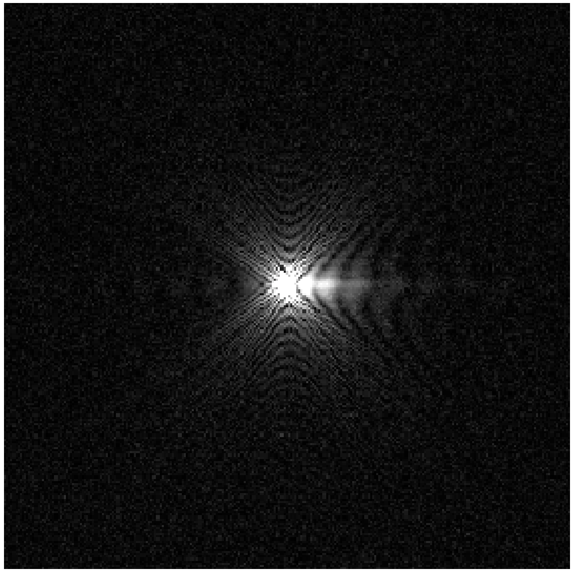
Universitätsklinikum Hamburg-Eppendorf

Advanced Numerical Methods in Neuroscience

k-Space!



Jürgen Finsterbusch and Selim Onat

Department of Systems Neuroscience

University Medical Center Hamburg-Eppendorf

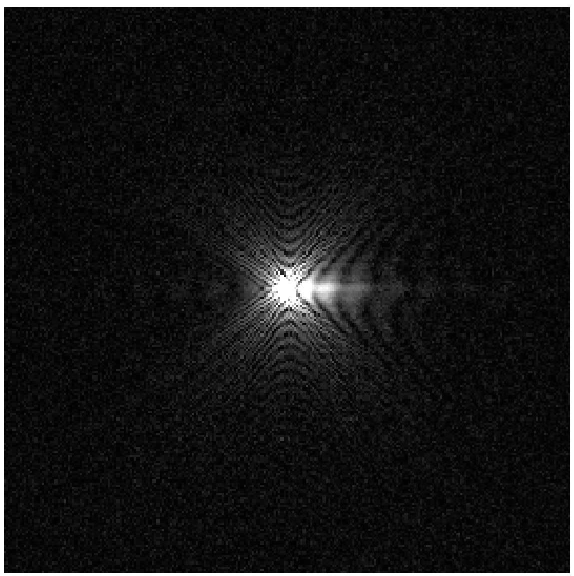
11.12.14

MR Imaging

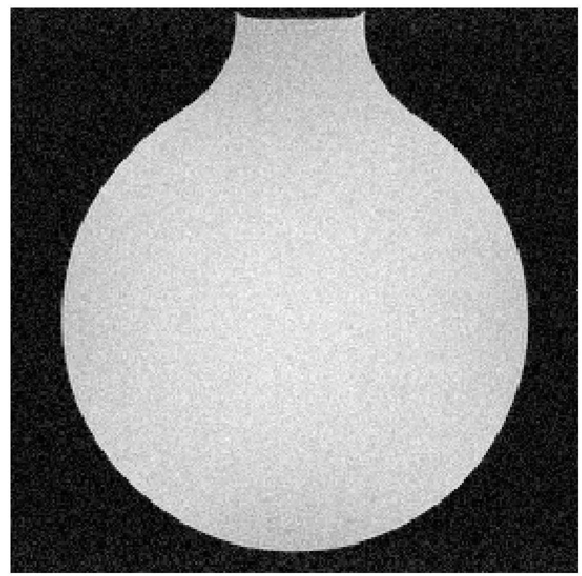
Motivation and Short Version

- MR imaging data are acquired in k-space
- k-space is the space of spatial frequencies, i.e. the Fourier space of the image space
- from the acquired (k-space) data images can be calculated with a Fourier transformation

MR data



Fourier Transformation (Image)



- some MR imaging properties and artifacts and problems / limitations of image acquisition techniques can be explained / understood when considering k-space

Kernspinresonanz

Zutaten …

- Atome mit einem Kernspin (magnetischen Moment):

  Wasserstoff (^{1}H)

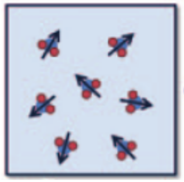
- starker Magnet

- Radiowellenantenne ("Spule")

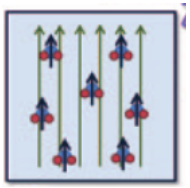
  mit Sender und Empfänger

Kernspinresonanz

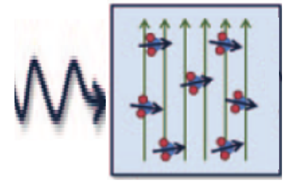
Wie funktioniert’s?



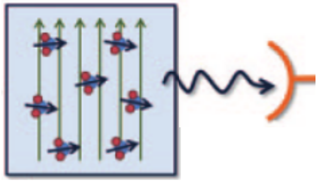
- Magnetisierung (im Magnetfeld)
  - magnetische Momente richten sich entlang des Magnetfeldes aus (ähnlich wie Kompassnadeln)
  - Wasser / wasserhaltiges Gewebe wird magnetisch



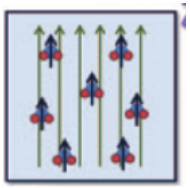
- Radiowellen: Anregung (“Hochfrequenz-/HF-Anregung”)
  - ein Radiowellenpuls “kippt” die Magnetisierung um einen bestimmten Winkel (“Kippwinkel”), z.B. um 90°



- Präzession und Induktion
  - darauf beginnt sie zu rotieren („Präzession“)
  - und induziert dabei eine Spannung in der Spule (ähnlich Dynamo)
  - diese Spannung wird gemessen und ist das MR-Signal („Echo“)



- Relaxation
  - Magnetisierung kehrt exponentiell zurück in den Ausgangszustand
  - Zeitkonstanten: T1 (Wiederaufbau) und T2(*) (Signalabfall)



Magnetisierung – Hochfrequenz-Anregung – Präzession – Signal (Echo) – Relaxation

Kernspinresonanz

Warum “Resonanz”?

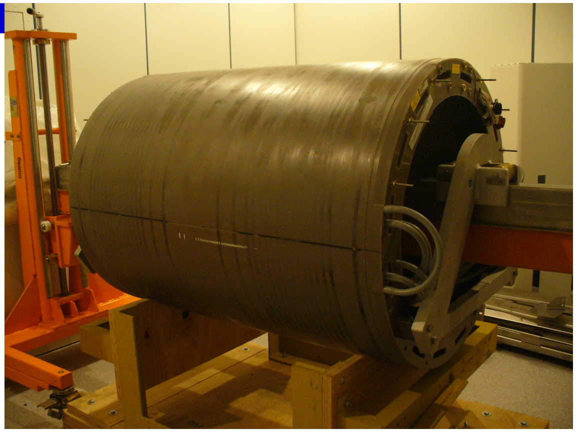
- Zusammenhang zwischen Feldstärke und Frequenz (Anregung, Signal):

  „Resonanzbedingung“

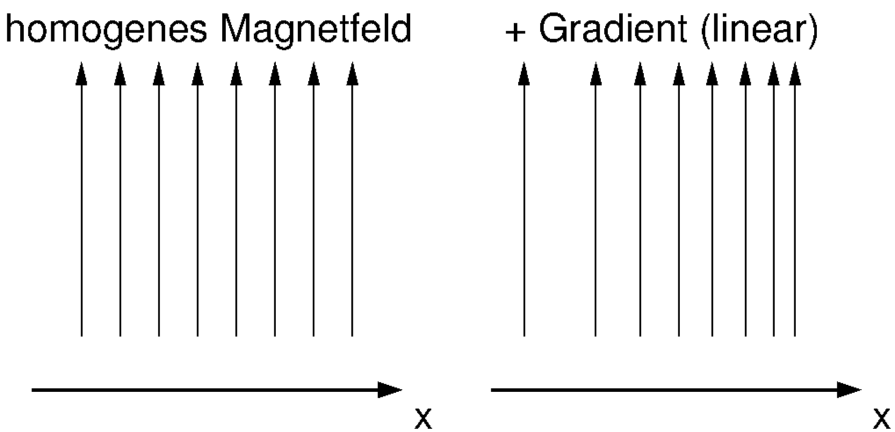
  $$\omega = \gamma \cdot B$$

  - ω: Frequenz
  - γ: Konstante des Atomkerns („gyromagnetisches Verhältnis“)
  - B: Stärke des Magnetfeldes
- Anregung
  - Frequenz der Radiowellen <u>muss</u> Resonanzbedingung erfüllen
- Echo / Signal
  - Frequenz <u>gegeben</u> durch Resonanzbedingung
- Beispiel:
  - Feldstärke 3T: MR-Frequenz für Wasser(stoff) 123MHz

