Echo Planar Imaging (EPI)

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EPI: a historical perspective

- One of the first Fourier imaging techniques[1]
  - Has immediately polarized the MR community into lovers and haters

- Gained importance only in late 90th of the past century
  - Accessibility of actively-shielded gradients
  - New applications: fMRI, DTI

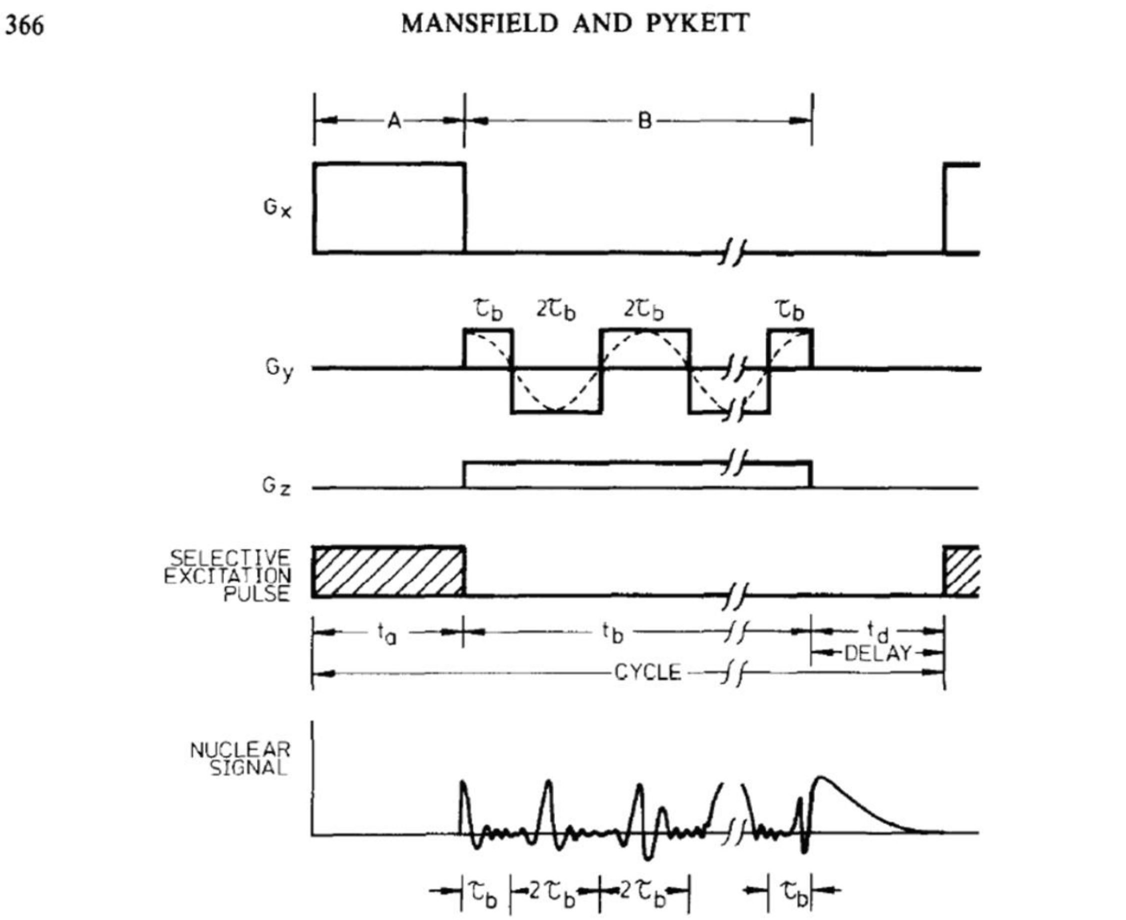
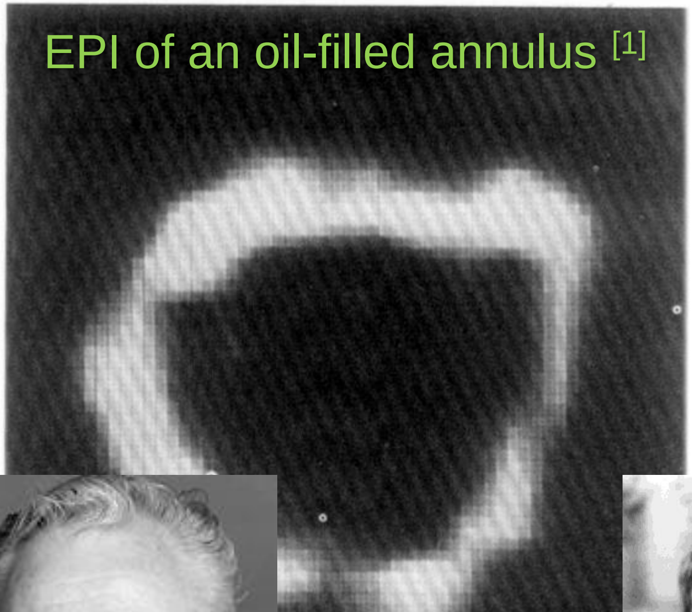
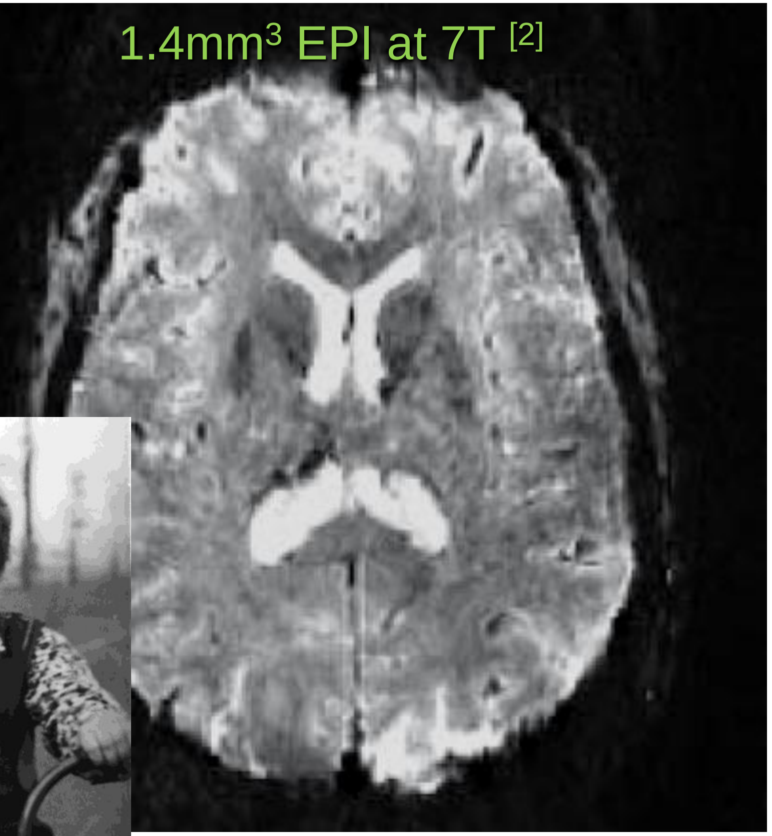


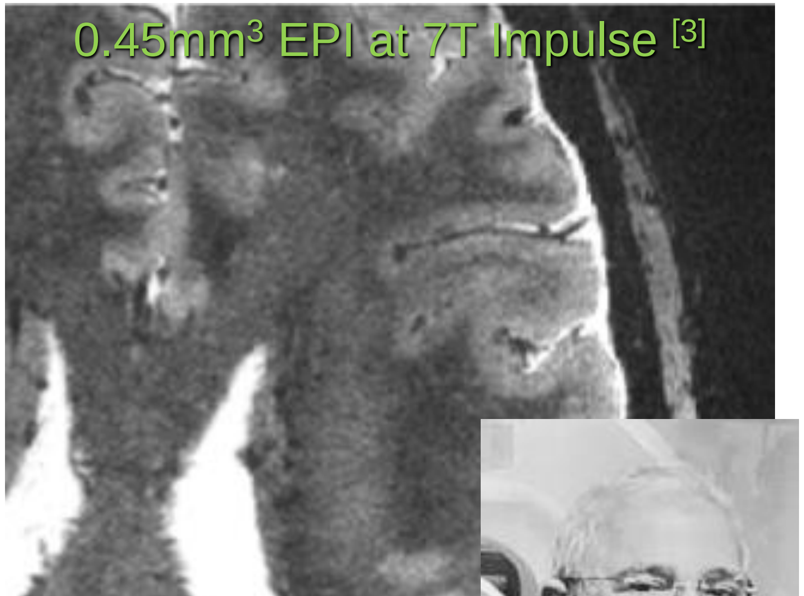
FIG. 9. Pulse and field gradient timing diagram for a two-dimensional echo-planar imaging experiment.

[1] Mansfield and Pykett “Biological and medical imaging by NMR” JMR 29,355-73 (1978)

EPI has gone a long way…







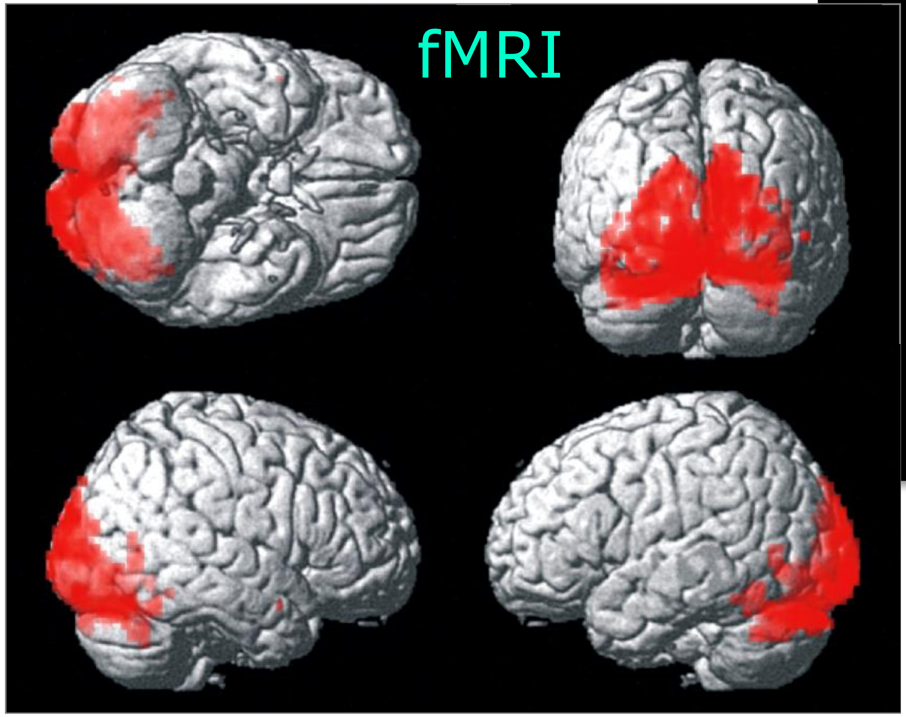
Sir Peter Mansfield

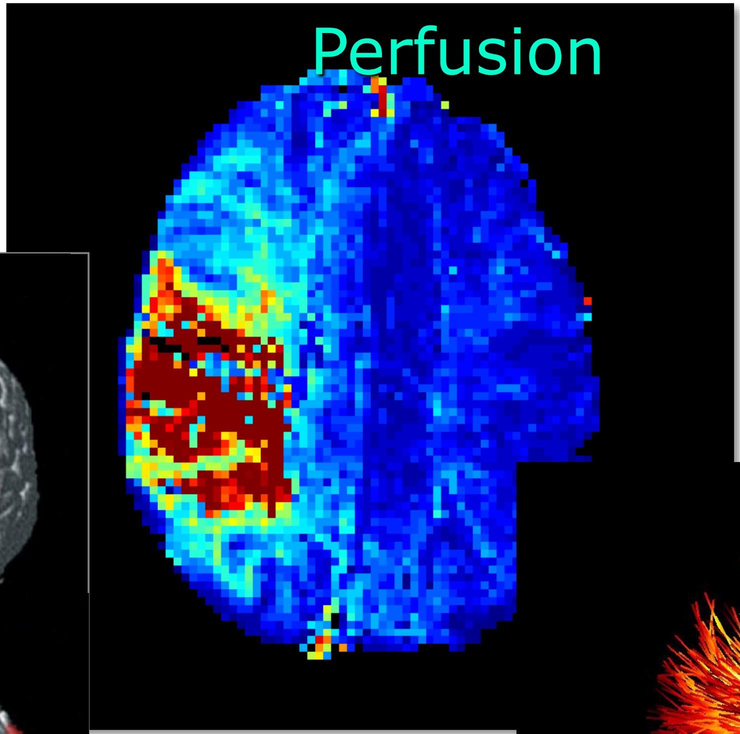
Maxim Zaitsev

David Feinberg

[1] Mansfield and Pykett “Biological and medical imaging by NMR” JMR 29,355-73 (1978)
[2] Speck O, Stadler J, Zaitsev M. “High resolution single-shot EPI at 7T” MAGMA 21:73-86 (2008)
[3] Feinberg D et al. Nature Methods 20, 2048-57 (2023)

