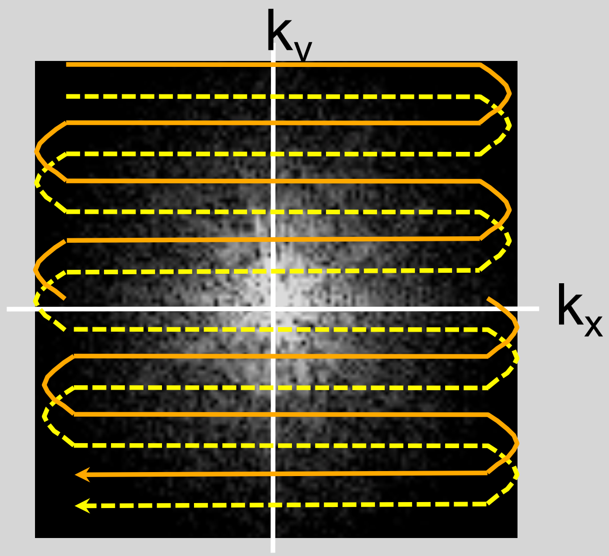
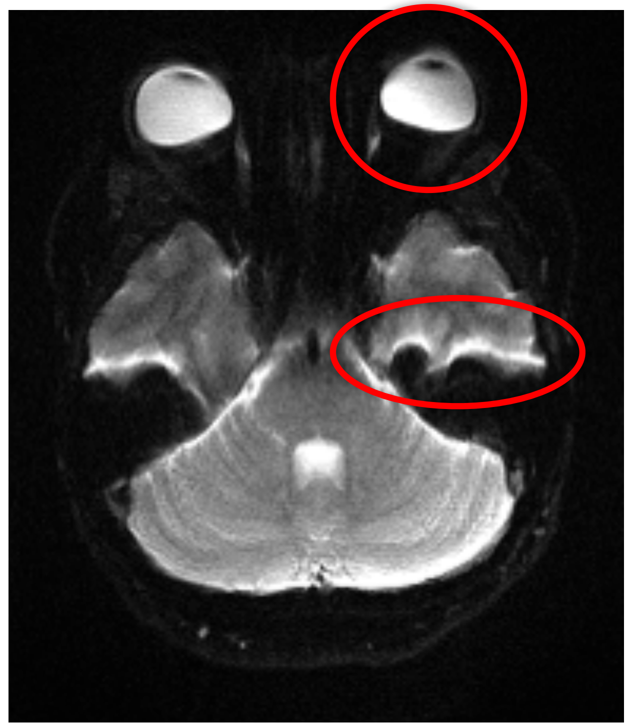
EPI

- Faster “Cartesian” approach
- Single-shot, Interleaved, segmented, half-k-space
- Delays, etc -> Phase corrections
- Flyback EPI
- GRASE



Thanks to Samantha Holdsworth!

EPI: Speed vs Distortion



Fast Spin
Echo (FSE)

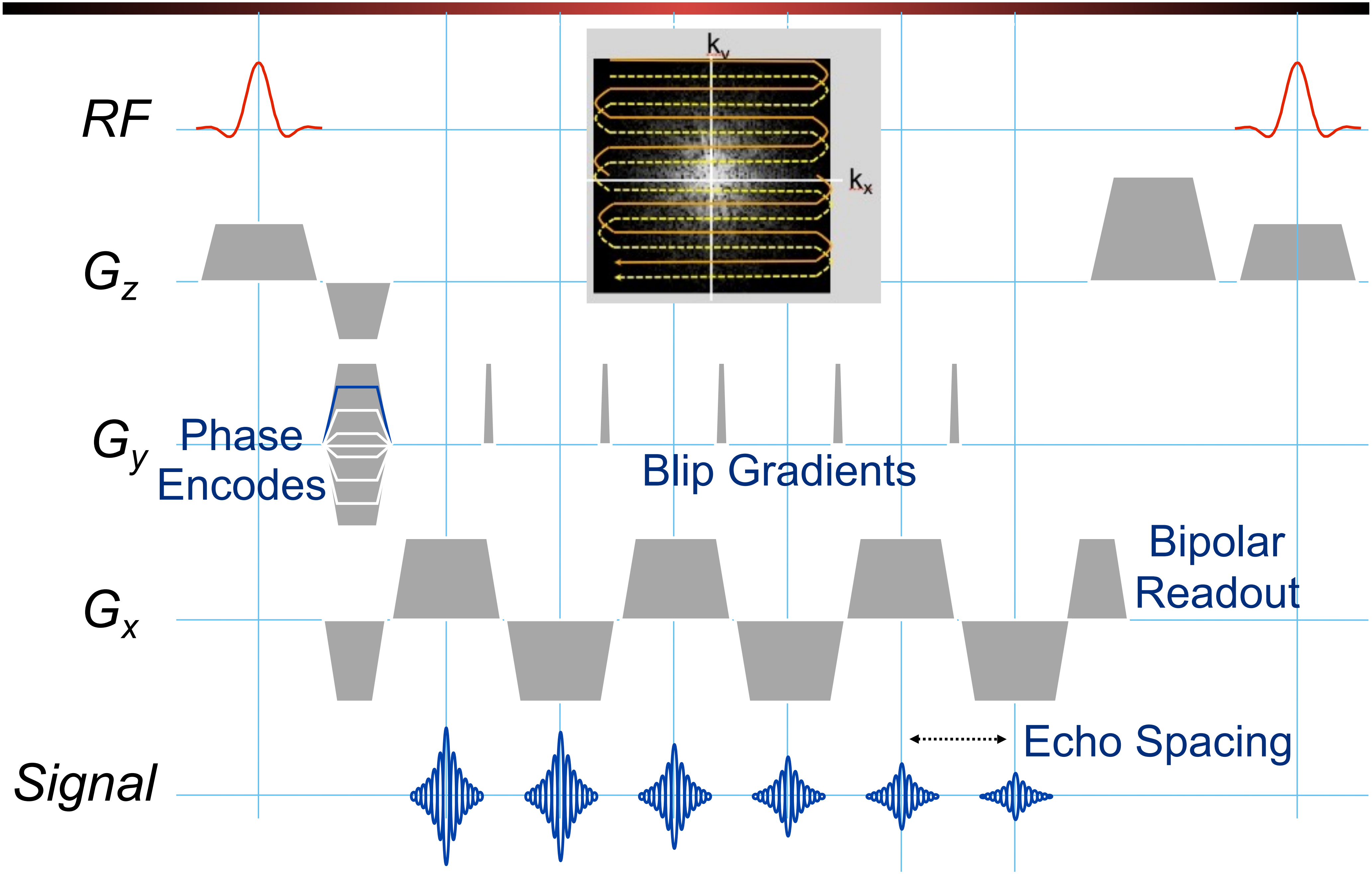
Echo Planar
Imaging (EPI)