Ortskodierung: Gradientenfelder



- zusätzlich zum statischen Magnetfeld
- lineare Abhängigkeit des Magnetfeldes vom Ort,
  in beliebige Richtung
- Amplitude zeitlich veränderbar,
  kann schnell an/abgeschaltet werden
- entscheidend: Stärke des Magnetfeldes wird verändert, *nicht* die Richtung



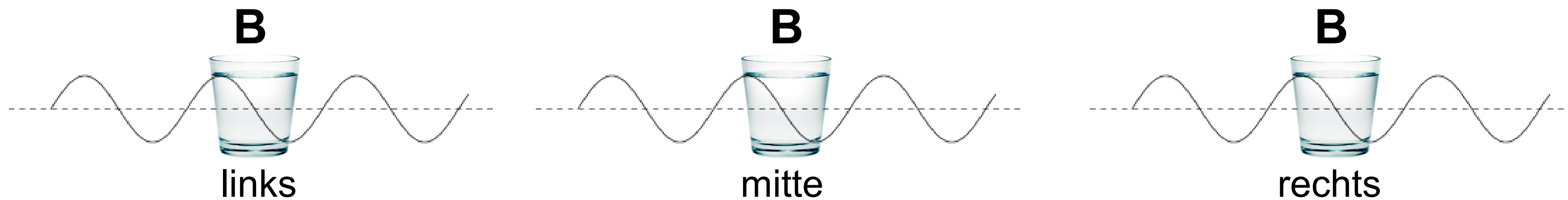
- typische Werte: $\pm$20mT über 0.4m, in 0.2ms
  d.h. sehr klein im Vergleich zum statischen Feld
- mit Gradientenfeld: MR-Frequenz hängt linear vom Ort ab,
  z:B. für x: $\omega=\gamma\cdot(B_0 + G_x\cdot x)$

Ortskodierung: Frequenz

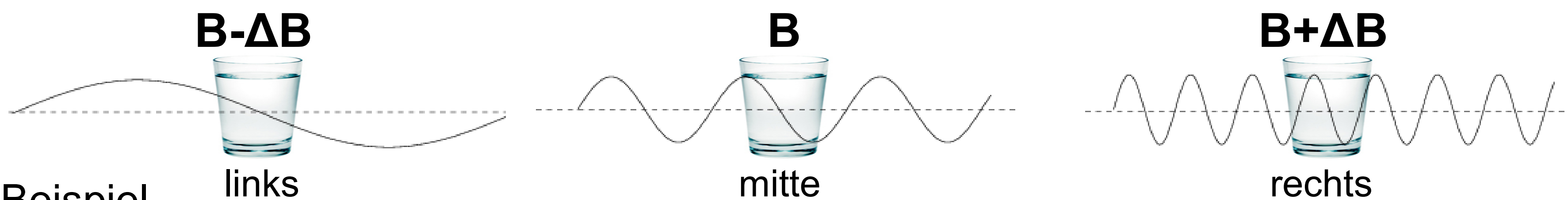
$$\boxed{\omega = \gamma \cdot B}$$

Signal (Echo)

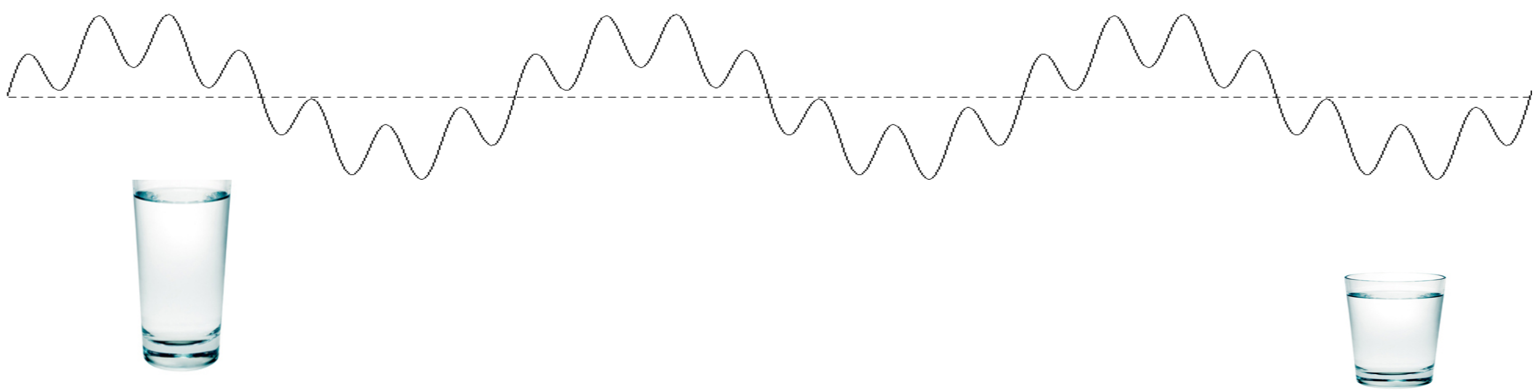
- ohne Gradientenfeld



- mit Gradientenfeld (von links nach rechts)



- Beispiel

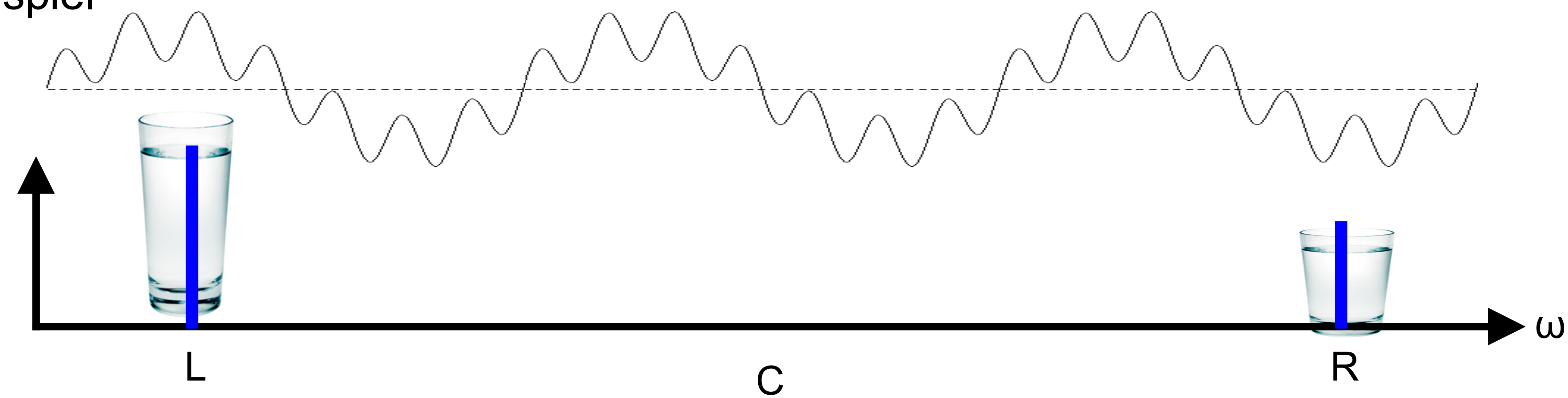


Ortskodierung: Frequenz

Etwas mathematischer

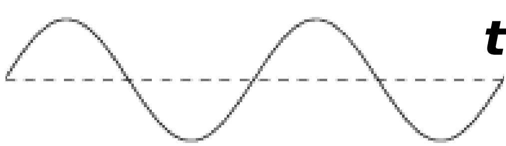
$$\boxed{\omega = \gamma \cdot B}$$

- Beispiel



- Frequenz-Analyse (Fourier-Transformation) liefert Signal-Verteilung entlang der Gradientenrichtung
- „Signal"-Raum und Bildraum sind Fourier-Paar