Today: EPI is a working horse…



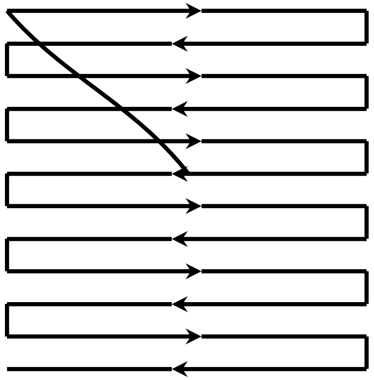


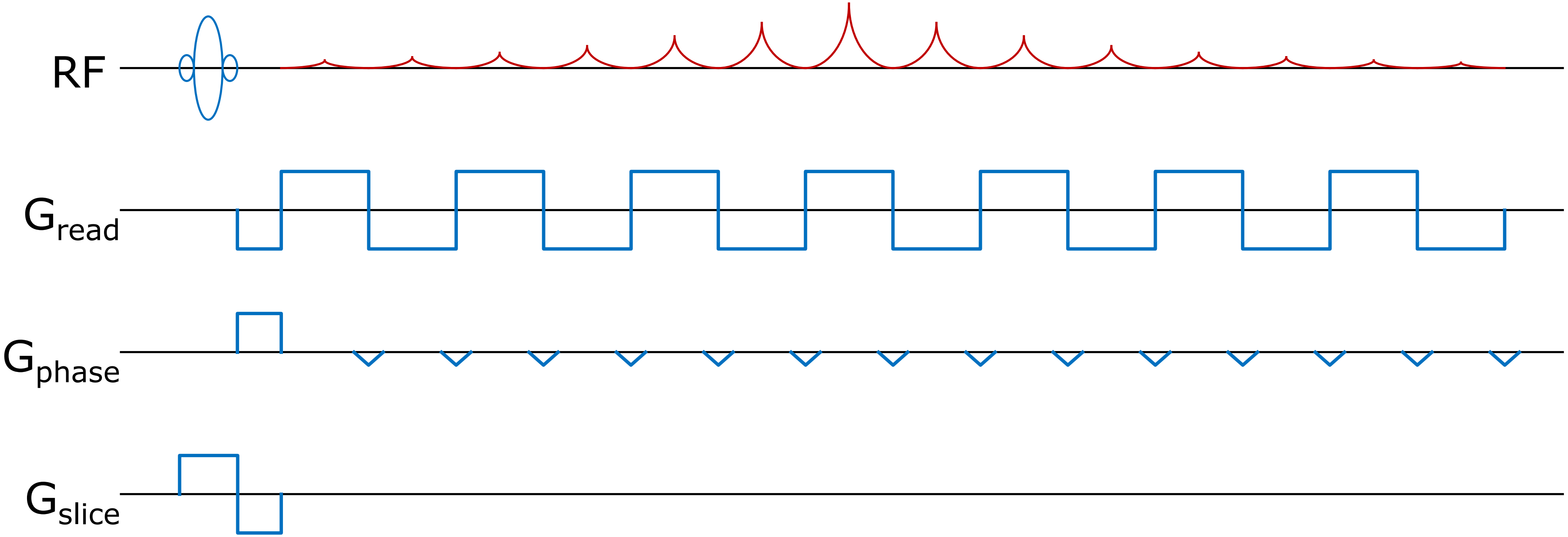
A plethora of EPI variants

- Segmented, read-out segmented, PROPELLER-EPI,…
- Accelerated: parallel imaging, multi-band, wave CAIPI,…
- Hybrid gradient/RF encoding (GRASE, RASOR, …)
- Contrast preparation modules (DTI, etc.)
- Focus on **single-shot EPI**: the most common collection of artifacts

EPI Sequence

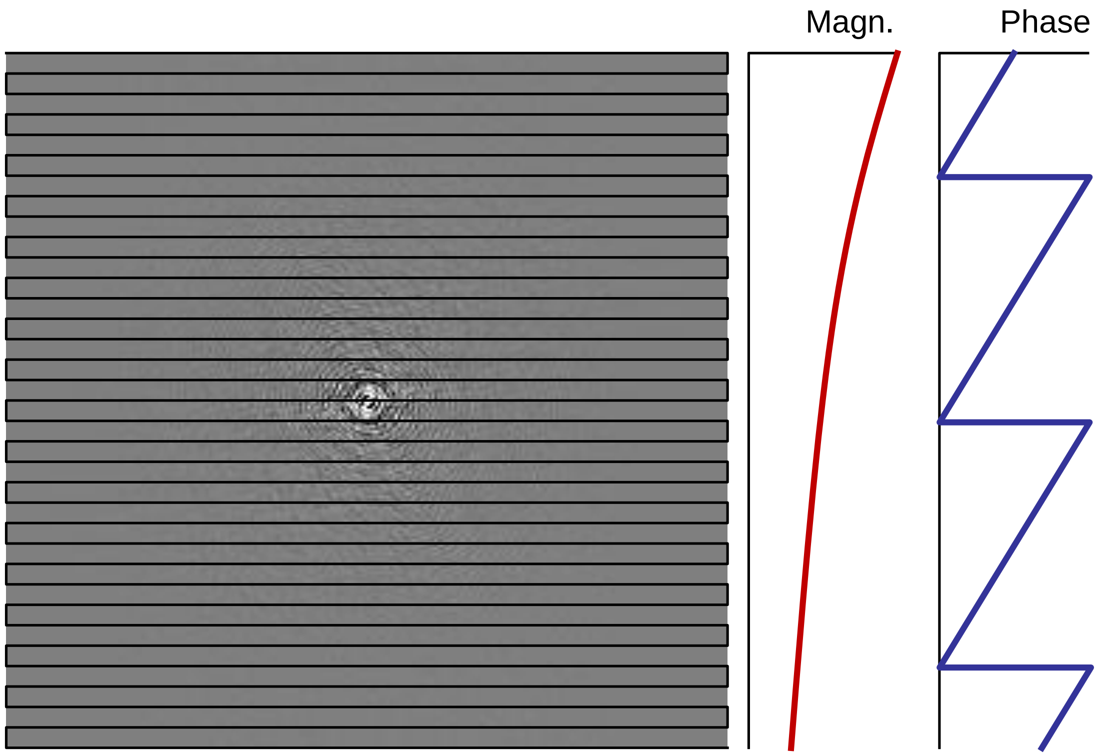
- Basic recipe:
  - Oscillating read-out gradient
  - Phase encoding “blips”



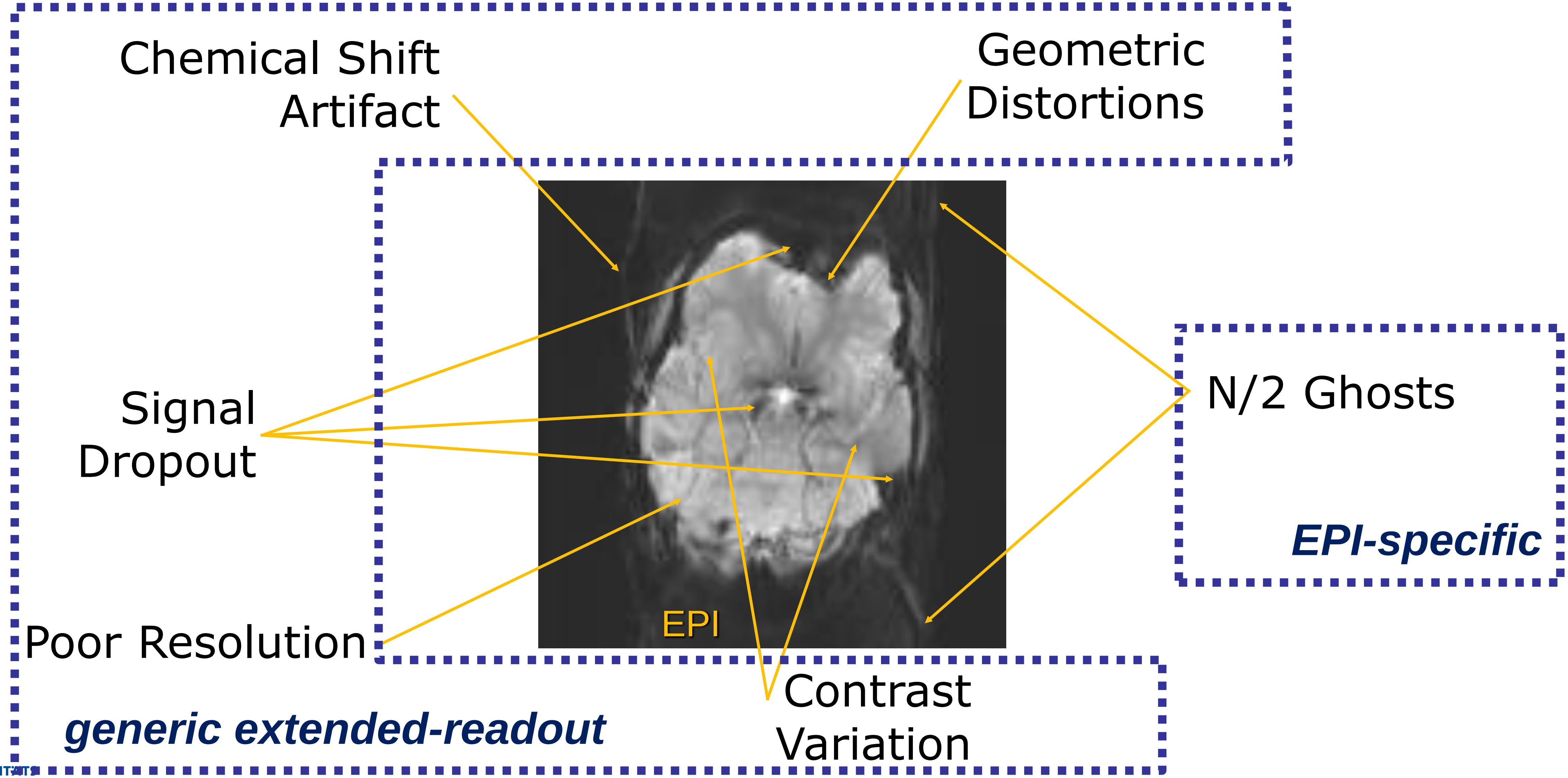


Why EPI is special?

- Single shot ≠ instantaneous
  - Signal evolution during readout
- Alternating readout polarity
  - Gradient & receiver imperfections
- Fourier reconstruction
  - Perfect encoding?
  - Deviations lead to artifacts…
  - Smooth deviations ➔ blurring, distortions
  - Periodic modulation ➔ ghosting



EPI artifacts at glance

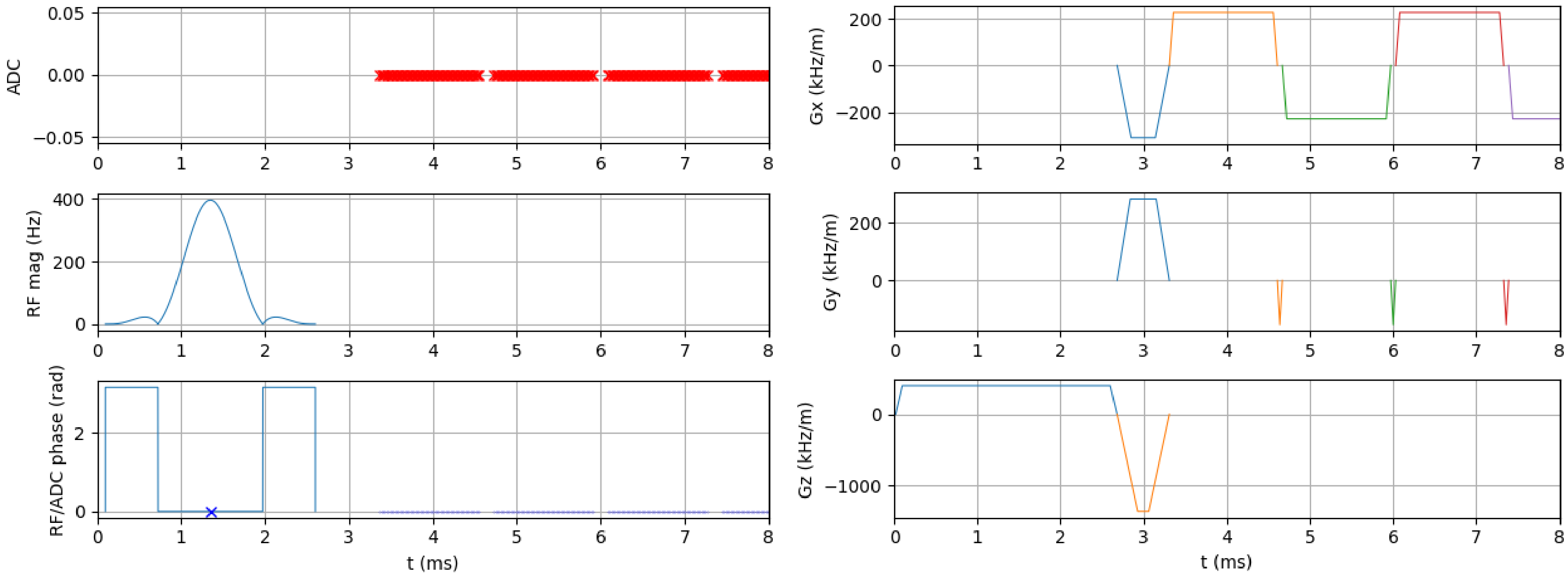


EPI optimization goals

- Avoid/compensate signal modulation due to oscillating readout
- Maximize sampling efficiency (ADC-on time)
  - Improve signal-to-noise ratio
- Shorten the echo train
  - Reduce blurring due to signal decay
  - Reduce distortions
- Avoid or suppress off-resonance effects
  - Suppress fat
  - Make sure B0 is as homogeneous as possible
- Use B0 distortion compensation techniques if possible