Slow ~ 3mins

Faster ~ 10 seconds

(T2-weighted image. Full brain coverage. Same target resolution.)

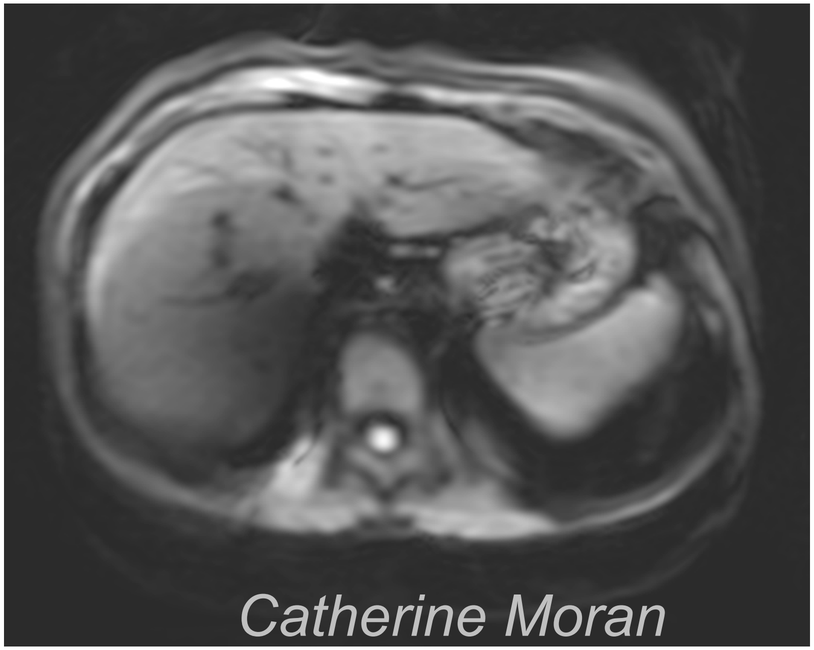
Echo-Planar Imaging (EPI)



EPI Calculations

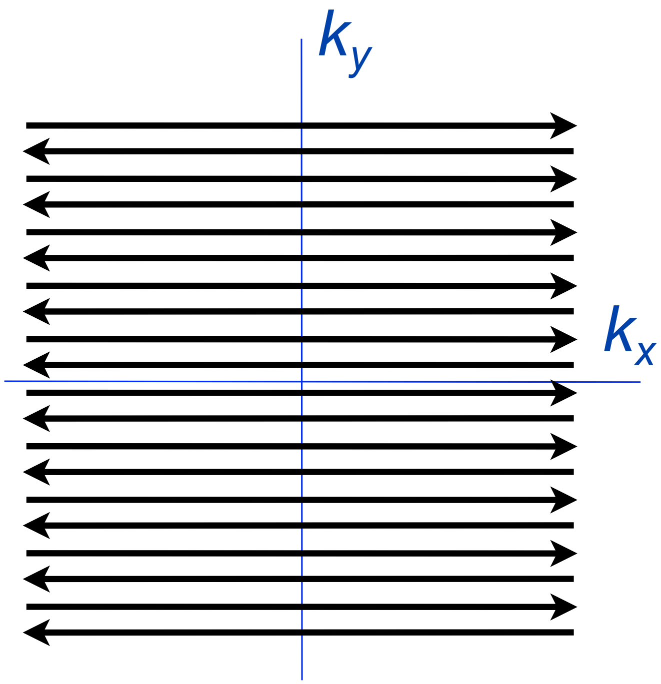
- T = ESP = Echo spacing. 1/T = effective bandwidth
  - Limited by gradients, readout resolution/duration
- Δk_y = 1/FOV
- Δk_y / T = k_y velocity (Hz/cm)
- Displacement = Δf (FOV) (T)
- T_2* decay over “echo train”
  - $\exp(-ETL \times T / T_2^*)$

