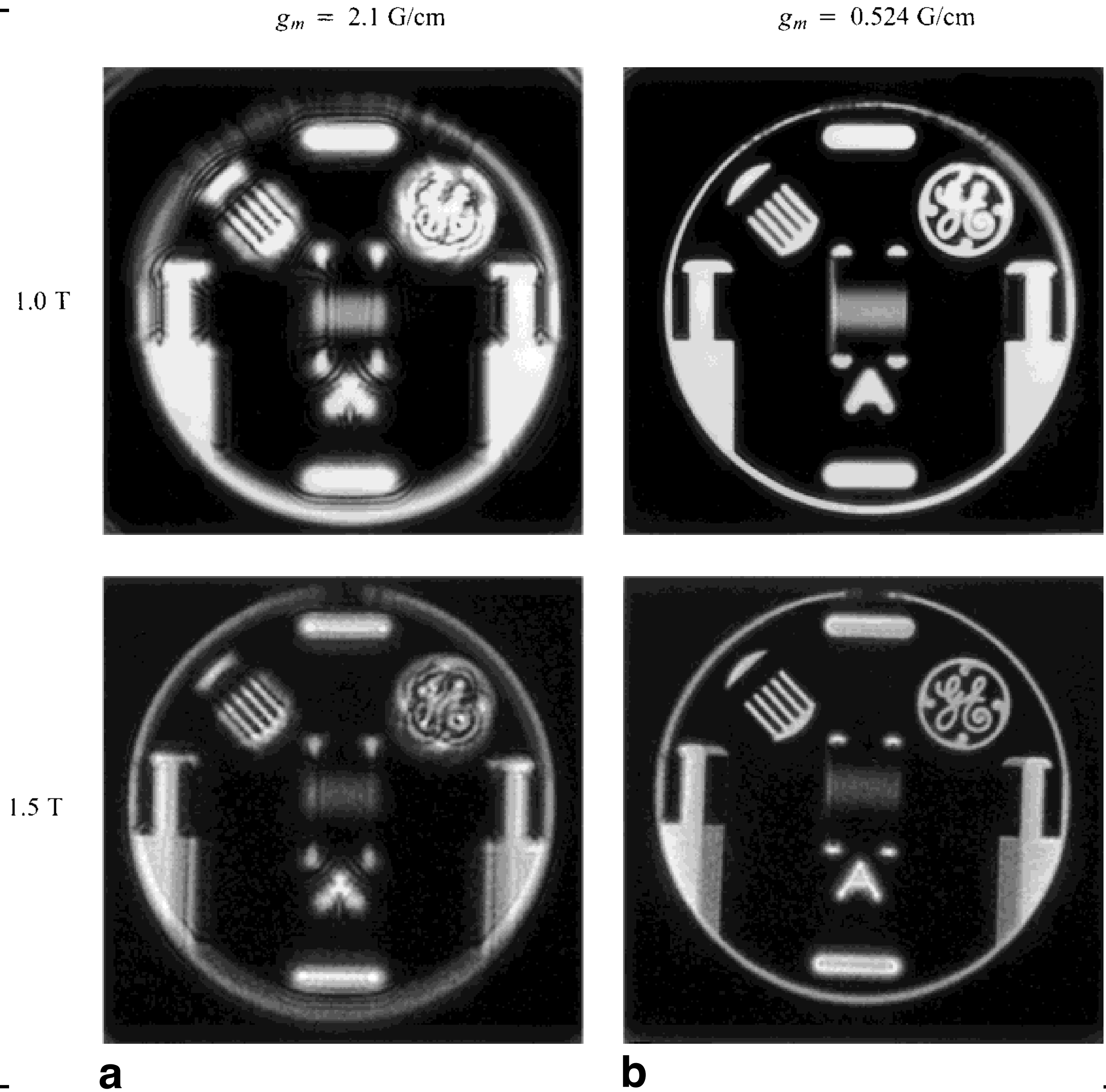
z=10 cm



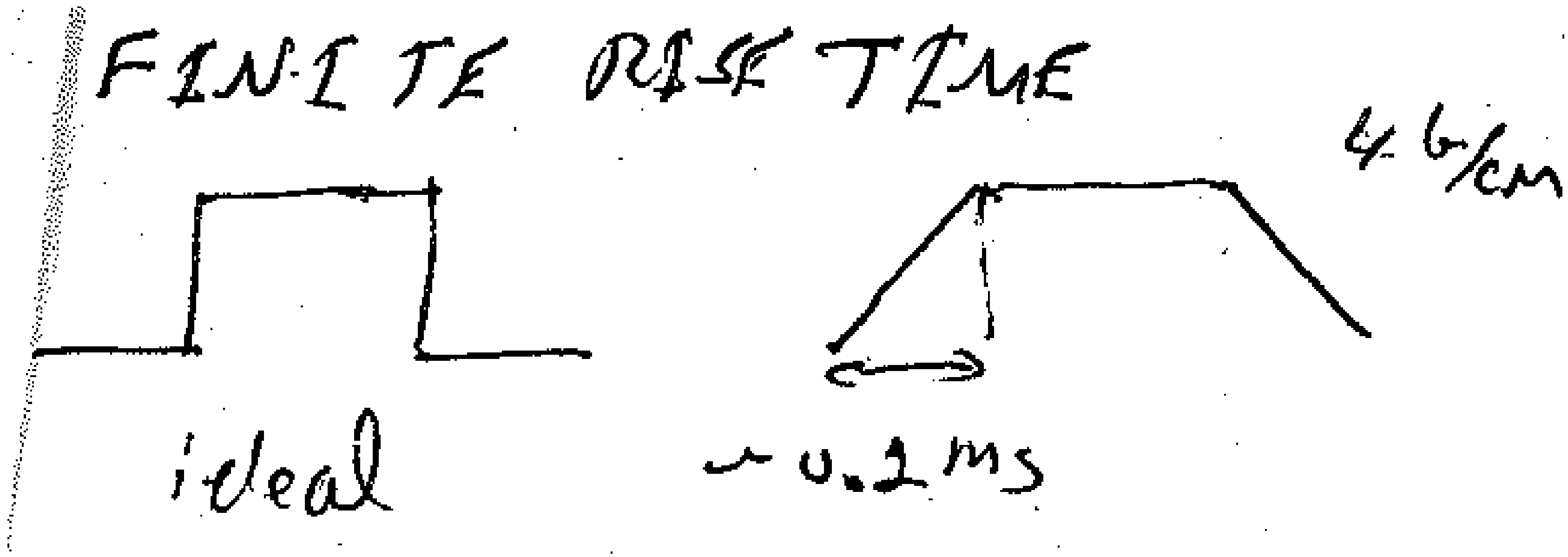
a **b**

@z=10cm

king et. al, MRM 41:103-112(1999)