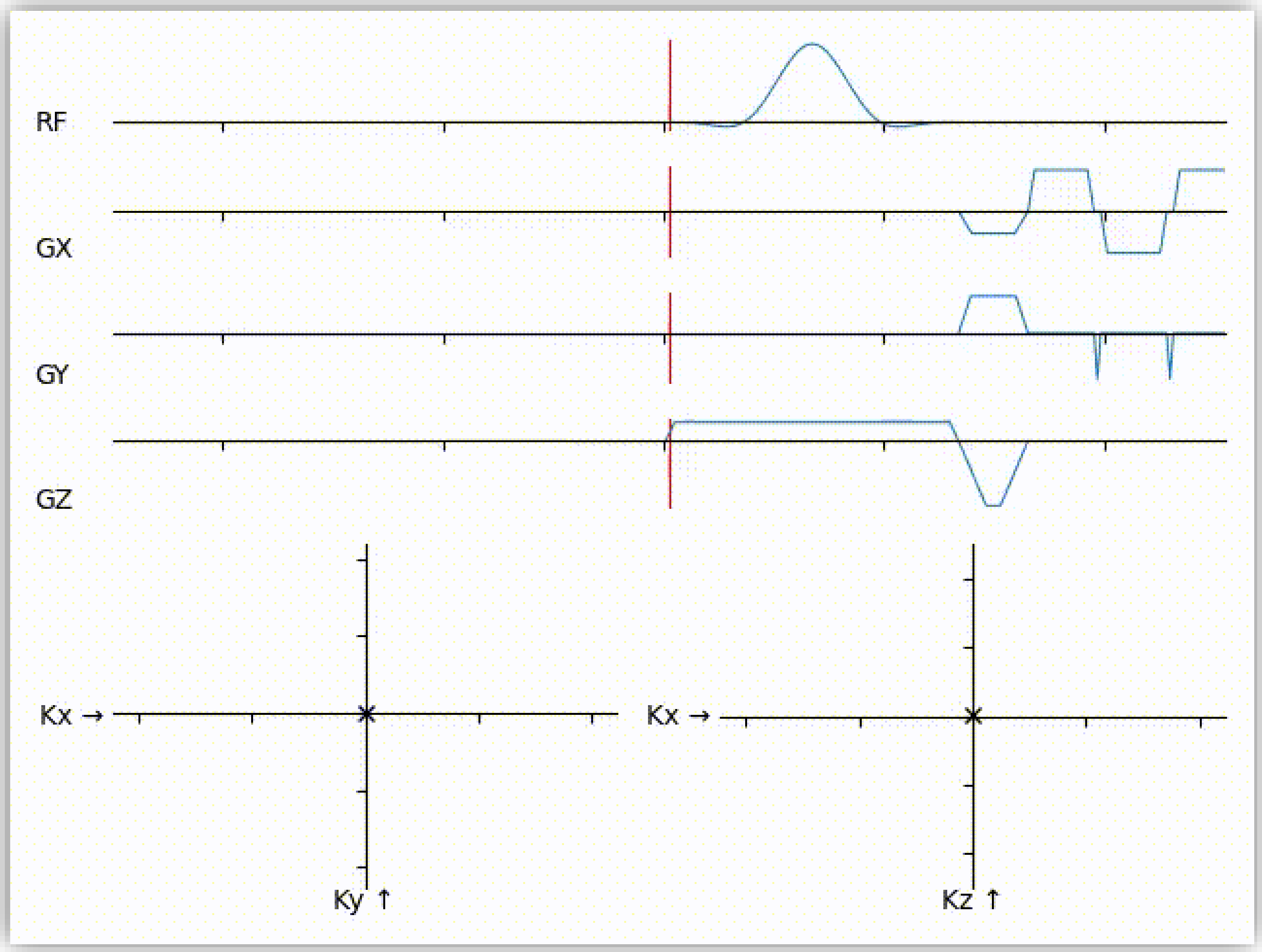
Basic EPI Readout in Pulseq

- Standard 2D excitation
- Define RO duration, calculate ADC and gradient objects
- Calculate PE and RO pre-phasing gradients, PE blips



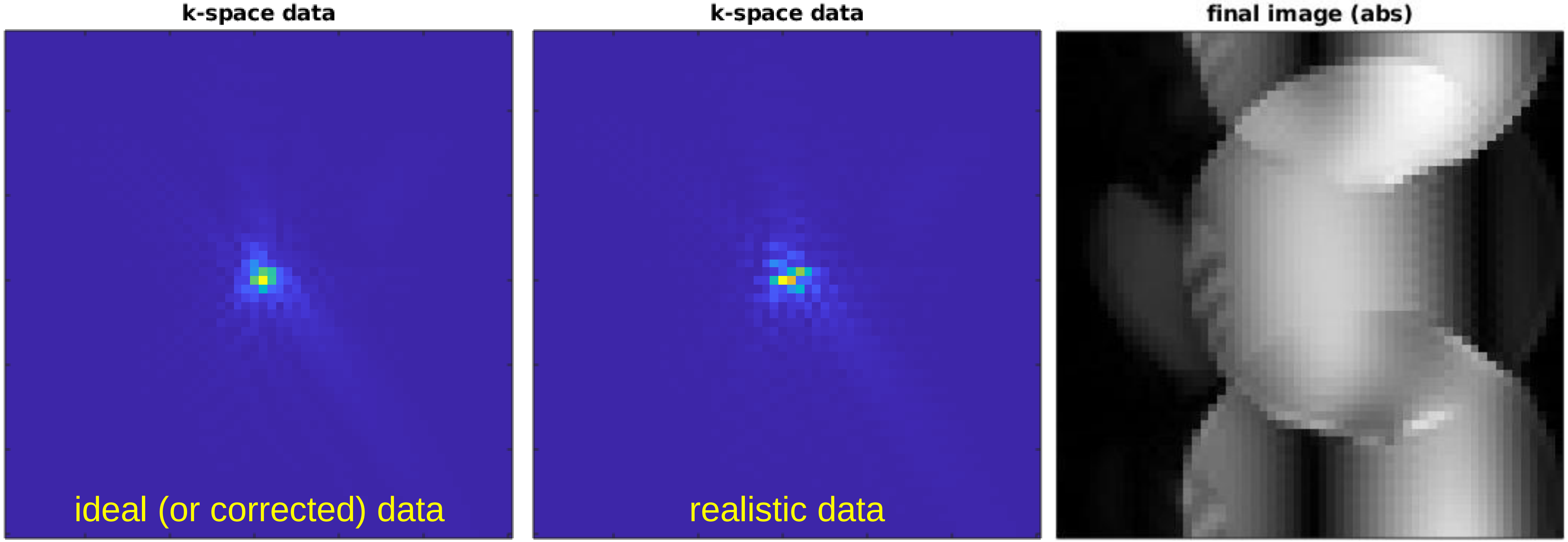
EPI trajectory video

powered by the pypulseq
Trajectory Animation Tool
by Frank Zijlstra



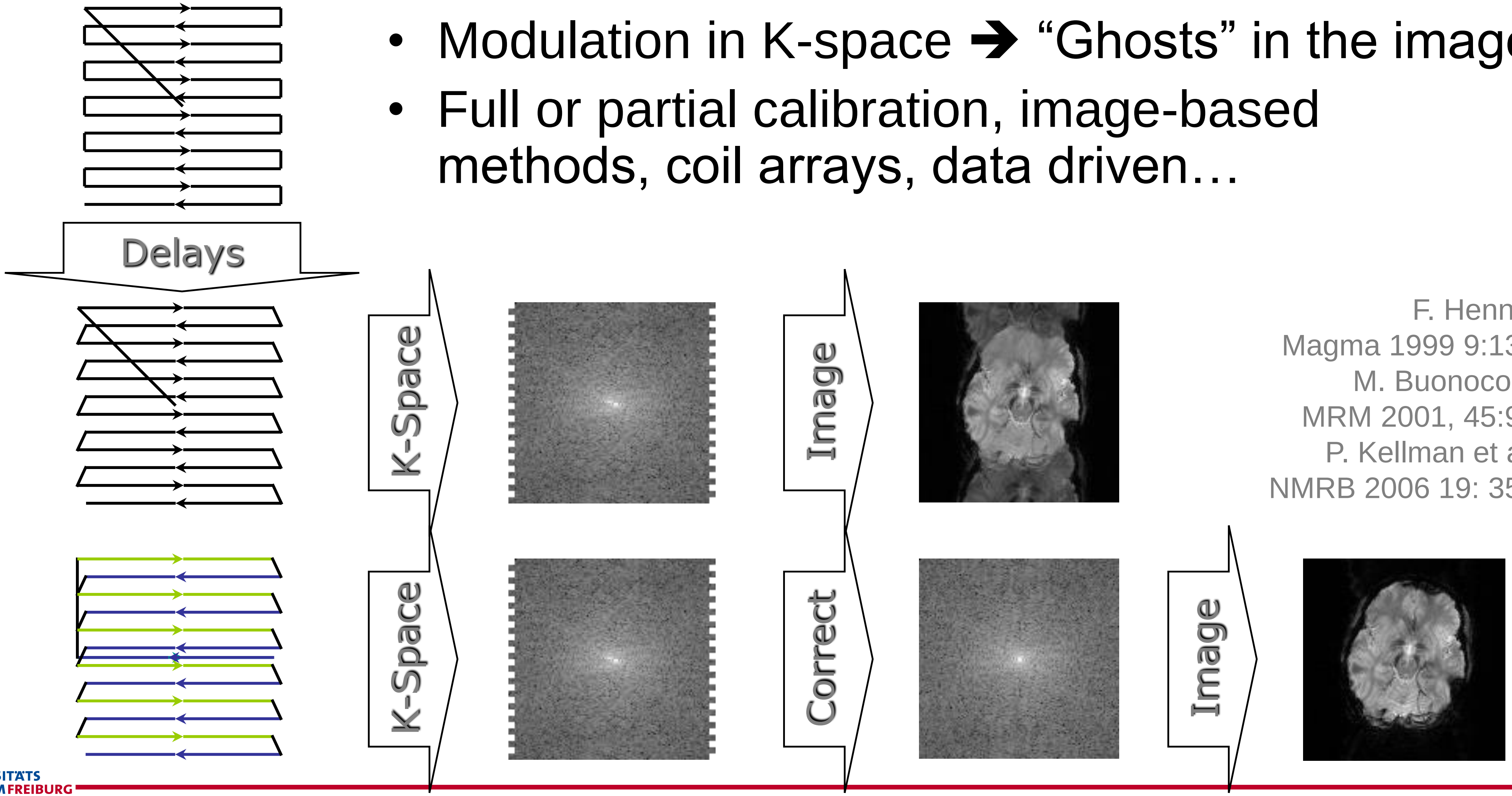
Get Familiar with EPI Data

- Delays between the gradient and the RF subsystems (RF+ADC)
  - Echoes are shifted in time ➔ in opposite directions in k-space
  - N/2 ghosting artifacts



EPI N/2 Ghosts – 3-echo Reference

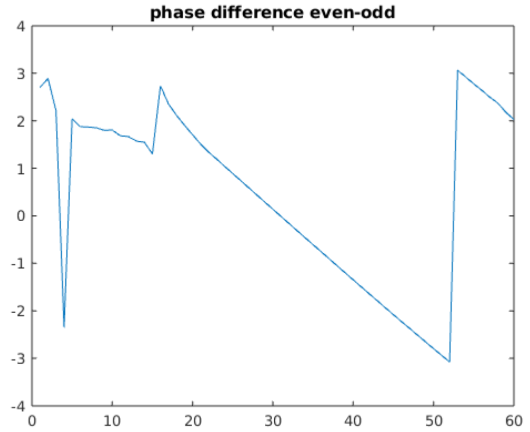
- Modulation in K-space ➔ "Ghosts" in the image
- Full or partial calibration, image-based methods, coil arrays, data driven…