Fat/Water Displacement in EPI

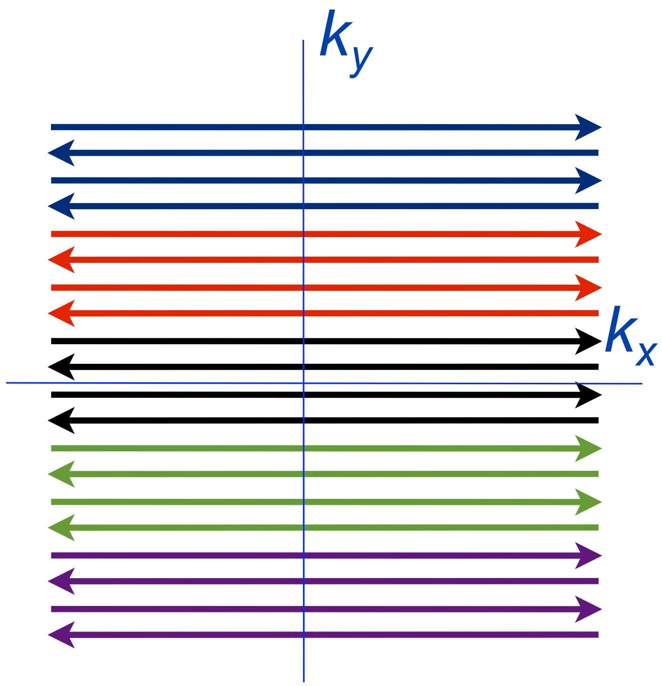


EPI Variations

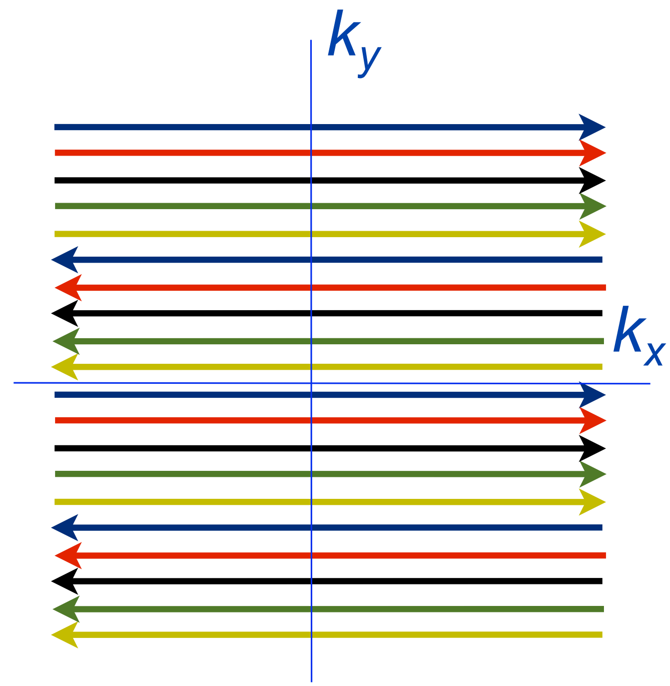
Single-shot



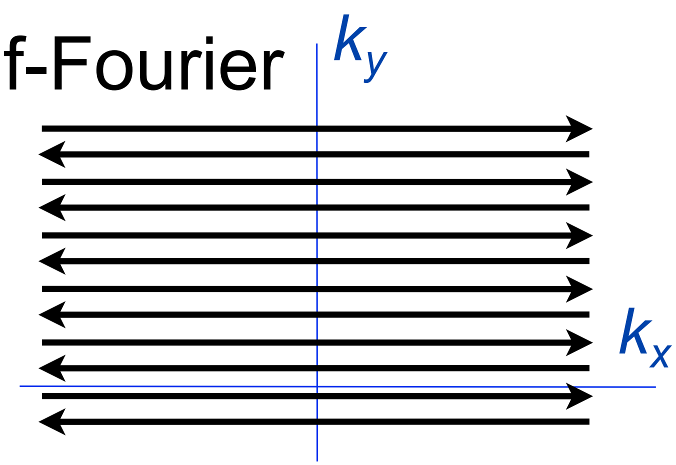
Segmented



Interleaved



Half-Fourier

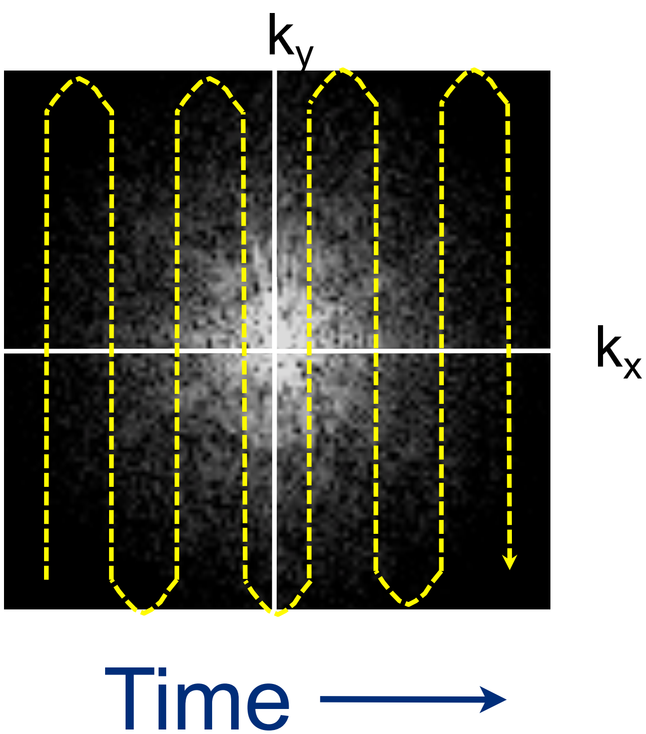


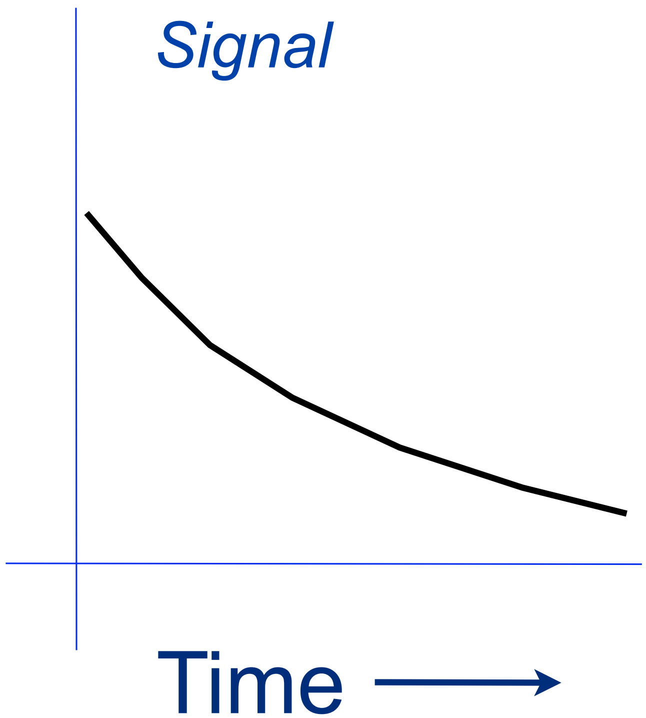
Interleaved and Single-Shot EPI

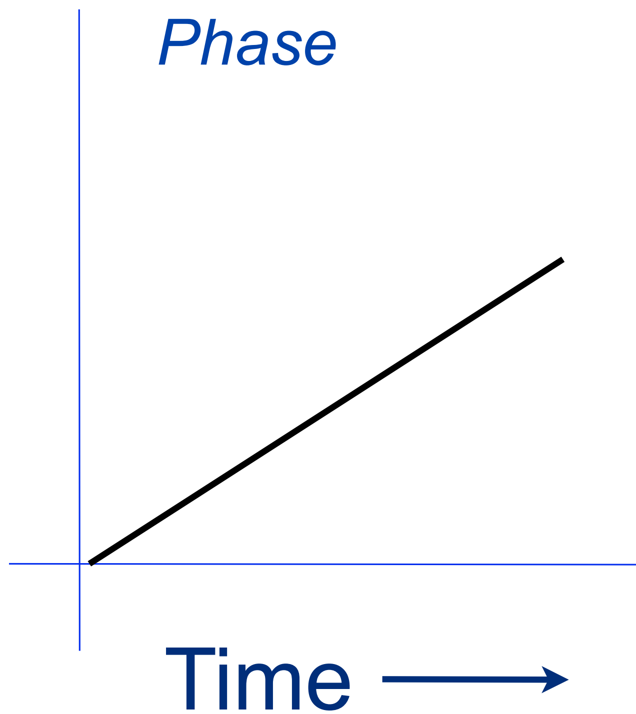
- Single-shot EPI:
  - All lines on one shot - reduces impact of motion
- Segmented EPI:
  - Acquire ETL *consecutive* lines - not used much
- Interleaved EPI (N_y = ETL x $N_{interleaves}$:
  - Acquire ETL lines per shot
  - Reduces T2* and distortion by $N_y/N_{interleaves}$
- Half-Fourier (k_y) often used (all methods)

Signal Modulation in EPI

- “Blip” direction traversal is slow
- T_2^* similar to echo-train T_2 modulation in FSE
- Low “effective bandwidth”
- Usually ignore readout direction effects