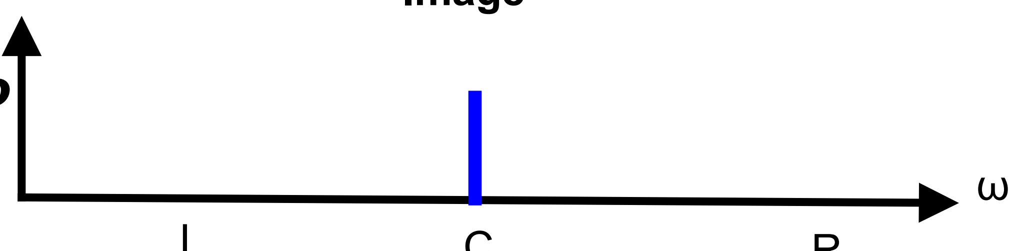
MR data



Image

Fourier transformation ⇔

Image

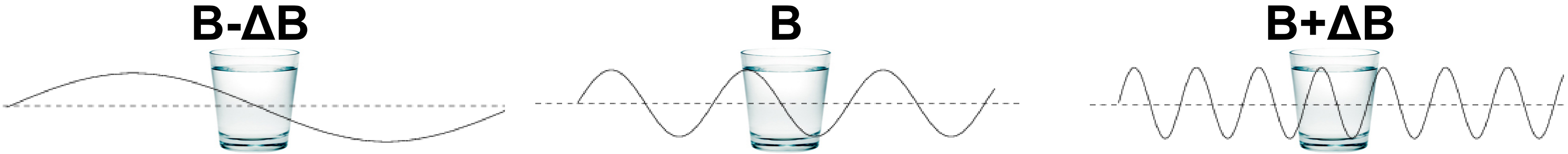


MR data

k-Raum

$$\omega = \gamma \cdot B$$

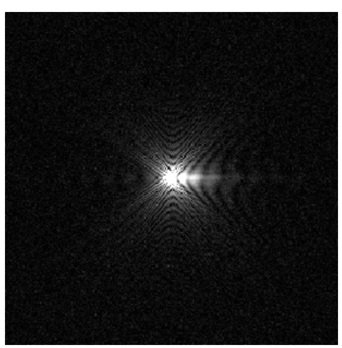
Etwas mathematischer …

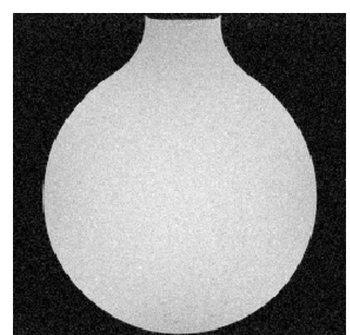


links mitte rechts

- bisher: G konstant
  - $k = G \cdot t$
- allgemeiner, z.B. wenn G zeitlich *nicht* konstant
  - $$k(T) = \gamma \int_0^T G(t)\,dt$$

  d.h. k ist das Zeitintegral der Gradientenamplitude
- für Schnittbild: Information in zwei Dimensionen erforderlich



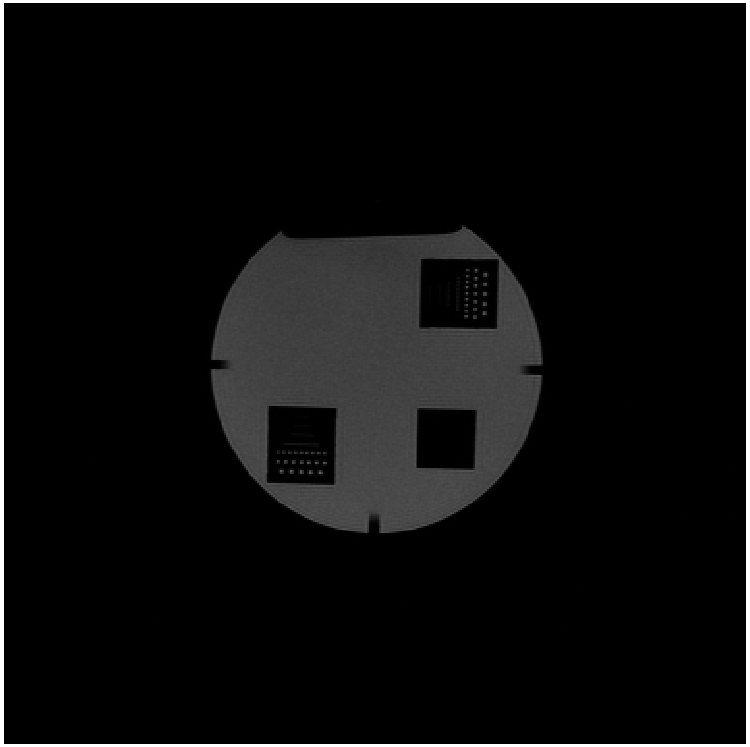


Exercise I

MR Image Rekonstruction:

flash_1mm_384mm.dat

- read complex MR data
- make a Fourier transformation and get an MR image
- what do you see?
- what do you have to consider?

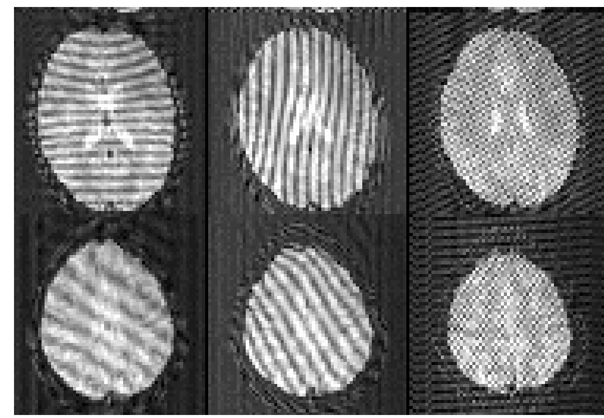


Exercise II

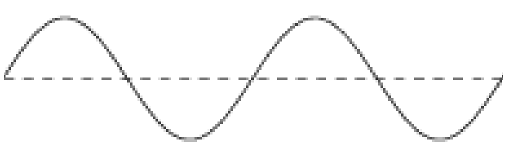
Spike Artifact

flash_1mm_384mm.dat

- read complex MR data
- add a high intensity peak somewhere in the matrix
- make a Fourier transformation and get the MR image
- vary intensity and position of peak
- what do you see?
- why?