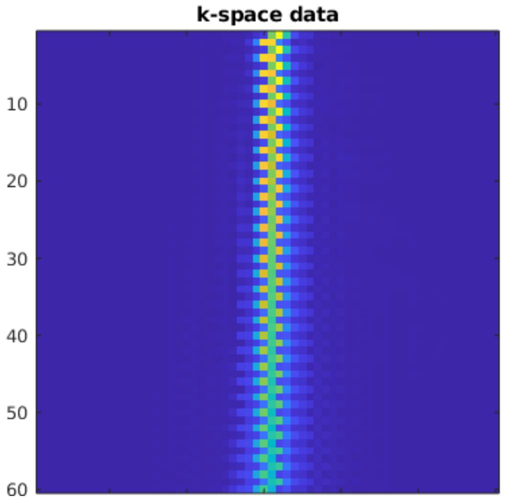


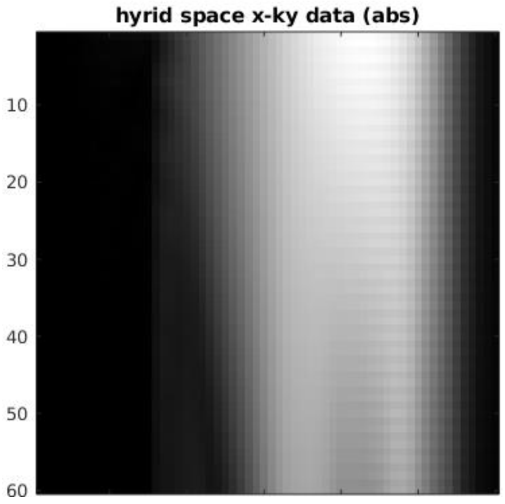
F. Hennel, Magma 1999 9:134.
M. Buonocore, MRM 2001, 45:96.
P. Kellman et al., NMRB 2006 19: 352.

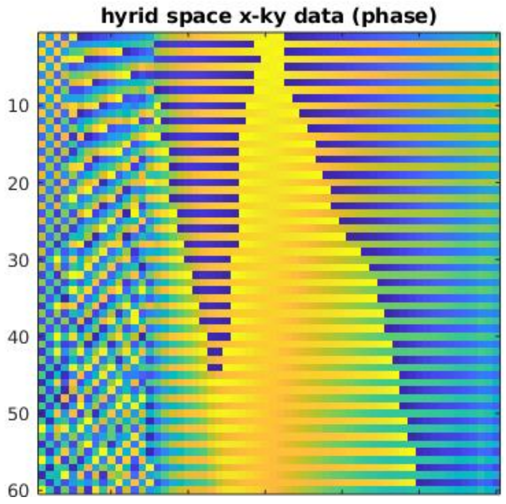
Example: Full Reference Scan

- Disable all phase encoding pulses
- All echoes should be equivalent
  - There is T2* decay
- Fourier transform in the read direction
  - Shifts ➔ phase ramps
- Detect phase difference
- Correct (either phase or delay correction)



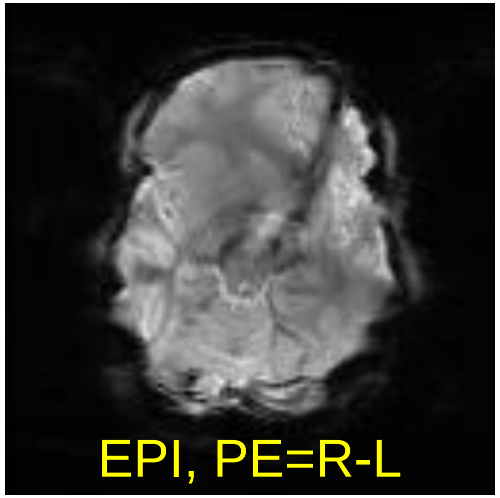






Geometric Distortions

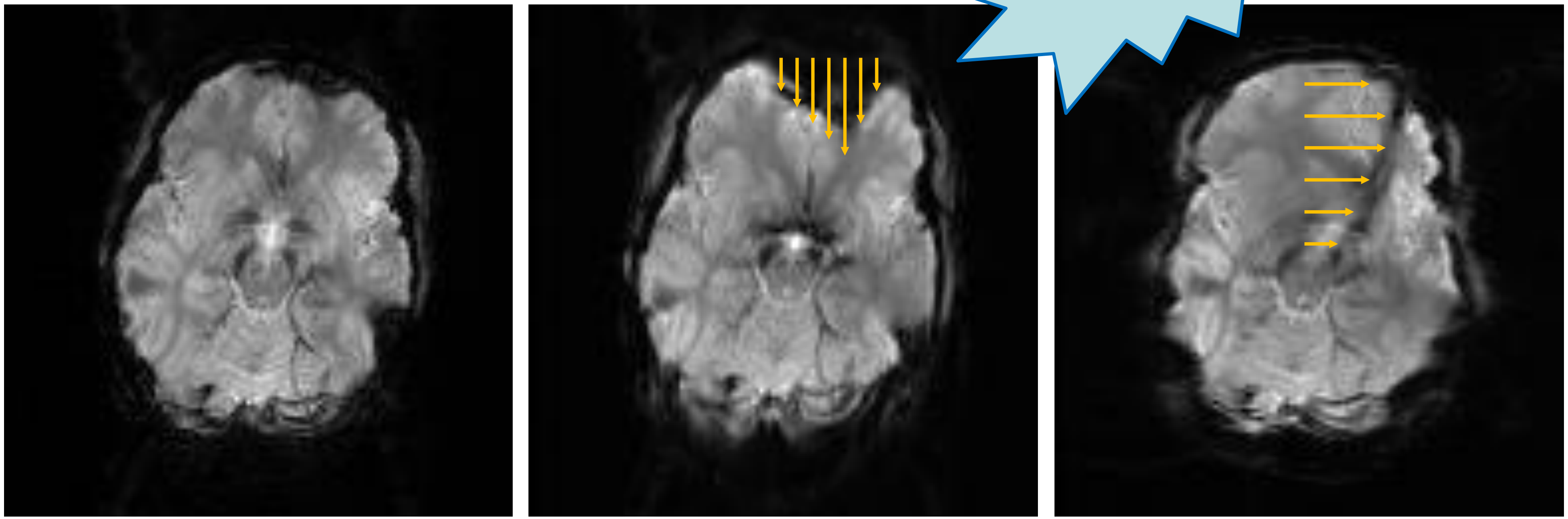
- EPI has two readout directions
  - Fast: which is typically considered as readout
  - Slow: which is also named “phase encoding direction”
- Very low readout bandwidth in the PE direction
  - High sensitivity to B0 inhomogeneities …
  - … and off-resonance effects such as fat-water shift
- Fat saturation
- Good shimming
- Readout time as short as possible (BW ~ 1/TA)



B_0-induced geometric distortions

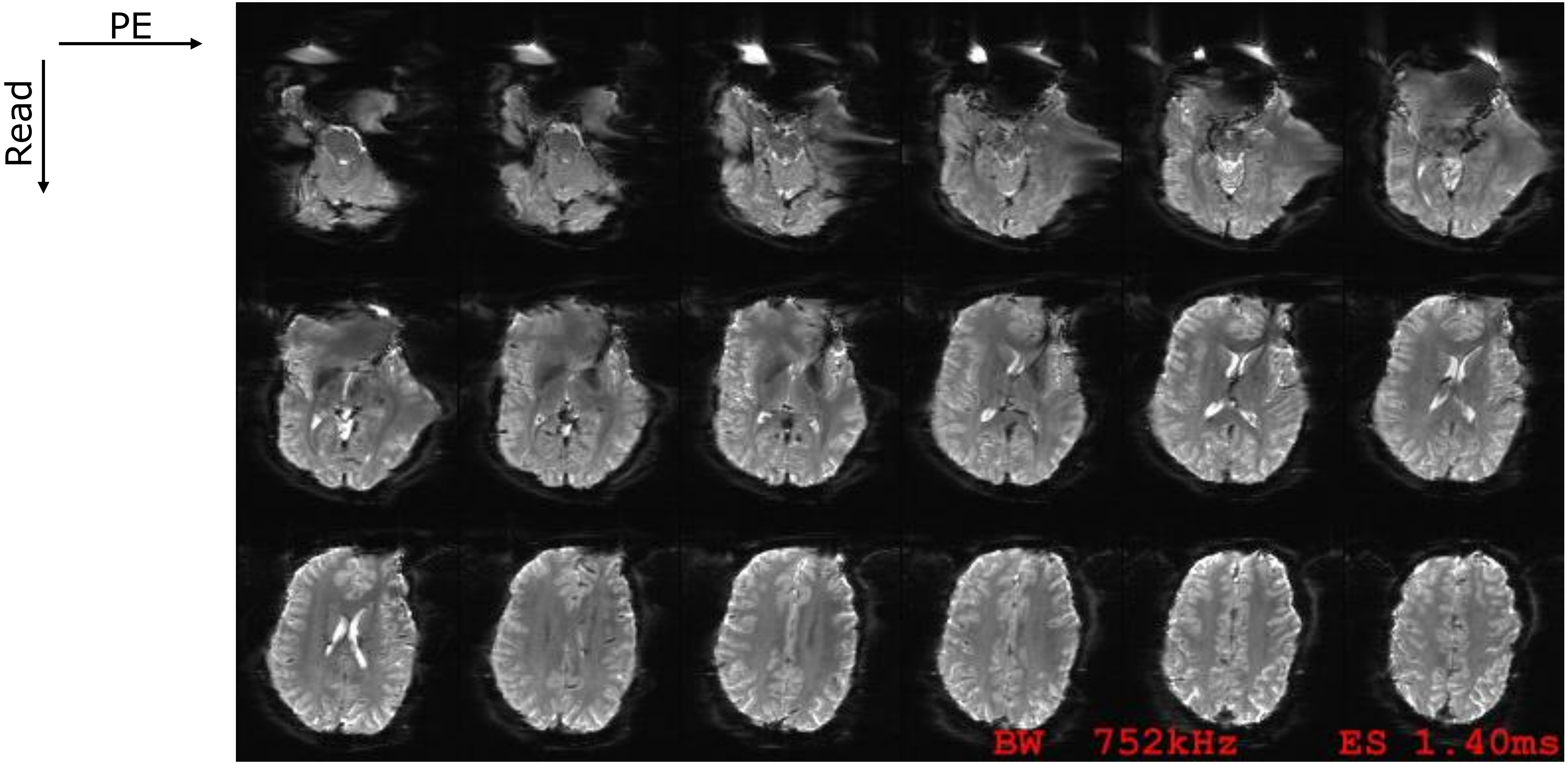
- Are shifts in phase encoding direction
- Depend on the phase encoding orientation
- Can be inverted by inverting the PE direction

same distortion magnitude!