Gradient Finite Rise-Time

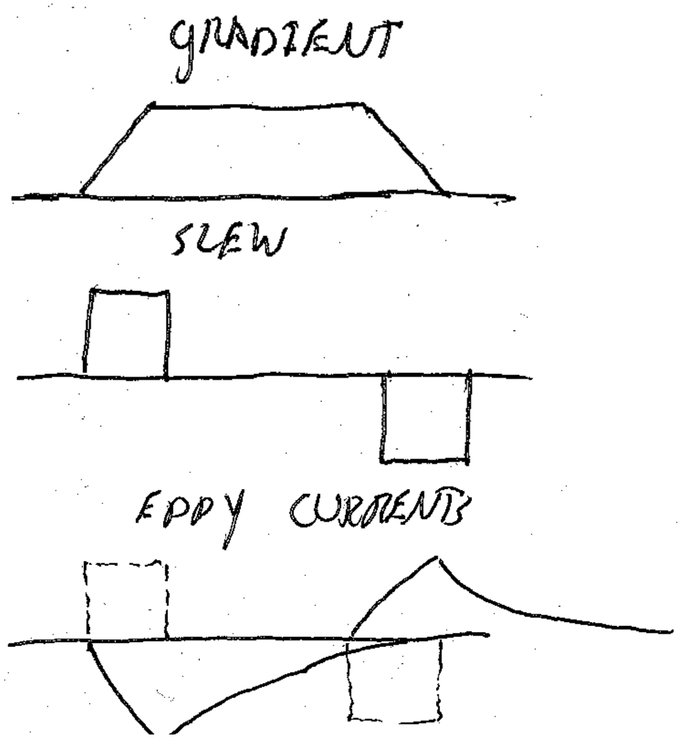


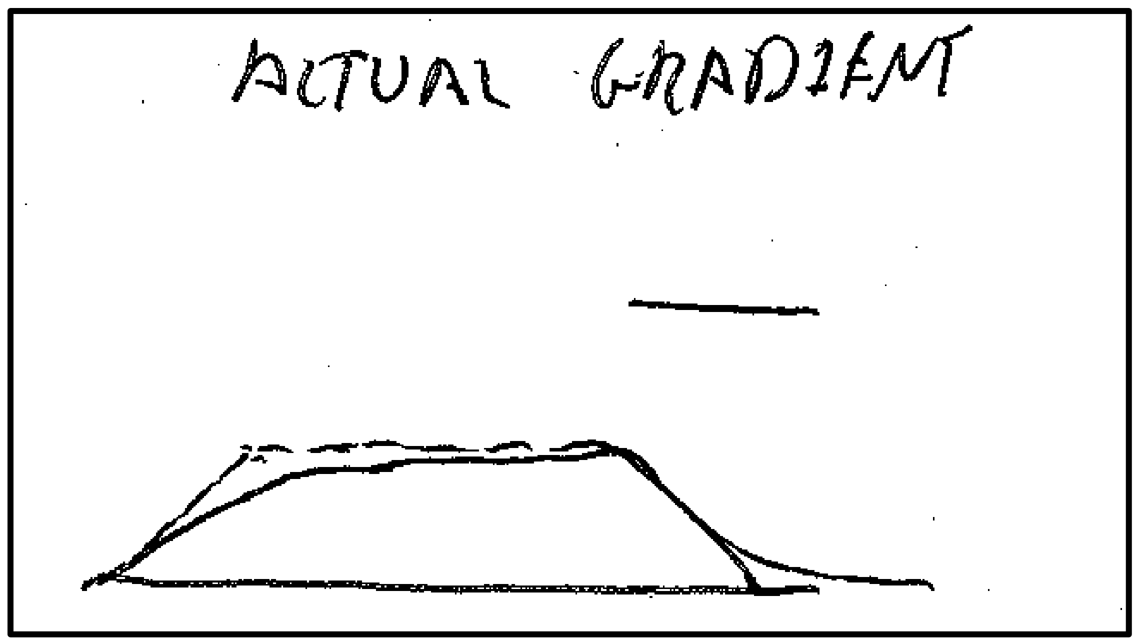
Even finite-rise-time rate! (often ignored)