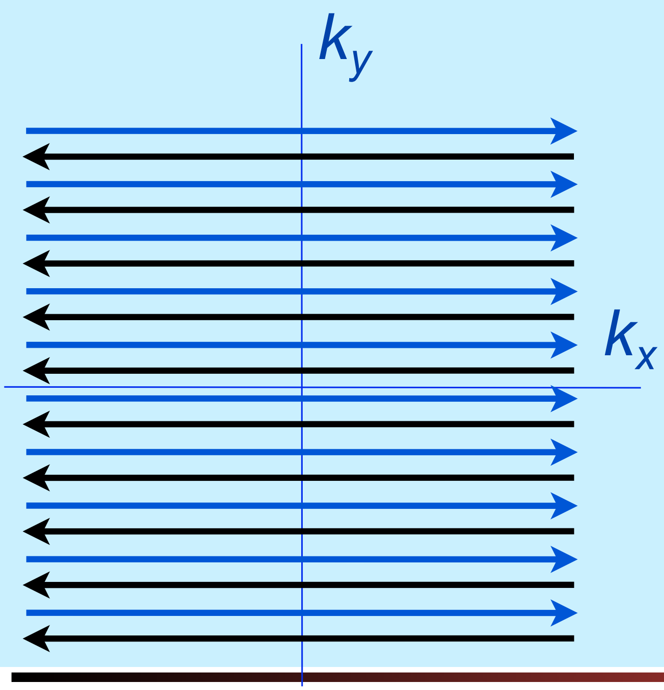


Signal/Phase Modulation

- *T2 = 100ms, Echo-spacing 1ms, 128 lines (full k_y)*
  - What is the signal loss?
    - k_y=0 at 64ms, so $e^{-0.64}$.
  - What is the fat/water displacement (3T) per FOV?
    - (0.44kHz)(1ms) = 0.44 cycles/ky line... 0.44 FOV!
    - *Use fat suppression!*
  - How do these change with 3x parallel imaging?
    - $e^{-0.21}$ and 0.13 FOV
  - With 2x reduced FOV?
    - (Like 2x PI) $e^{-0.32}$ and 0.4 $FOV_{orig}/2$

Other Effects - Single-Shot (SS) EPI

- What are some effects of bidirectional readouts?