Gradient Echo | EPI, PE=A-P | EPI, PE=R-L

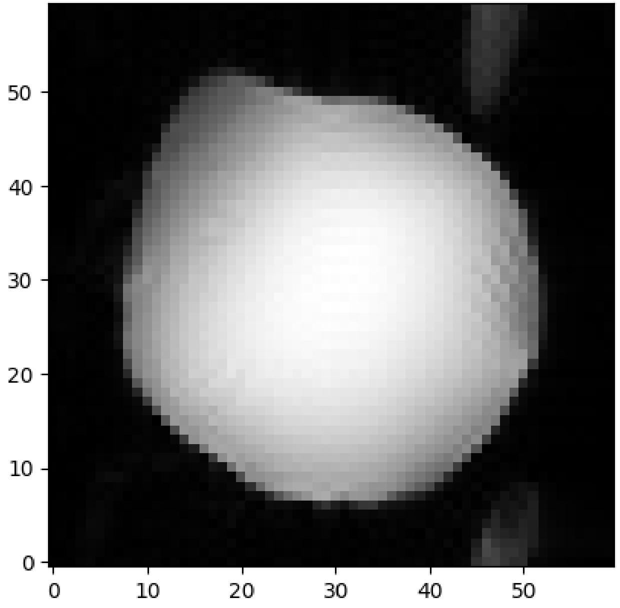
Reducing distortions with bandwidth



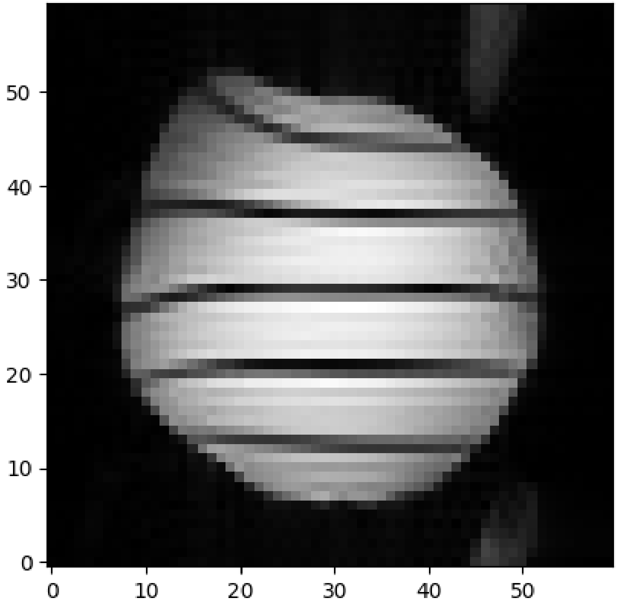
- Maximize PE-bandwidth / minimize echo spacing (ES)

Visualize Distortions in a Phantom

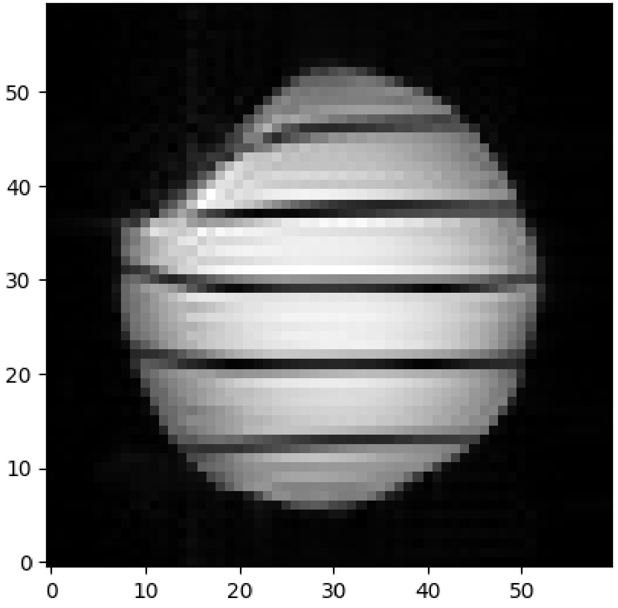
- Phantoms with geometric structures are expensive
  - Structures are likely to induce own distortions
- Use saturation RF pulses to “burn in” lines
  - Multi-slice excitation pulse is a good tool



original 60x60 EPI

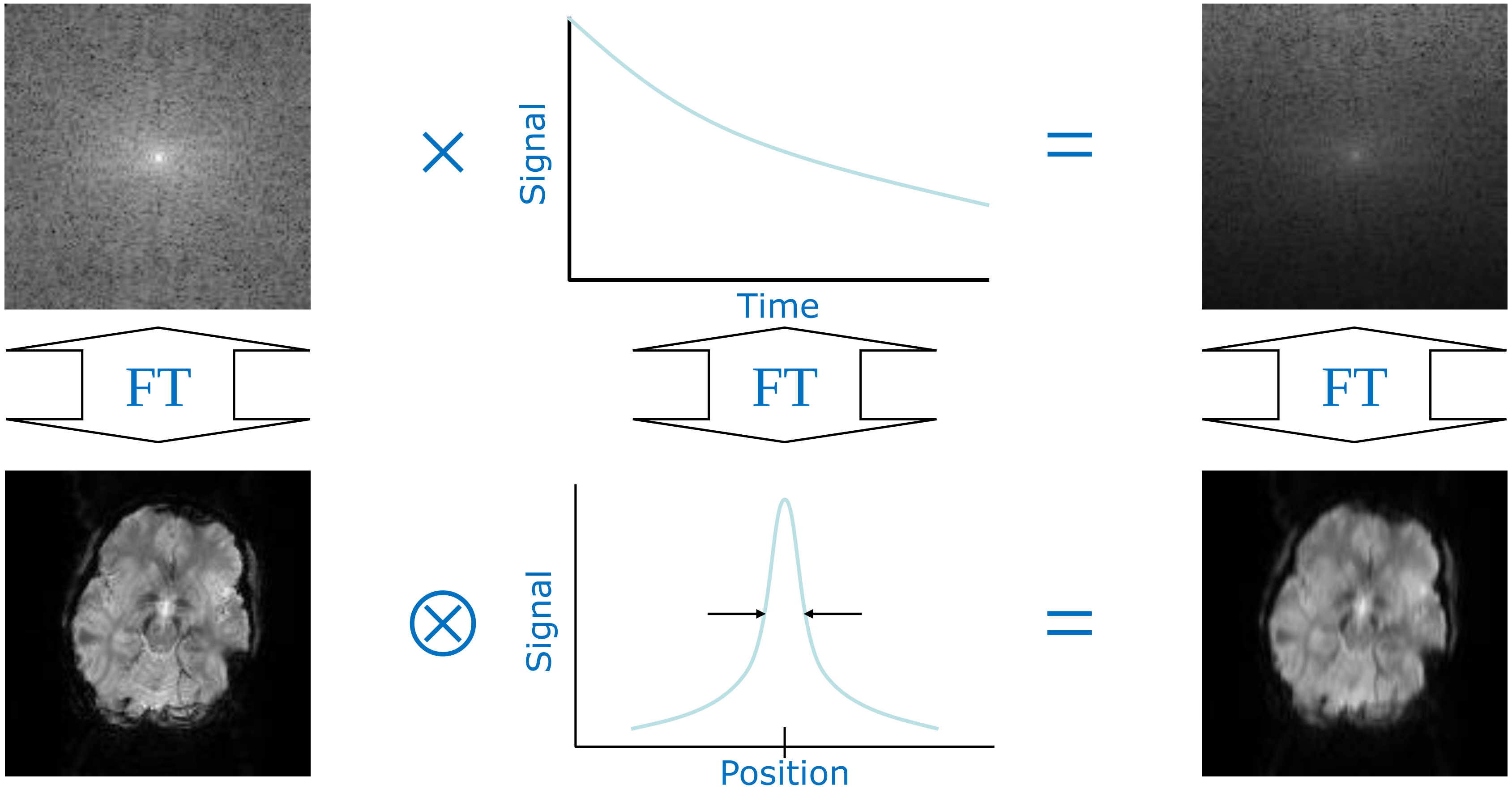


mb-sat 60x60 EPI



mb-sat 60x60 EPI pe-inv

Another Reason to Hurry: Resolution Loss



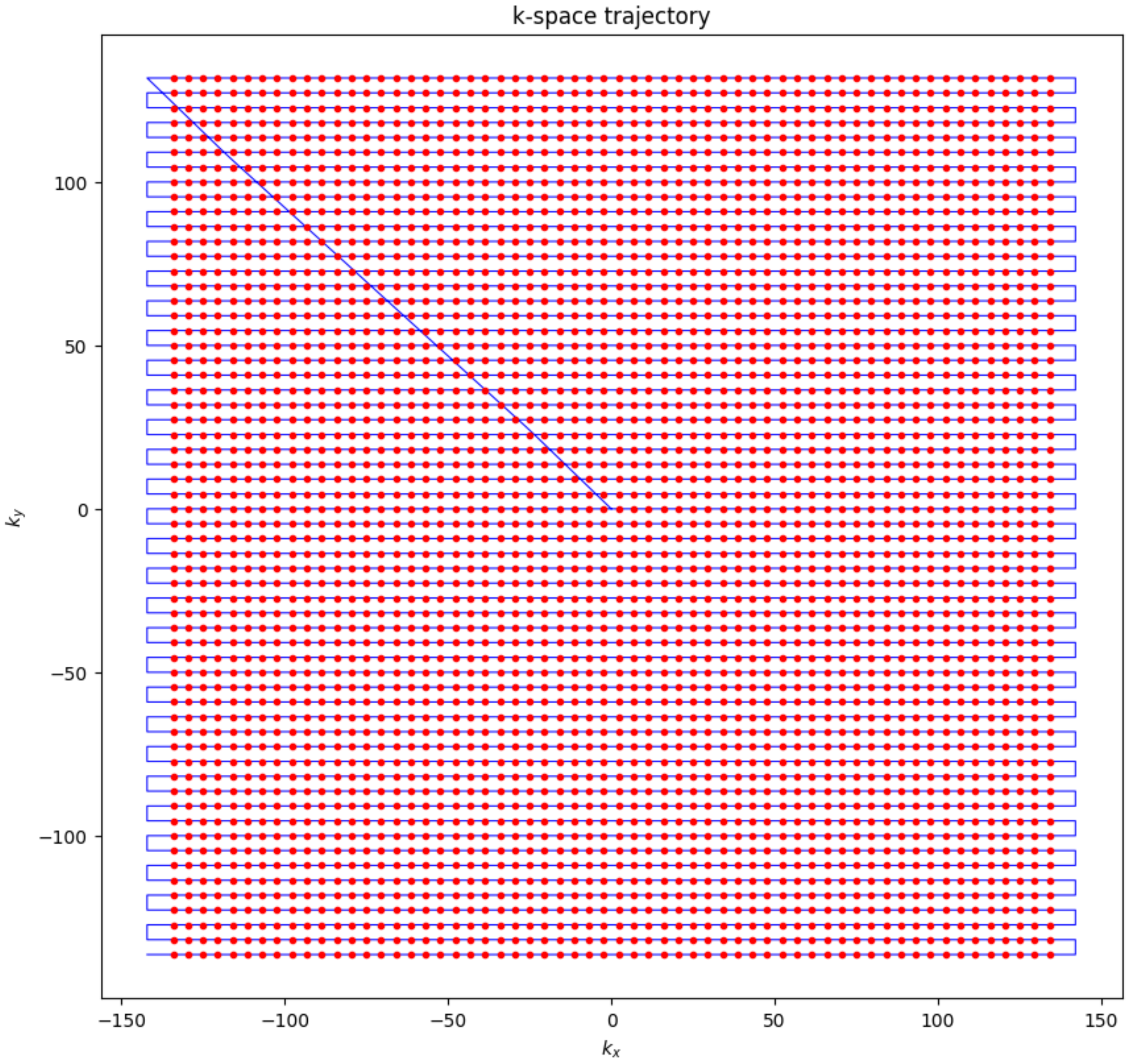
- Shorten full readout time: echo-spacing, BW, parallel imaging

Back to the Basic EPI Readout in Pulseq

- Plot the k-space trajectory
  - Looks good!? Why worry?
- Let's run seq.testReport()

Number of blocks: 121
…
<u>TE: 0.042050 s</u>
TR: 0.084850 s
…
Max gradient:
    308e3 280e3 1357e3 Hz/m == <u>7.25</u> 6.59 31.89 mT/m
Max slew rate:
    4.545e9 5.050e9 5.431e9 Hz/m/s == 106.76 118.62 127.57 T/m/s
…

- Let's try to make it faster…



Basic EPI: shorten readout?