MR data

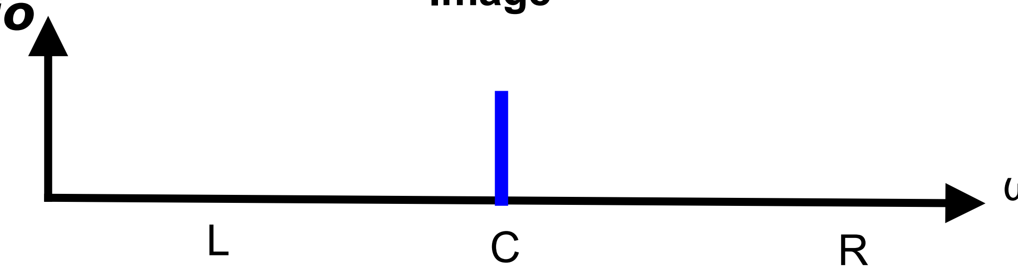


Image

Fourier transformation

$\Leftrightarrow$

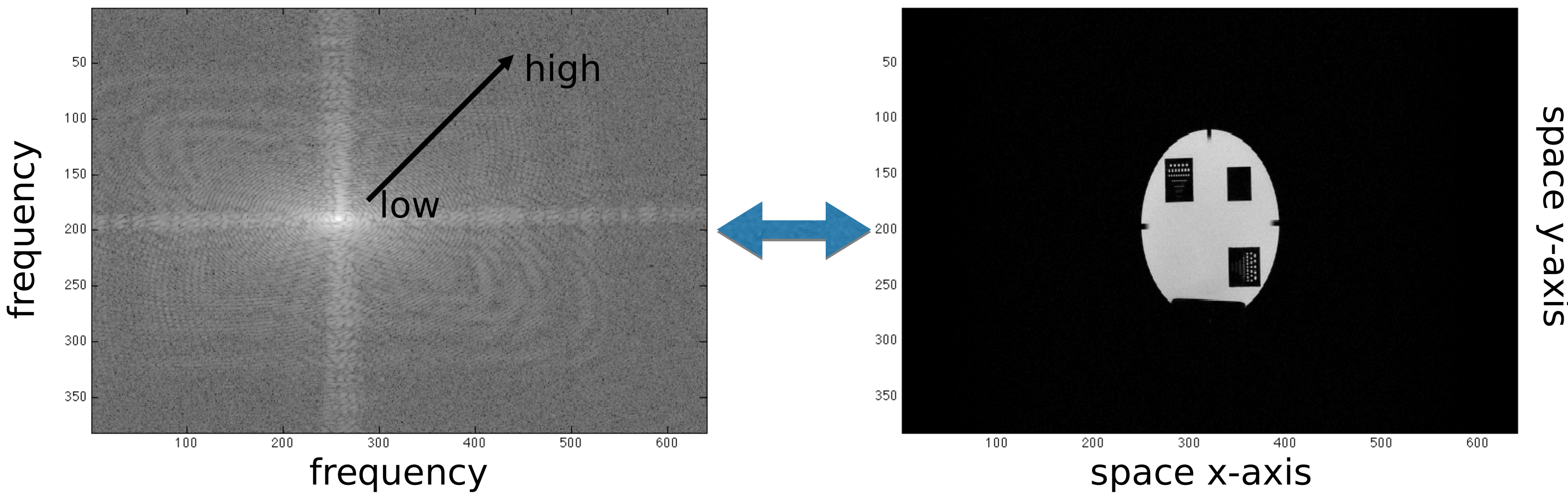
Image



MR data

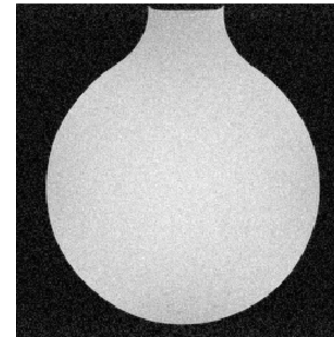
k-space <—> world space

- Data is acquired in the k-space



k-Raum

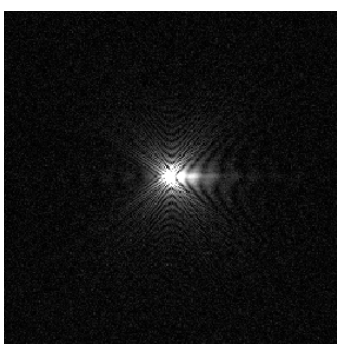
MR-Bildgebung

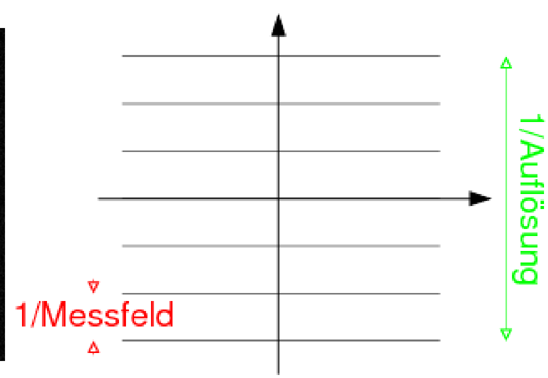


- Objektschnitt ist zweidimensional
- ideal: das Signal für alle Werte im k-Raum messen
- Problem
  - k-Raum unendlich groß
  - k(T) beschreibt Linie im k-Raum (“Trajektorie”)

$$k(T) = \gamma \int_0^T G(t)\,dt$$

- meist: kartesische Abtastung, d.h. parallele Linien
  - abgedeckter Bereich definiert Auflösung
  - Zeilenabstand der Linien definiert Messfeld (field-of-view)





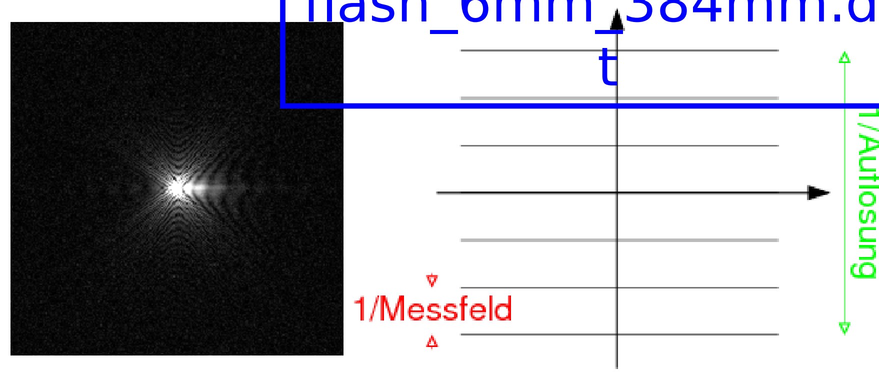
- Objekt ⇔ k-Raum → MR-Daten ⇔ Bild

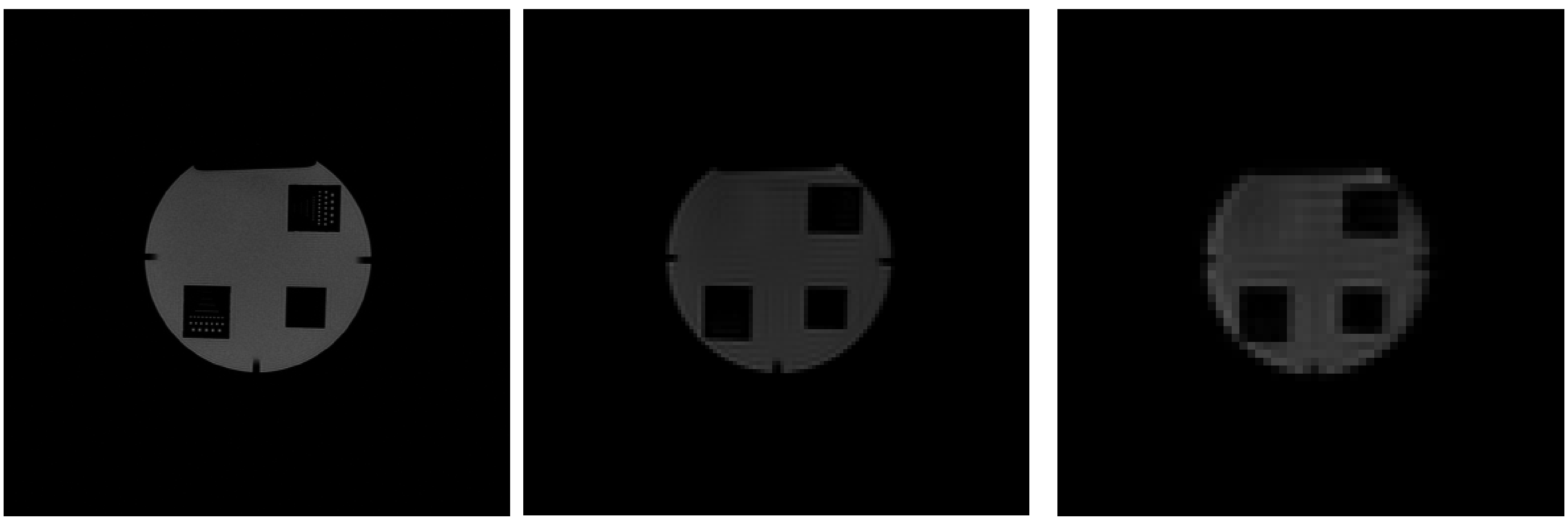
Exercise III

Resolution:

- read complex MR data
- make a Fourier transformation to get the MR images
- what is different in the images?
- what is different in the raw data?
- why are the images different?

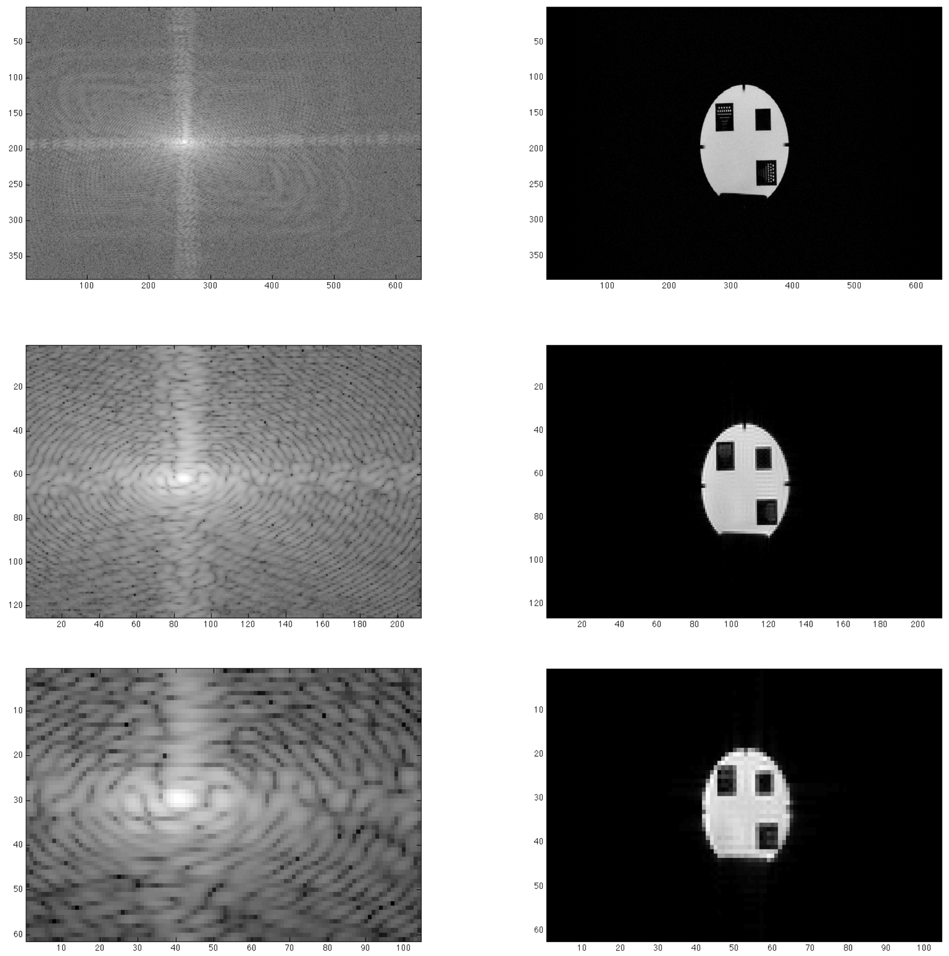
flash_1mm_384mm.dat
flash_3mm_384mm.dat
flash_6mm_384mm.dat





Effect of Resolution

- same frequency range is acquired but with increasing steps.