SS EPI - Odd/Even Decomposition

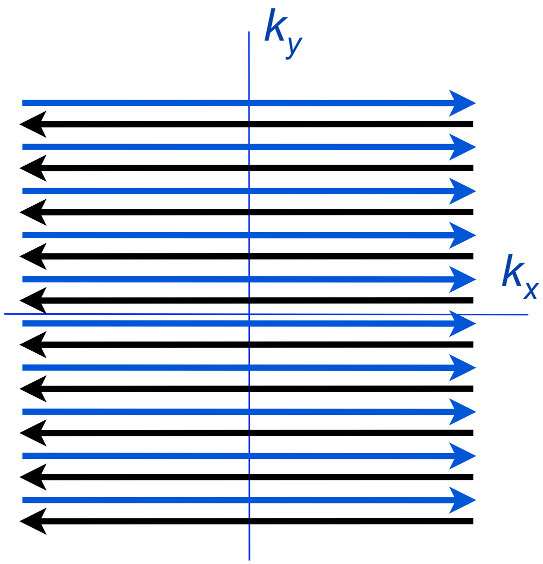
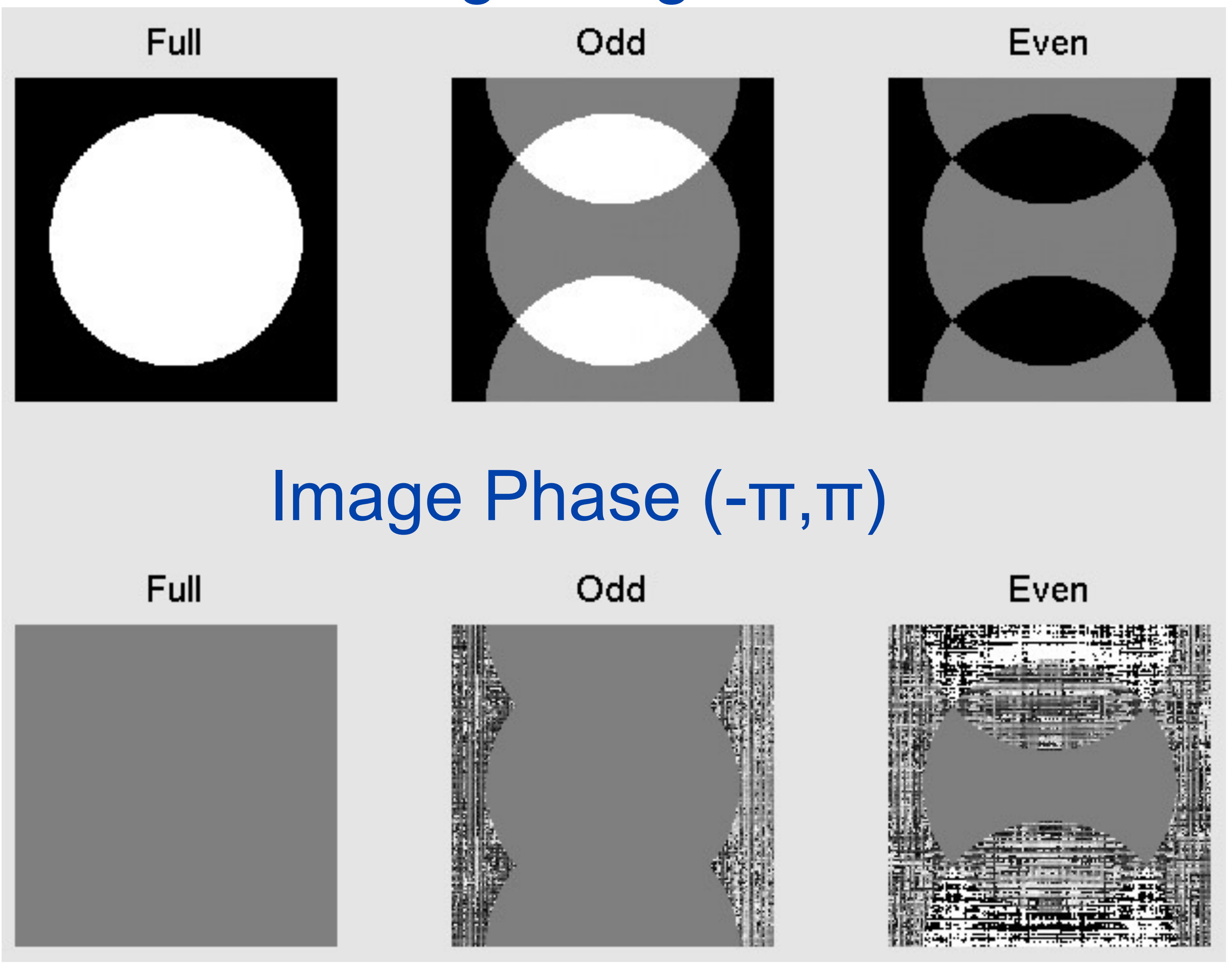