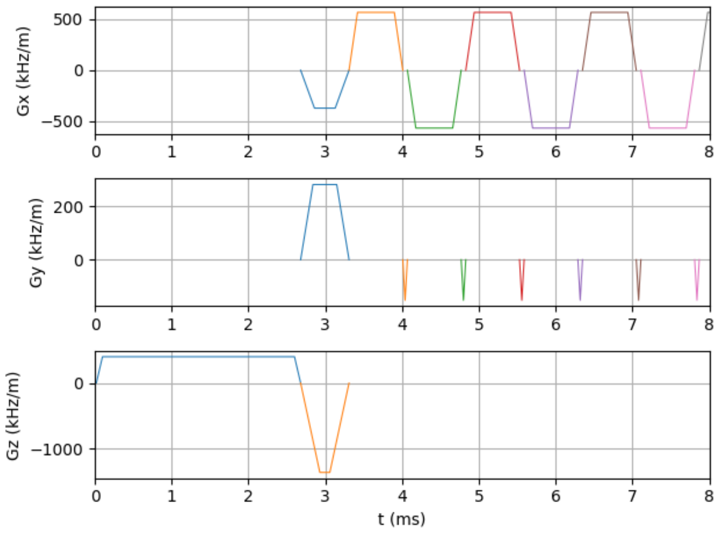
ro_duration: 1200us -> 480us

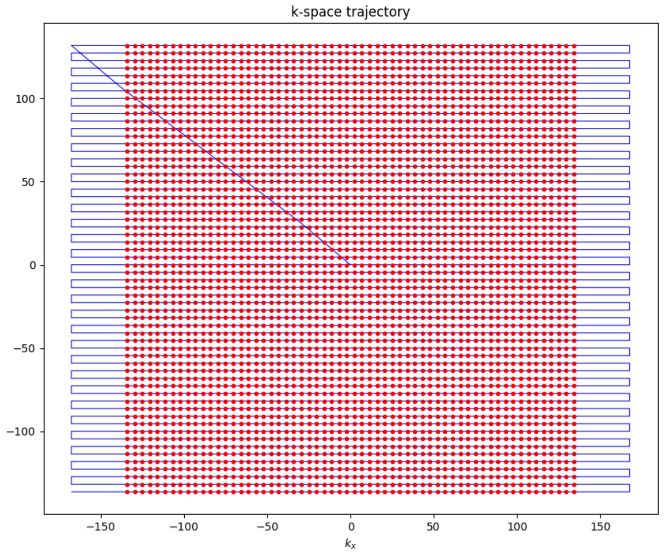
TE: 42.1 ms -> 24.3 ms

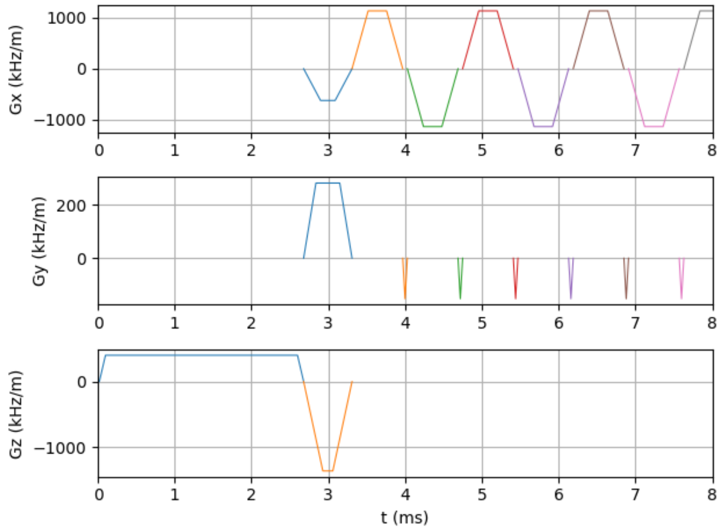
ro_duration: 480us -> 240us

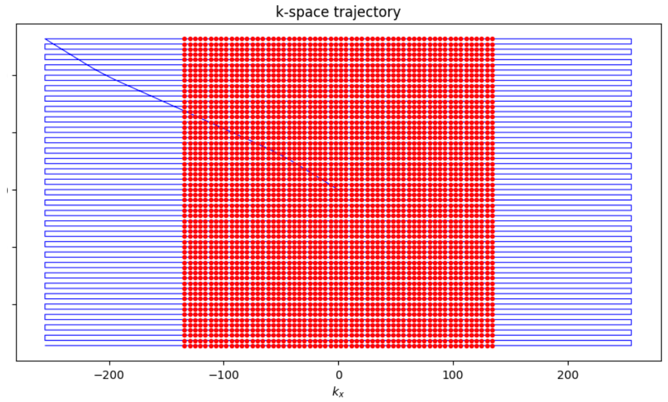
TE: 24.3 ms -> 23.2 ms

- Useless “detours” in k-space grow
- Timing does not improve much
- Sampling efficiency suffers



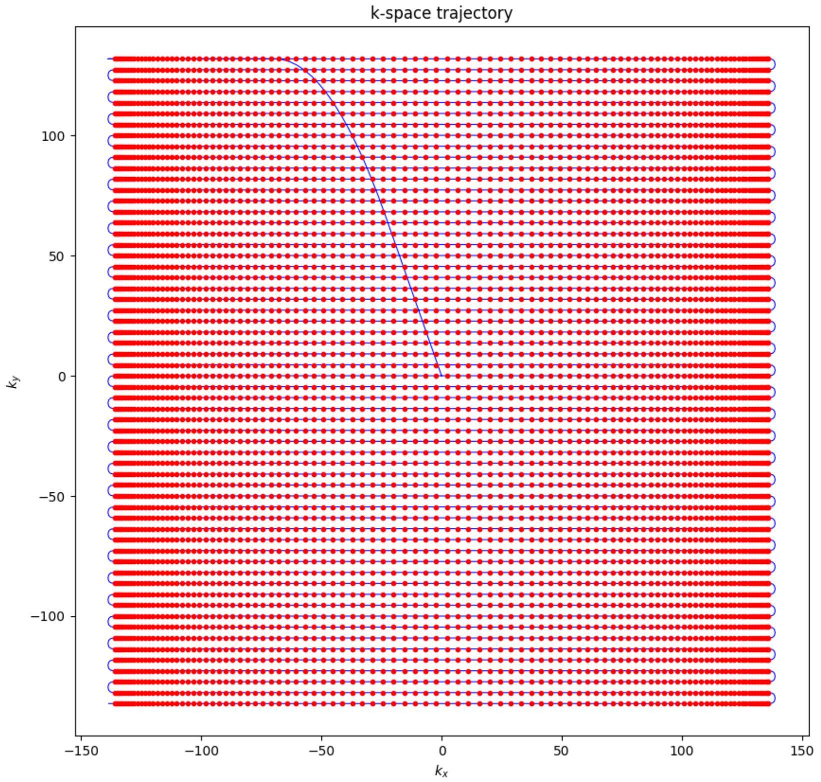


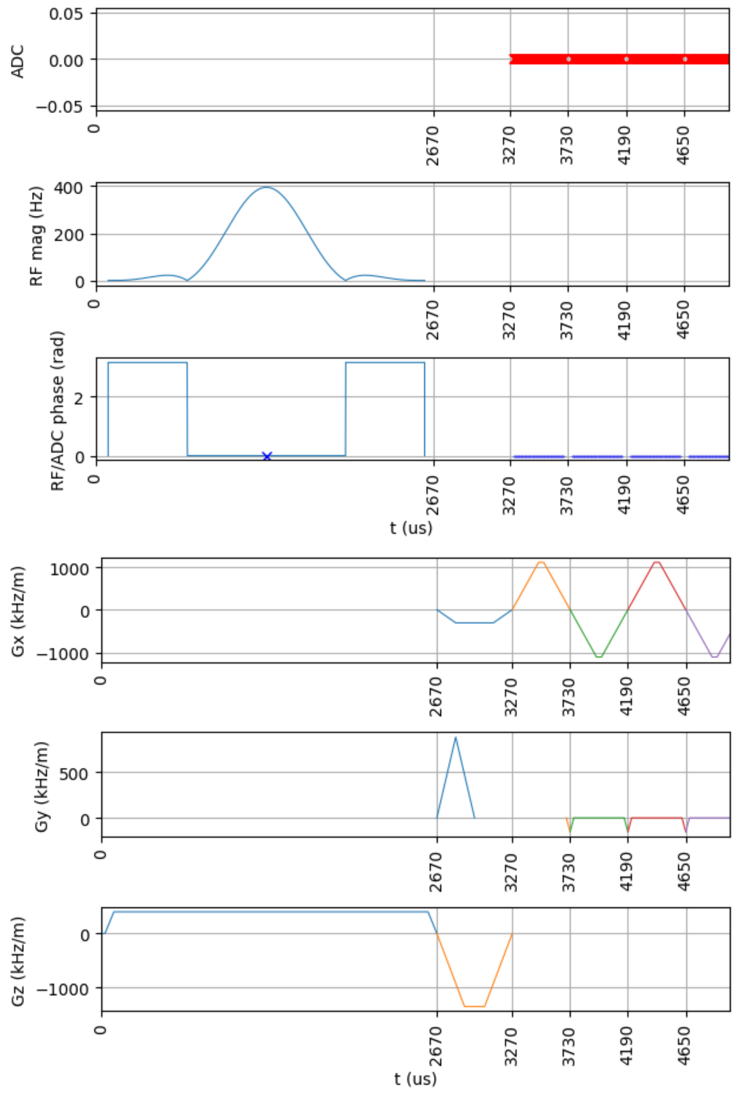




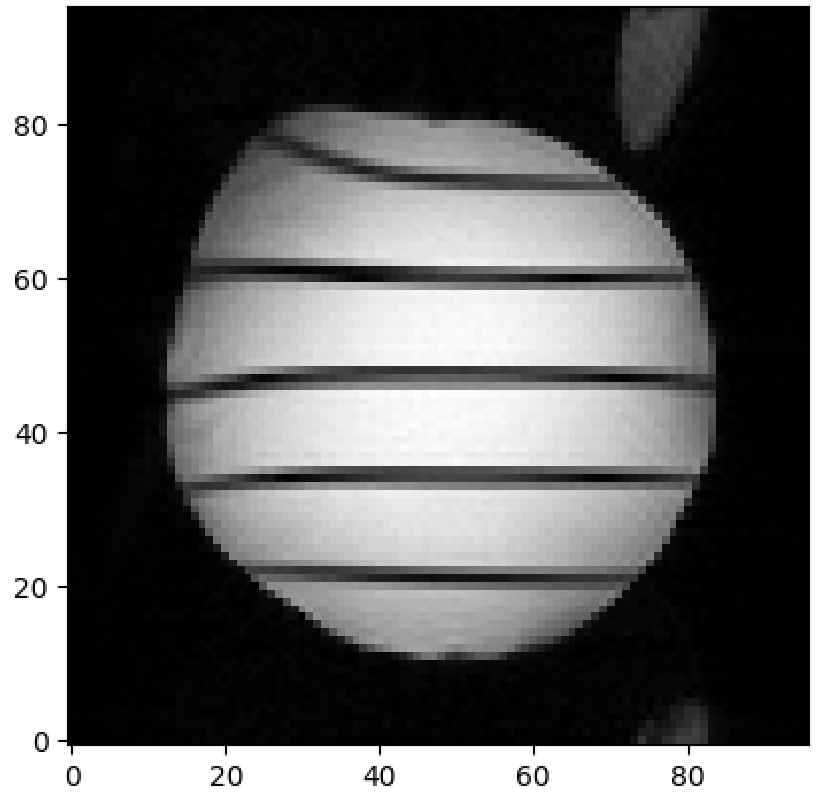
EPI with Ramp Sampling

- Dramatically shorten T_{ESP}
- Increase acquisition efficiency
- Additional steps in the image recon
  - Gridding in the read direction

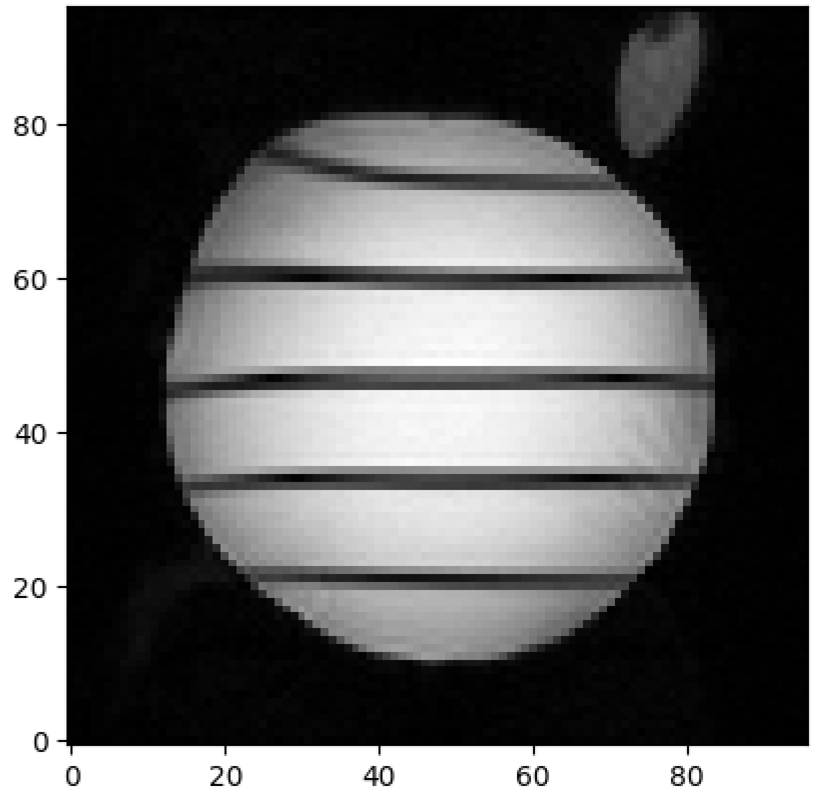




Basic EPI vs EPI with Ramp Sampling



basic 96x96 EPI



96x96 EPI with ramp sampling

Protocol Optimization and Further Options

- Fat suppression
- Ghosting reduction
- Distortion minimization
  - Distortion correction
- Readout acceleration
  - Multi-shot
  - Parallel imaging
- Overall acceleration – simultaneous multi-slice (SMS)
- Avoid PNS & acoustic resonances