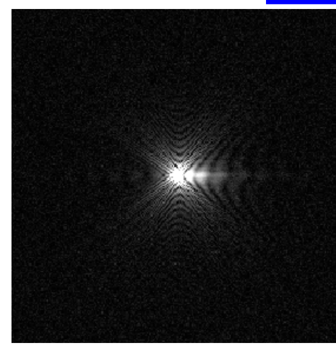


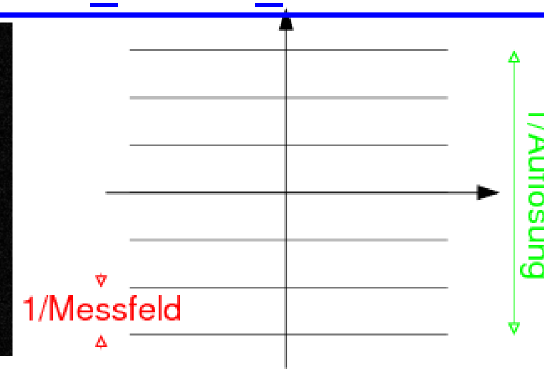
Exercise IV

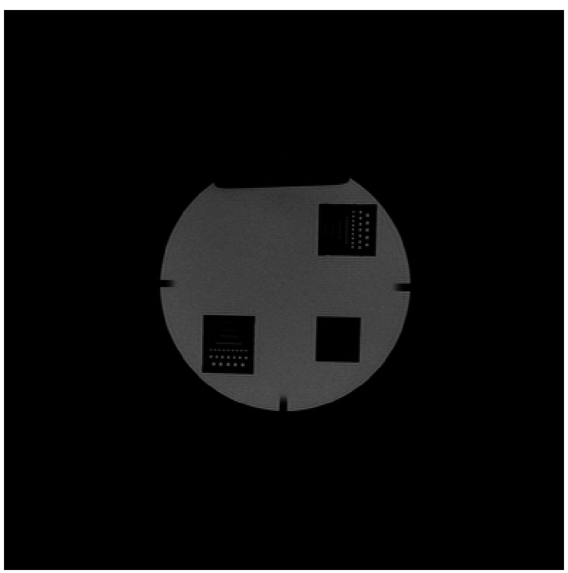
Field-of-View

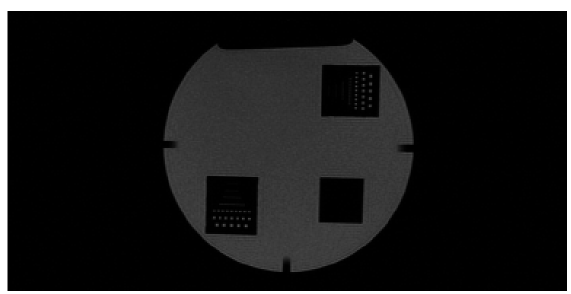
- read complex MR data
- make a Fourier transformation to get the MR images
- what is different in the images?
- what is different in the raw data?
- why is one of the images different?
- which data set would you prefer?

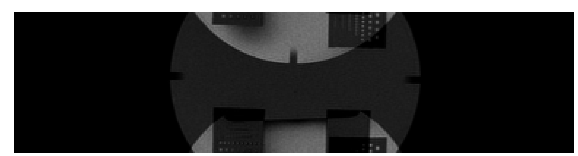
flash_1mm_384mm.dat
flash_1mm_192mm.dat
flash_1mm_96mm.dat





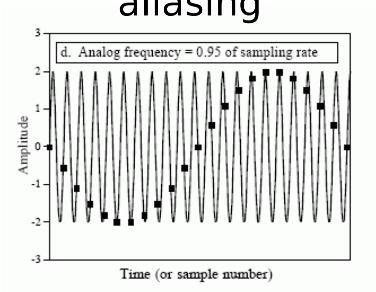




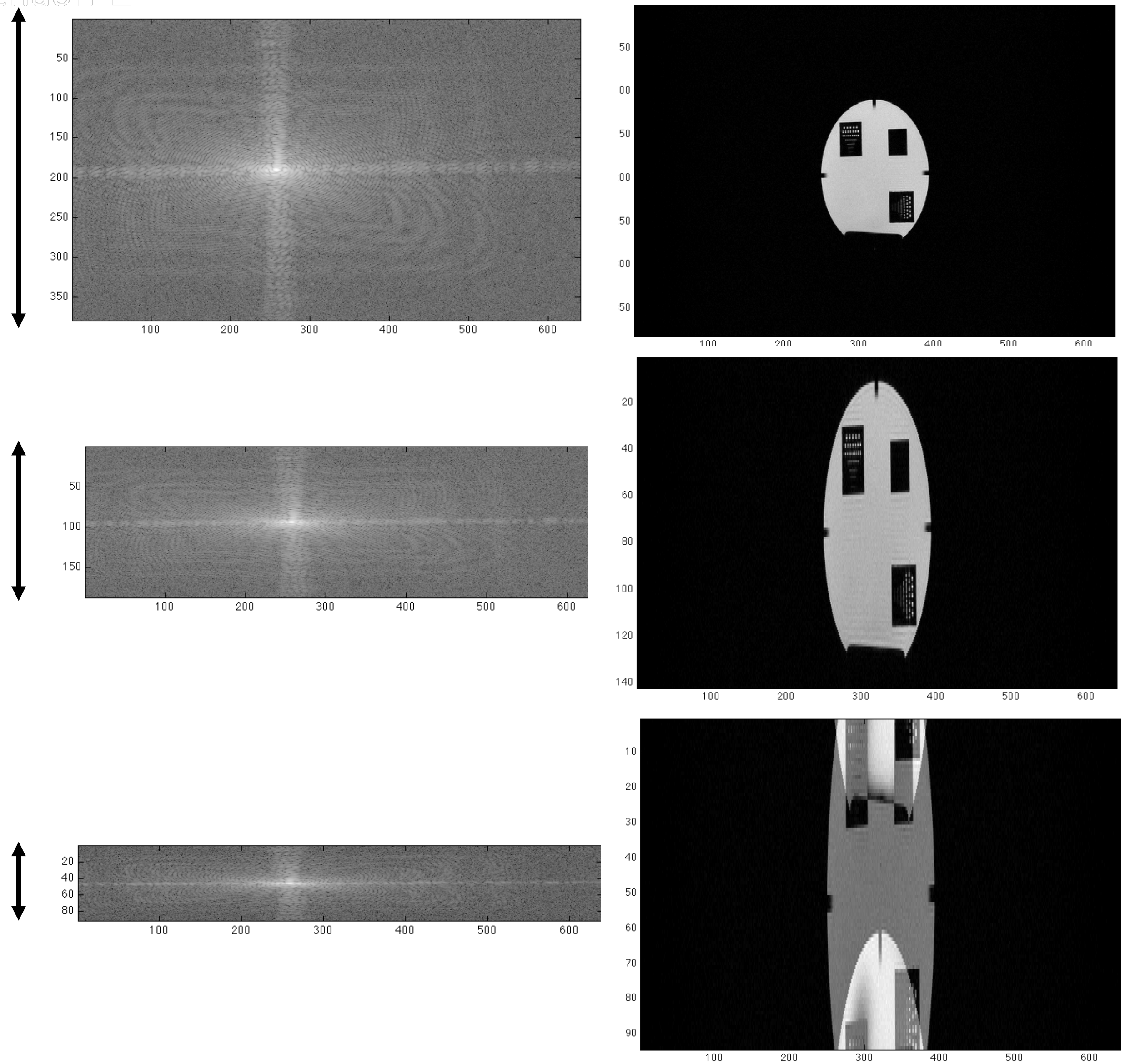


Effect of Field of View

aliasing



Same frequency range is covered but at different sampling densities / frequency resolutions.