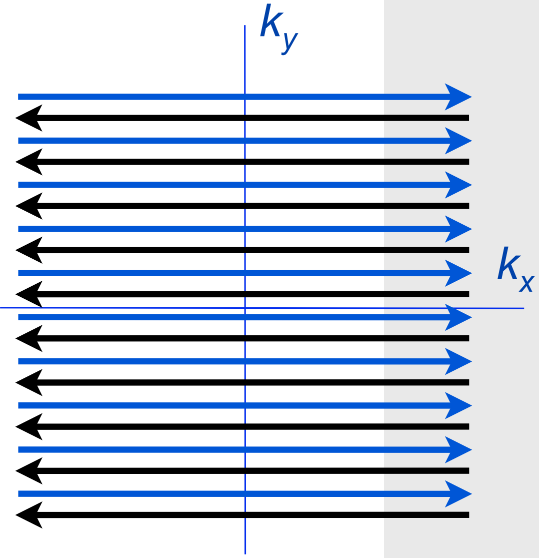
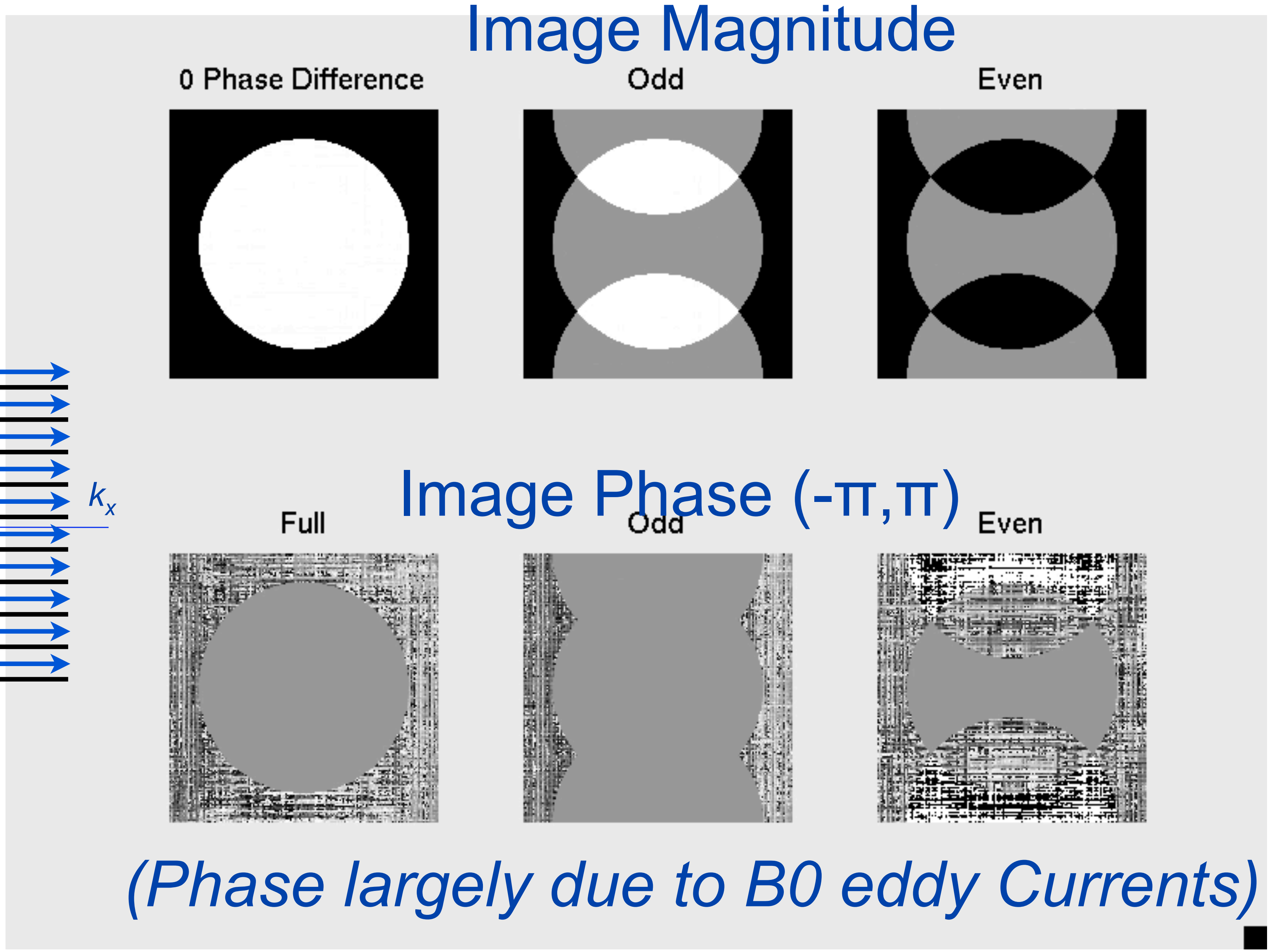