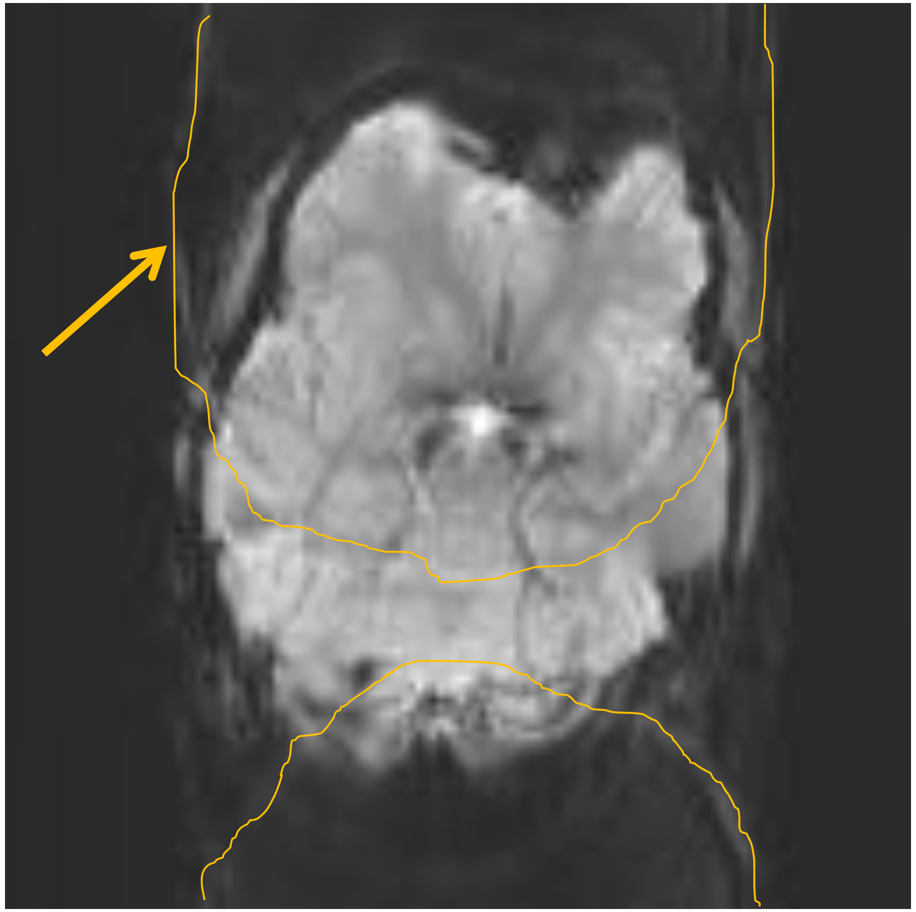
Chemical Shift Artifact & Fat Suppression

- Water-fat separation: ~3.4 ppm
  - At 3T $\sigma \approx 425$Hz
- Low bandwidth per pixel in PE direction

$$\Delta y = \omega_0 \sigma / BW_{pe};$$

$$425/10.4 \approx 40 \text{ pixels}$$

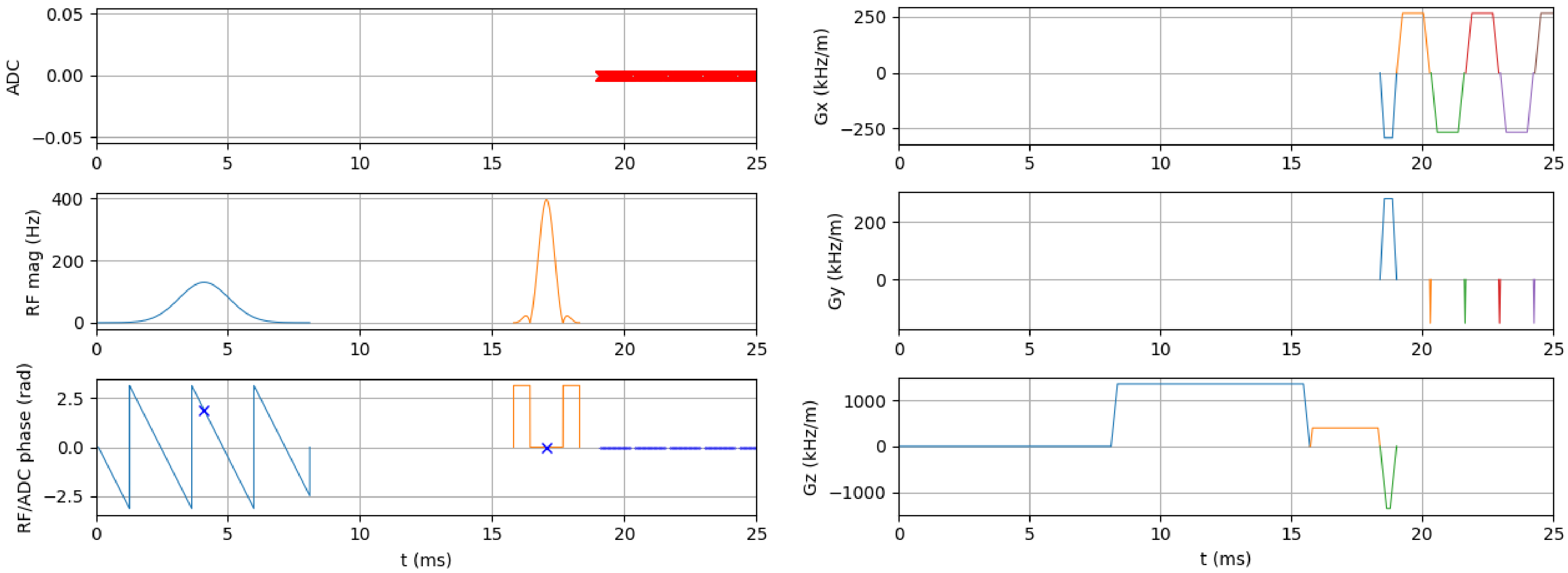
(~30% of FOV)



- Fat suppression
  - Fat saturation, water excitation
- In Pulseq examples: off-resonance Gaussian pulse before every excitation

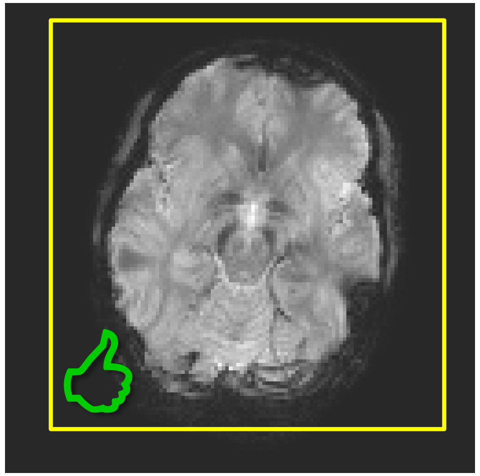
Fat Saturation in Pulseq

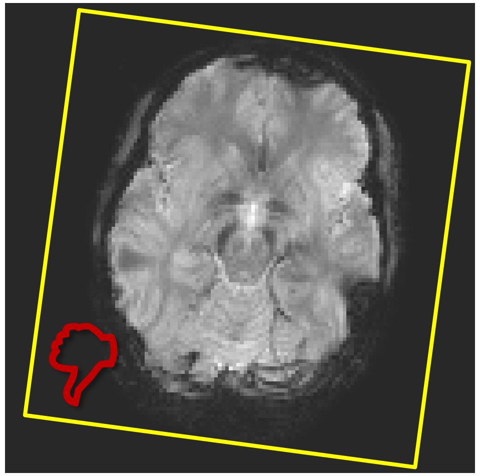
- Gaussian pulse at -3.45ppm followed by a spoiler
  - Implementation by some major manufacturer
  - Other vendors use different RF pulses (e.g. minimal phase SLR)

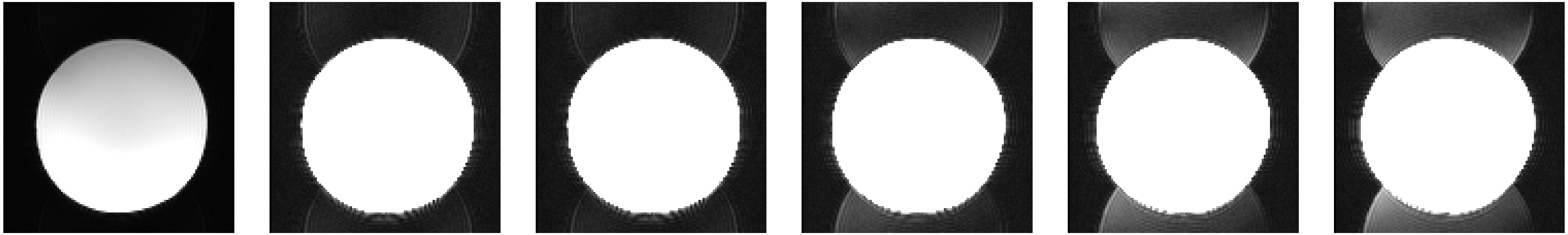


Ghosting: practical advice #1

- For RO use pure gradient
  - Preferably X or Z axis (PNS)
  - Avoid double-oblique slices
  - No in-plane rotation



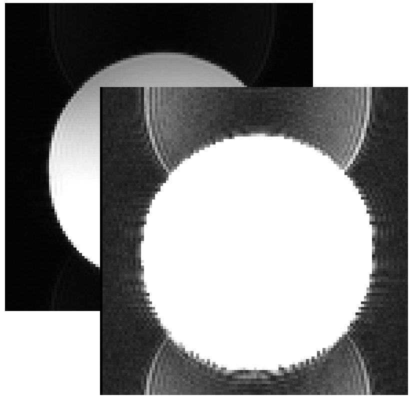


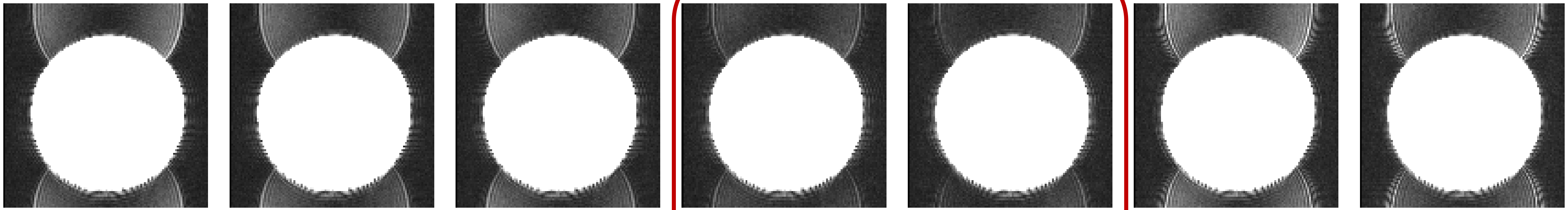


normal scaling | overscaled | 0° | 10° | 20° | 30°

Ghosting: practical advice #2

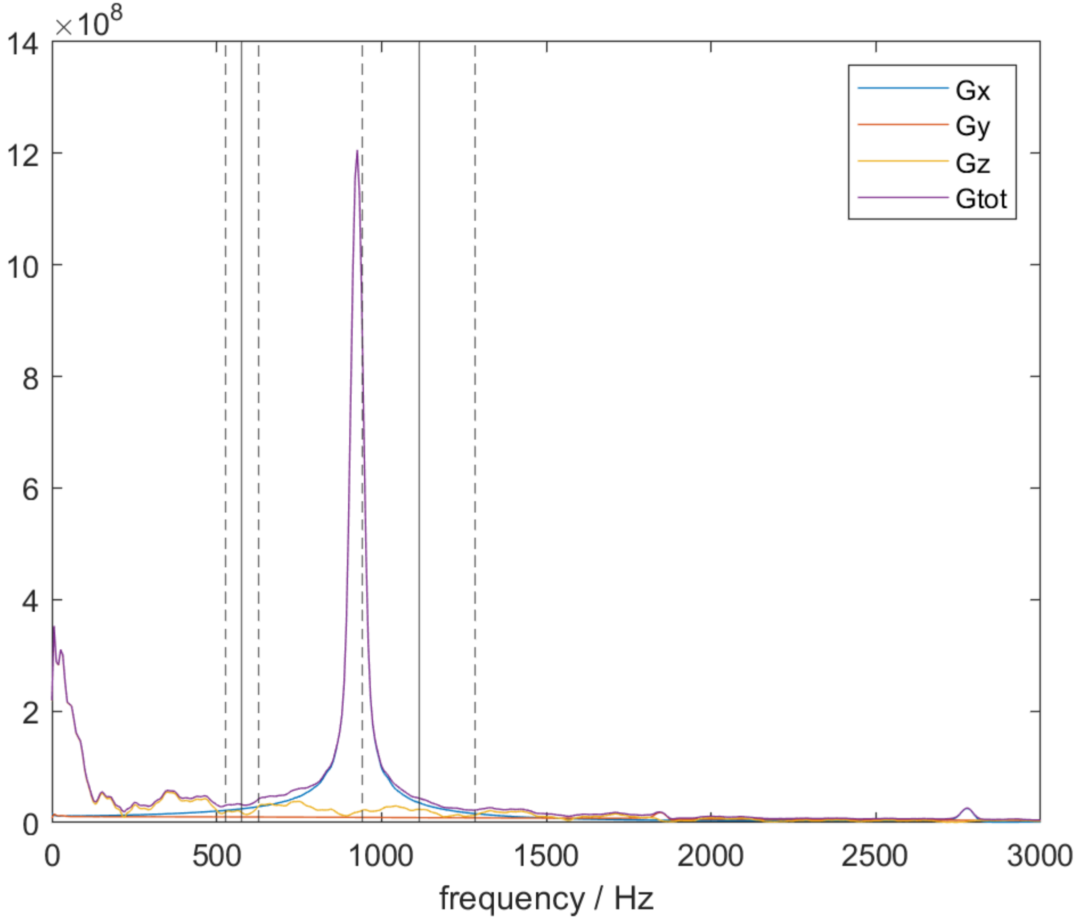
- Optimize readout bandwidth / echo spacing
- Do “step left / step right” check
- Avoid mechanical resonances of the gradient system
    - Often the quietest echo spacing setting is the best