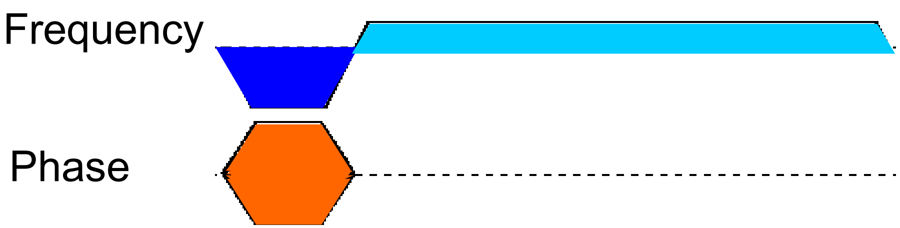


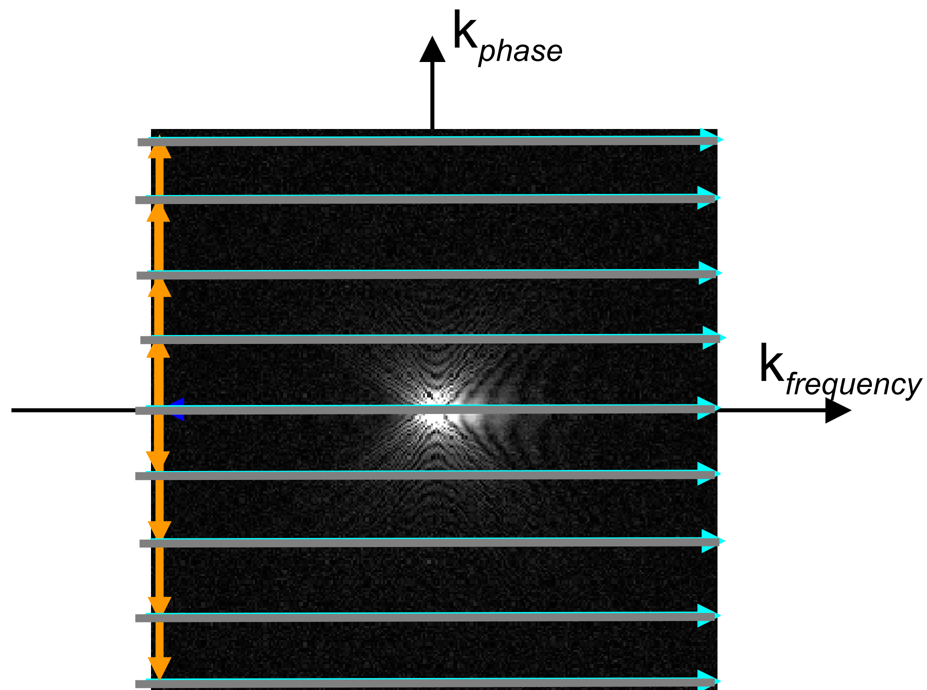
Pulse Sequence: FLASH

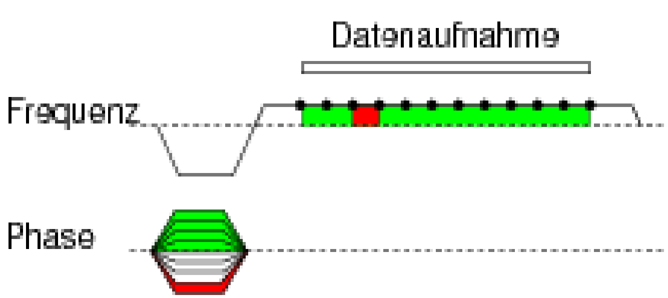
- pulse sequence ⇔ *k(T)*

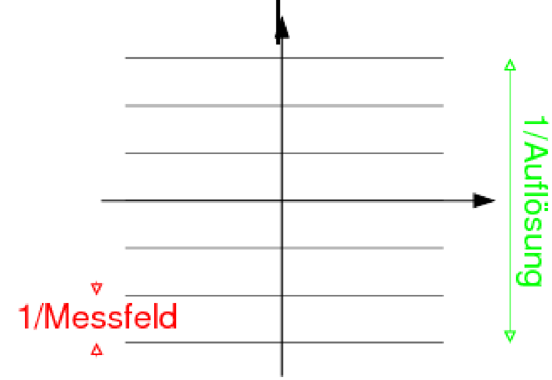
$$k(T) = \gamma \int_0^T G(t)\,dt$$

  – FLASH



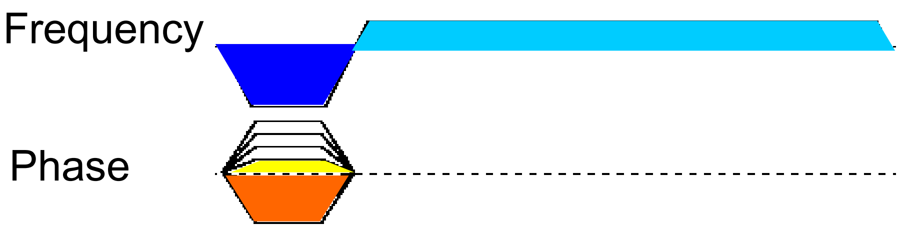




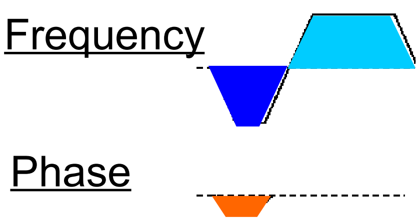


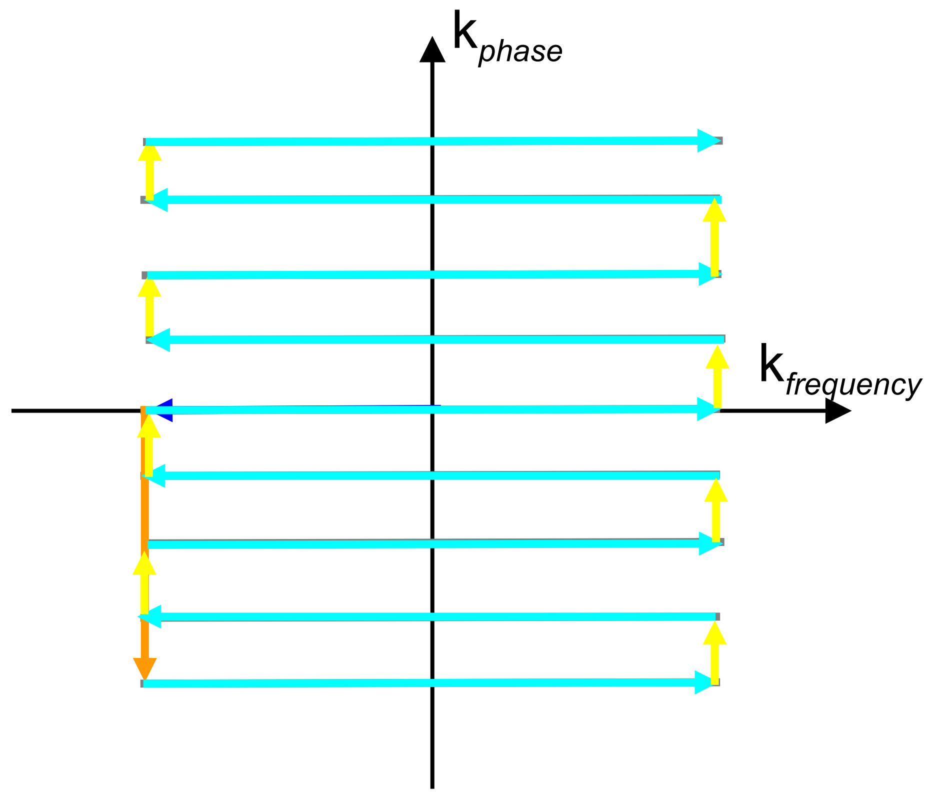
Pulse Sequence: Echo-Planar Imaging

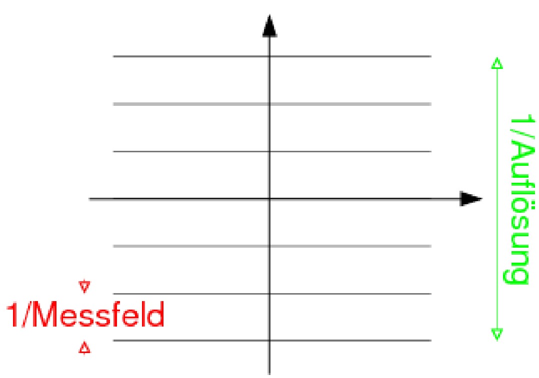
- pulse sequence ⇔ *k(T)*
  - FLASH

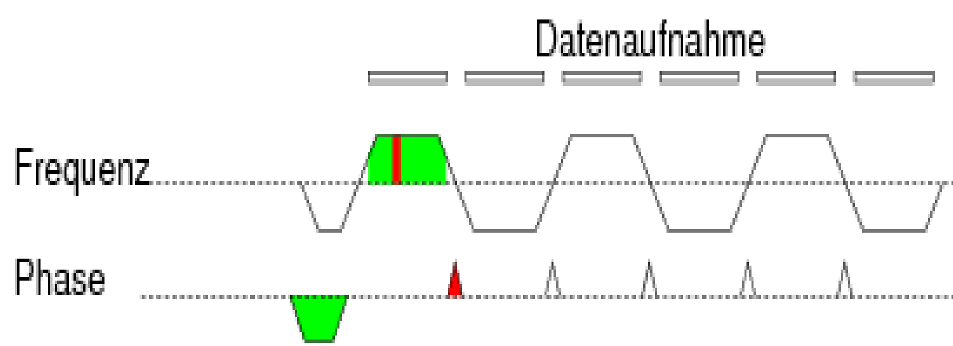


  - echo-planar imaging



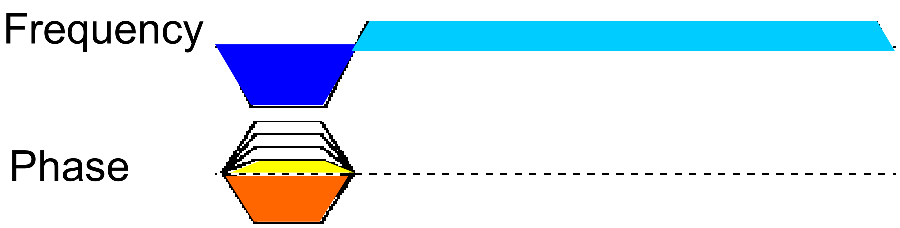