Eddy Currents

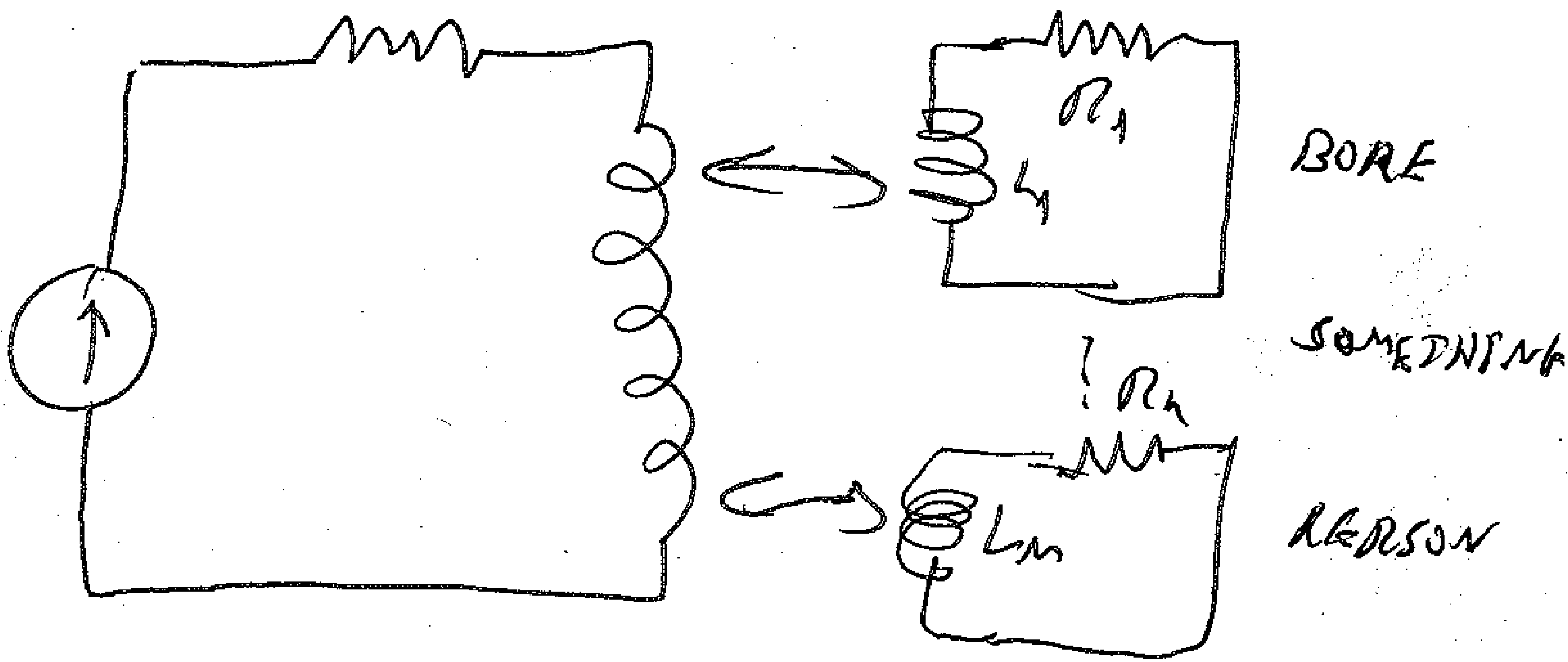
Generated By ELECTRIC FIELD FROM CHANGING MAGNETIC FLUX.

BUILD UP IN TIME VARYING GRADIENTS AND DECAY IN CONSTANT $\propto$ SLEW RATE





$$B_e(\vec{r}, t) = b_0(t) + \vec{r} \cdot \vec{g}(t) + \dots +$$



Eddy Currents

$$g(t) = -\frac{dG}{dt} \circledast e(t)$$

$$e(t) = H(t) \sum \alpha_n e^{-\frac{t}{t_n}}$$

step function

intensity

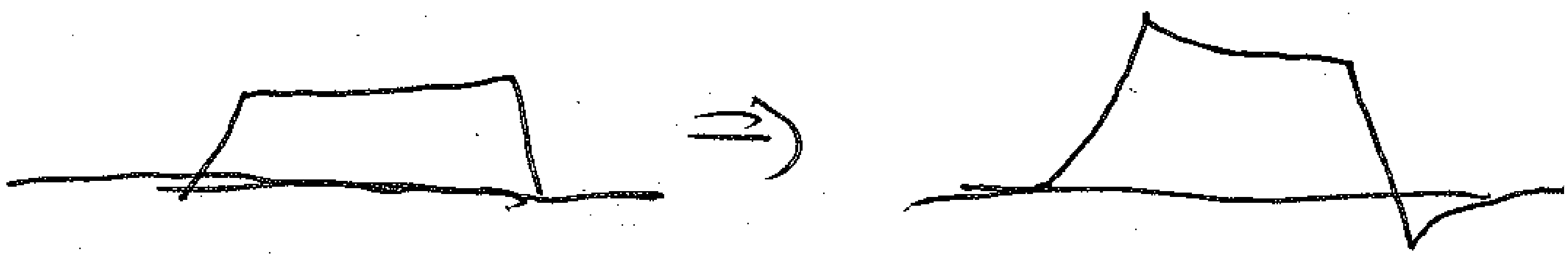
time constant

Pre-emphasis

PREMPHESIS!

B_0 → chung exciter phase

gradient



FOR SHORT TIME constants

$G_{net}(t) = G_{applied}(t - \alpha\tau)$

Benstein ch. 10.3