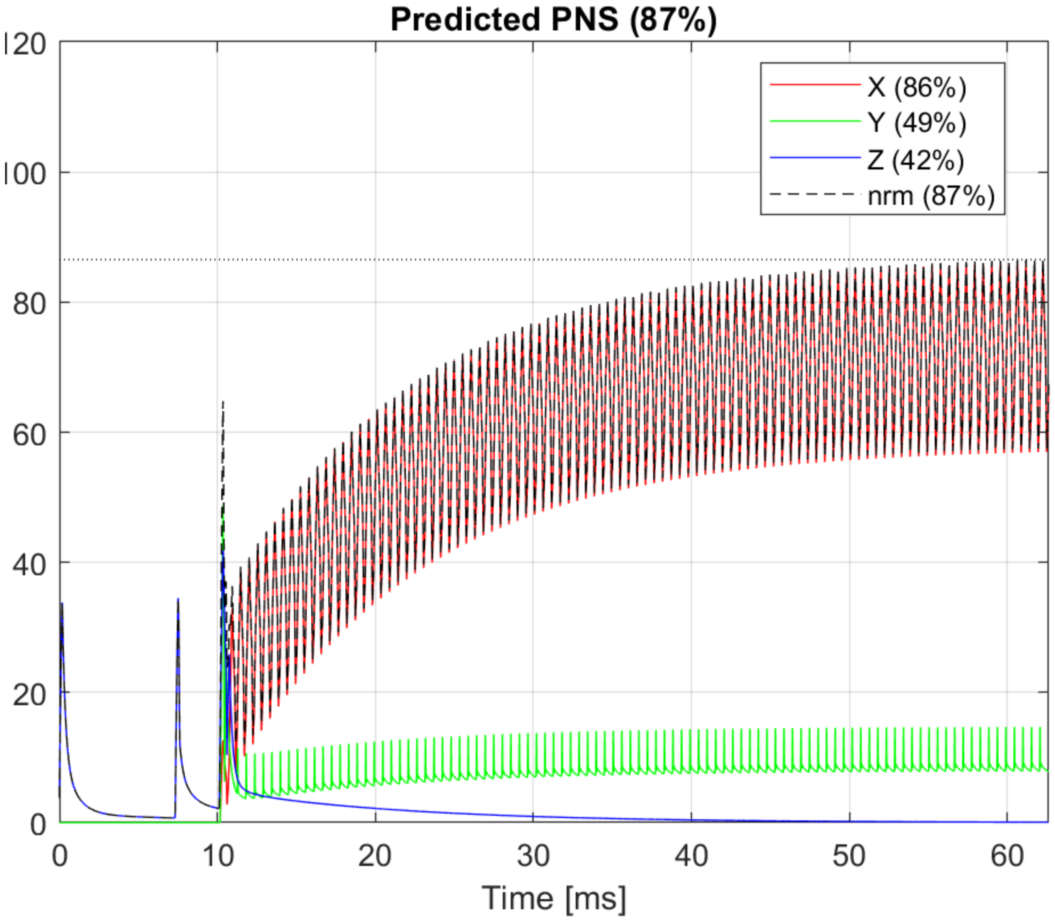


1653 Hz/pix 1717 Hz/pix 1786 Hz/pix 1860 Hz/pix 1941 Hz/pix 2029 Hz/pix 2126 Hz/pix

More Troubles to Avoid



mechanical resonances of the gradient system



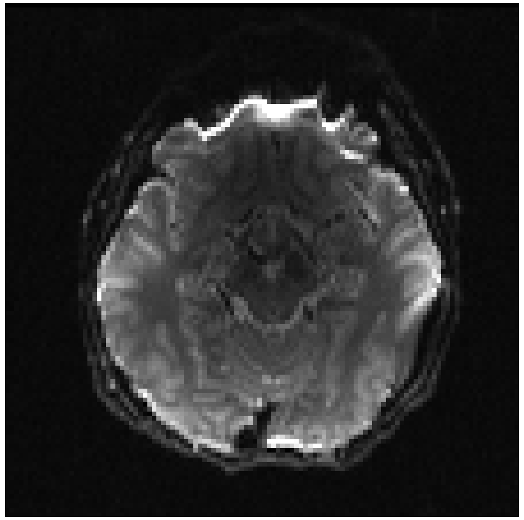
peripheral nerve stimulation (PNS)

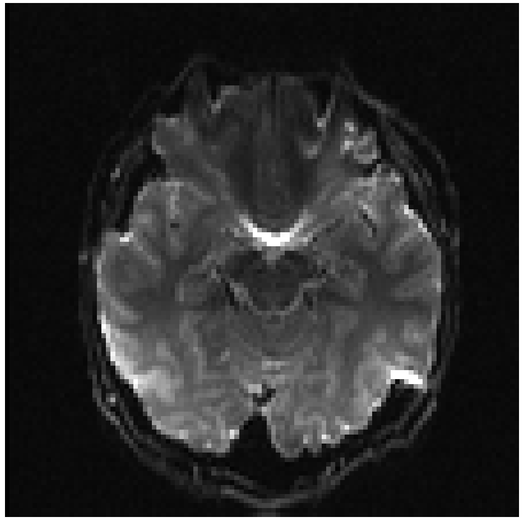
Summary & outlook

- EPI is an established technique
- Good image quality if operated properly
- Numerous new options: SMS, randomized sampling, non-linear image reconstruction

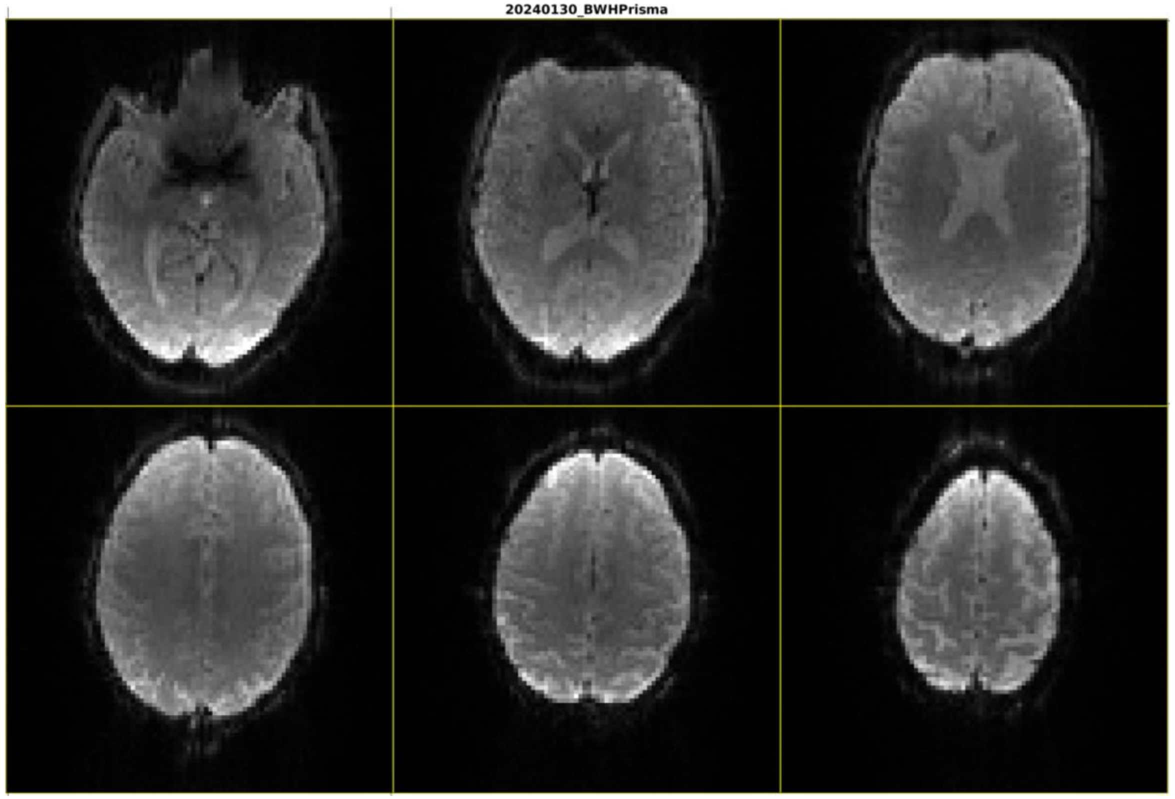
- Need to recognize, understand and avoid artifacts

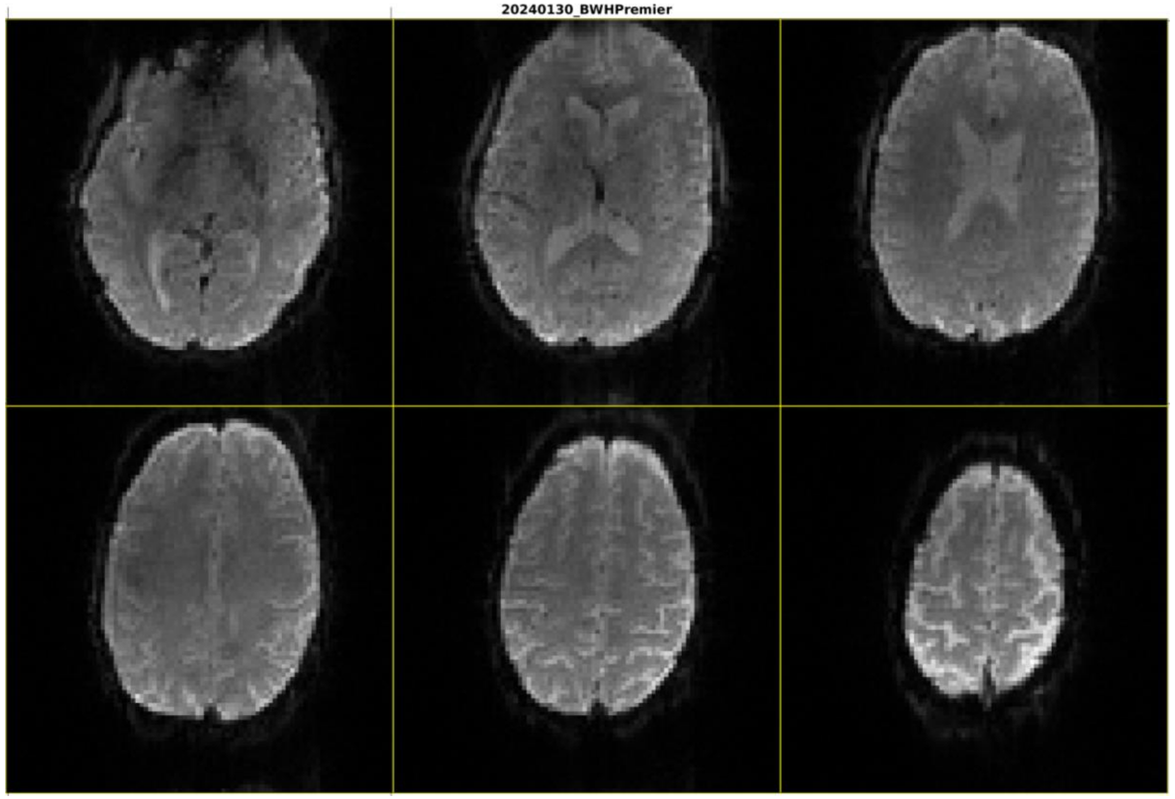
- Do a pilot run for each specific application
  - Check whether PE inversion gives more favorable distortions





Outlook: towards cutting-edge fMRI





Multi-Vendor SMS-EPI protocol for fMRI applications (ABCD)

https://harmonizedmri.github.io/

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Pulseq MATLAB

pypulseq Python

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