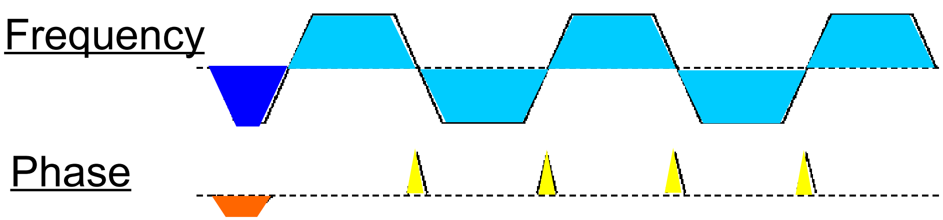


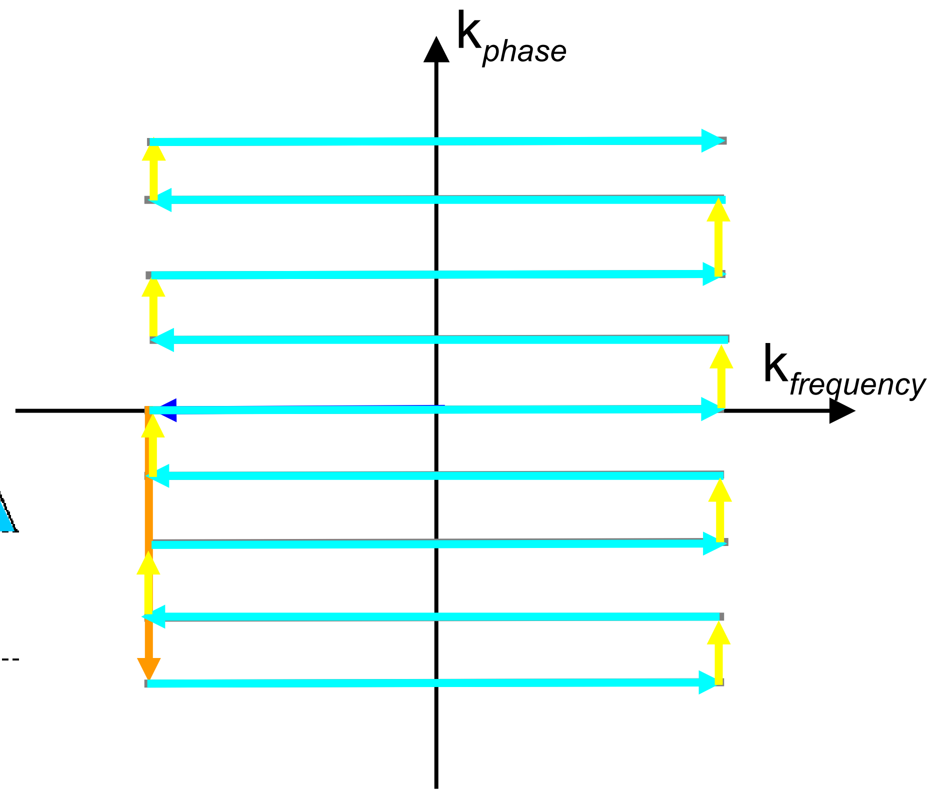
Pulse Sequence: Echo-Planar Imaging

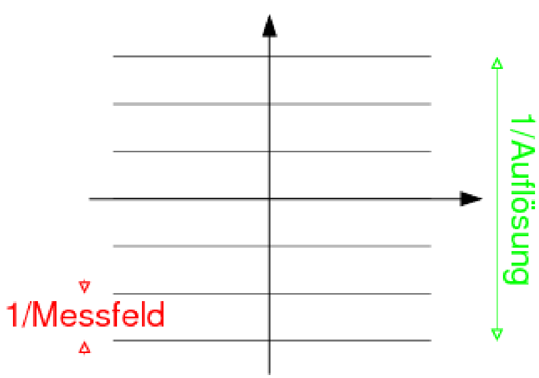
- pulse sequence ⇔ *k(T)*
  - FLASH

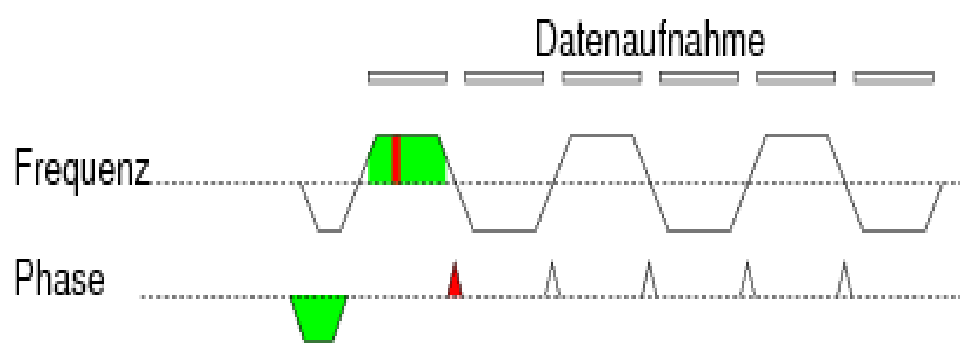


  - echo-planar imaging





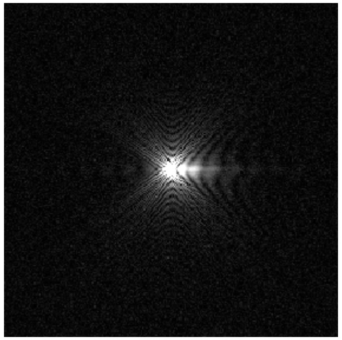




Echo-Planar Imaging

Properties

- all signals required for image acquired after a single RF excitation
- very fast
- sensitive to artifacts
  - odd lines: positive gradient pulse, even lines: negative gradients
  - different echo times for different lines:
    relaxation, frequency offsets, geometric distortions