Image Magnitude



SS EPI - Alternating Constant Phase





SS EPI - Linear k-space Phase

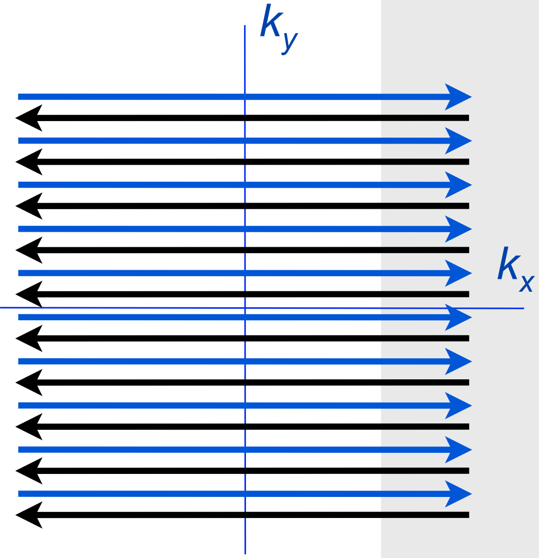
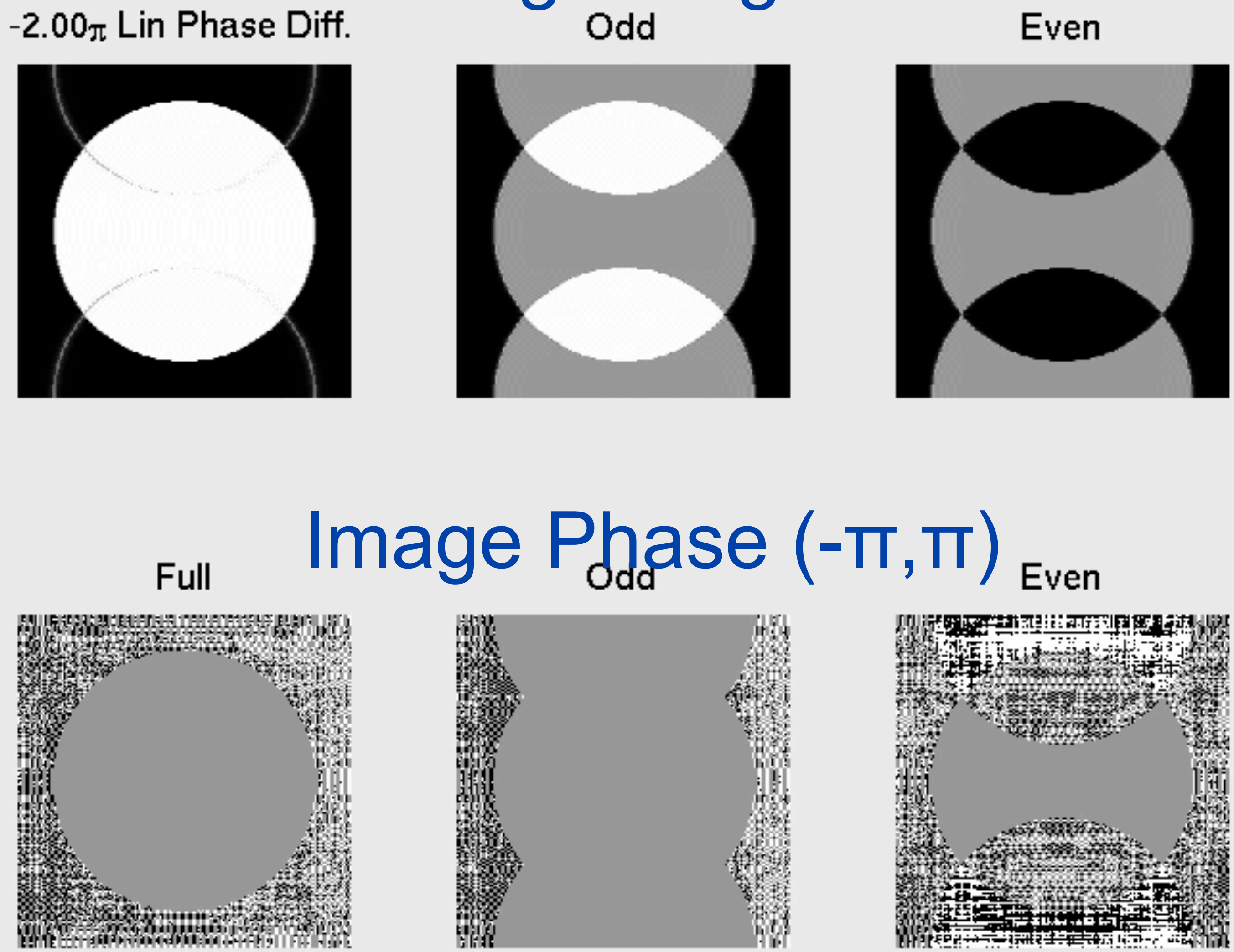