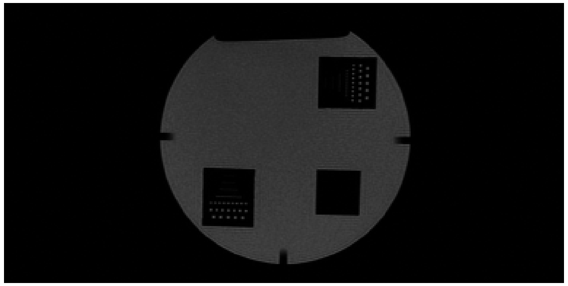


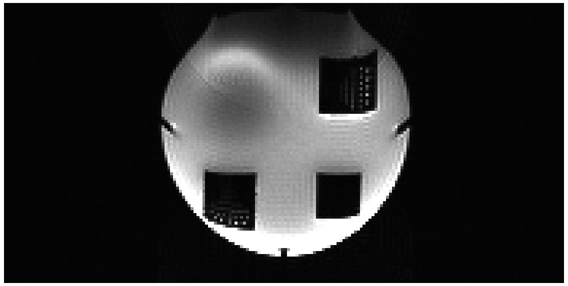
Exercise V

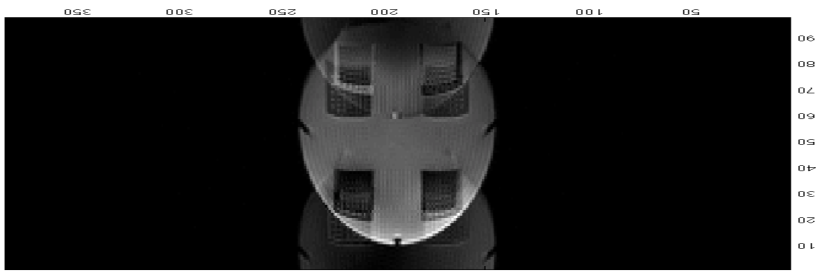
Echo-Planar Imaging

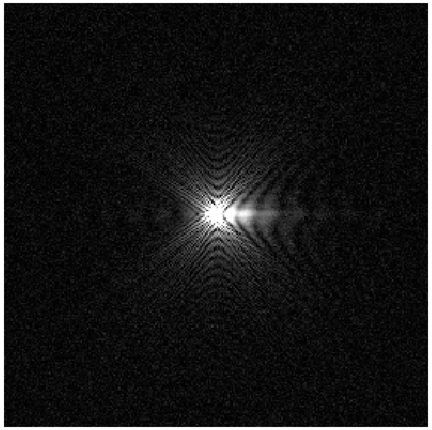
flash_1mm_192mm.dat epi-se_2mm.dat

- read complex MR data
- make a Fourier transformation to get the MR images
- what is different between FLASH and EPI images?



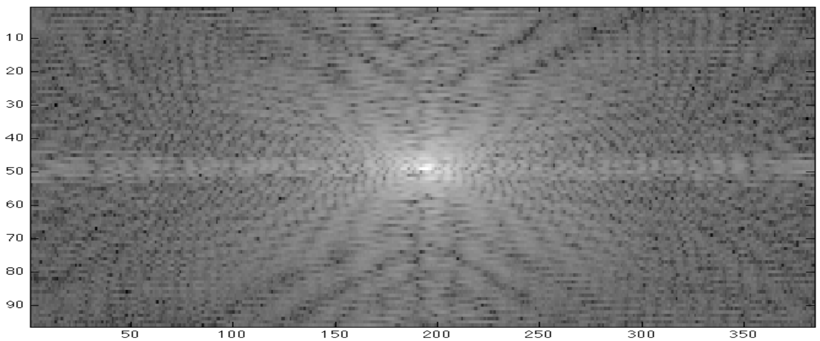


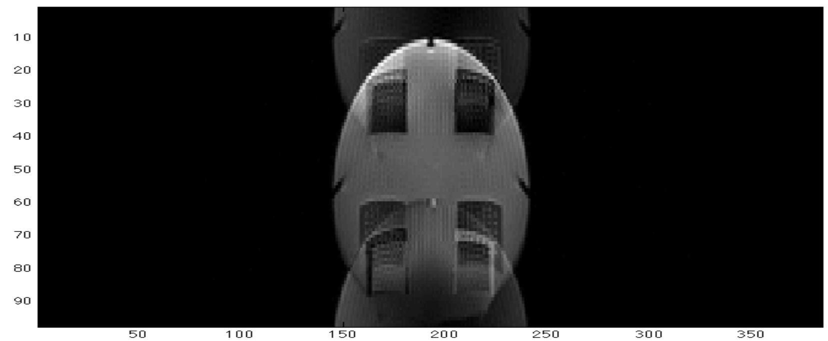


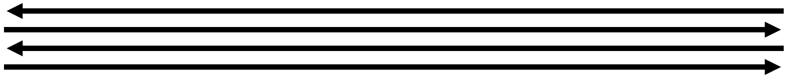


Source of Ghosting

- odd vs. even lines





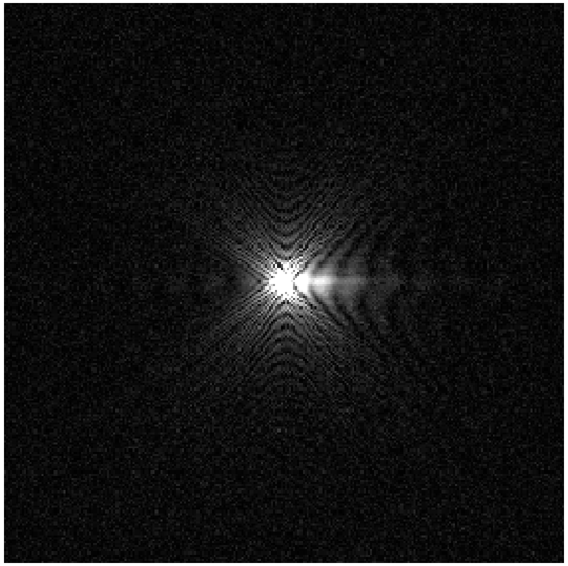


Exercise VI

flash_1mm_192mm.dat epi-se_2mm.dat

N/2 ghosting

- read complex MR data
- make a Fourier transformation to get the MR images
- add a phase offset to every 2nd line in the FLASH data
- vary the phase offset
- what happens to the images?
- what looks EPI-like?

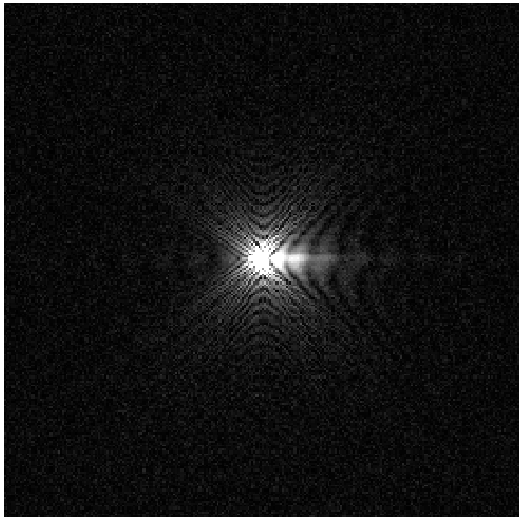


Exercise VII

Image Blurring / Resolution

flash_1mm_192mm.dat

- read complex MR data
- make a Fourier transformation to get the MR images
- multiply MR data with exponential decay along line direction
- vary decay factor or exponential decay
- what happens to the images?
- why?



Point Spread Function I

- make an empty array
- add a point somewhere
- make a Fourier transformation to get in „MR data“ in k-space
- multiply „MR data“ with exponential decay along line direction
- vary decay factor or exponential decay
- make a Fourier transformation of the modified „MR data“ to get „MR images“
- what do you see?
- why?

Exercise IX

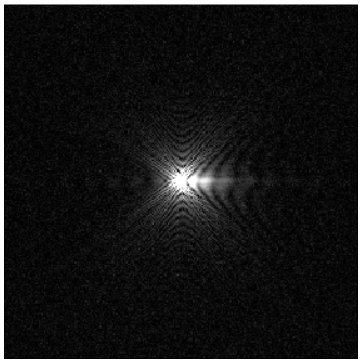
Point Spread Function II

- make an empty array
- add somewhere two neighbouring points
- make a Fourier transformation to get in „MR data“ in k-space
- multiply „MR data“ with exponential decay along line direction
- vary decay factor or exponential decay
- make a Fourier transformation of the modified „MR data“ to get „MR images“
- what do you see?

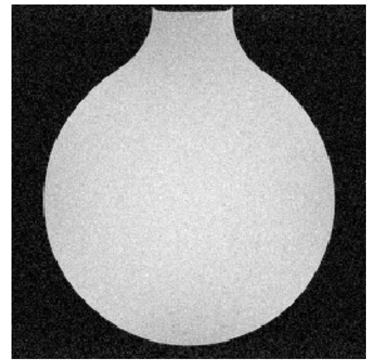
Summary

- MR imaging data are acquired in k-space, the Fourier space of the image space
- MR data need to be Fourier transformed to get MR images

MR data



Fourier Transformation (Image)



- usually parallel lines are acquired, in multiple shots or a single shot
- MR data are only a subset of the objects k-space representation defining the resolution (area) and the field-of-view (sampling density)
- MR data may be disturbed / corrupted yielding artifacts, in particulart for single-shot sequences
  - spikes
  - N/2 ghosting
  - image blurring
  - frequency offset shifts
  - geometric distortions
  - …

Done.

Thanks!