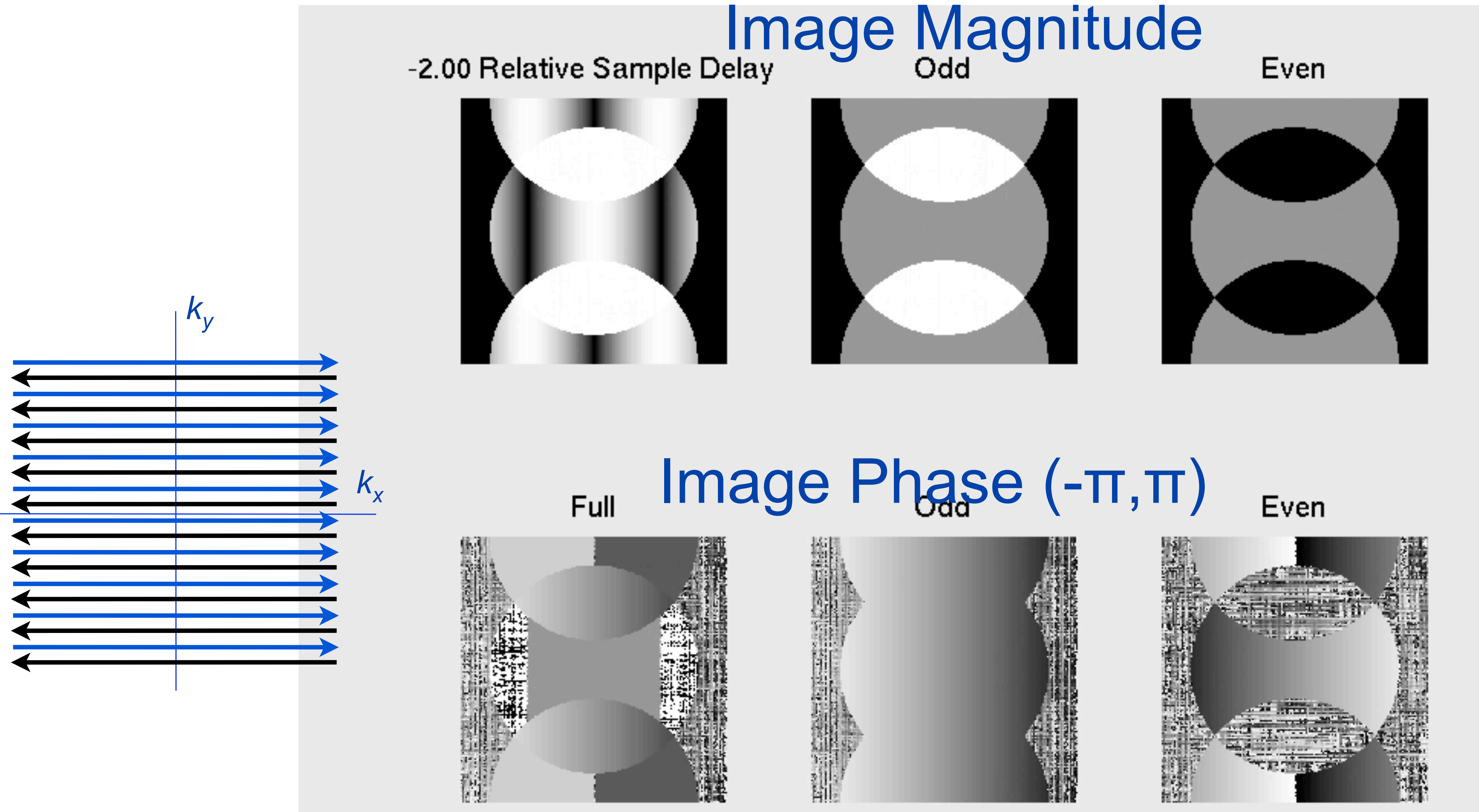
Image Magnitude

Image Phase (-π,π)



(Phase largely due to off-resonance)

SS EPI - k-space Delays



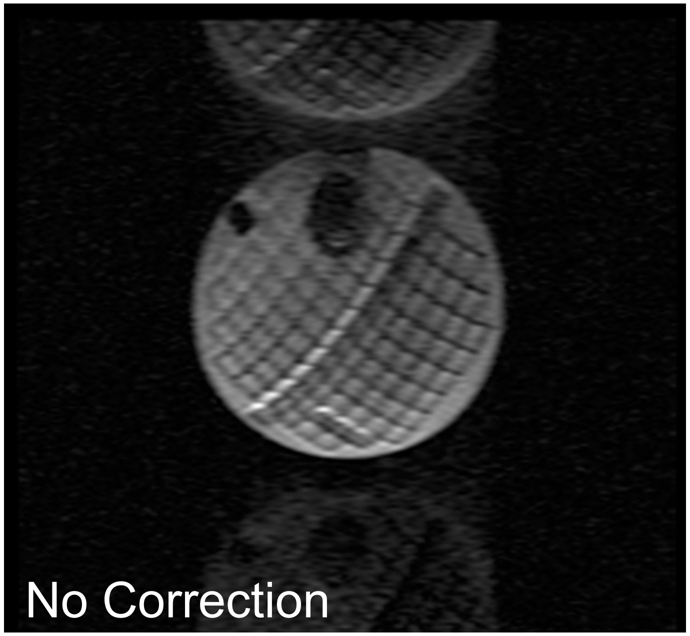
(Gradient delays and Eddy Currents)

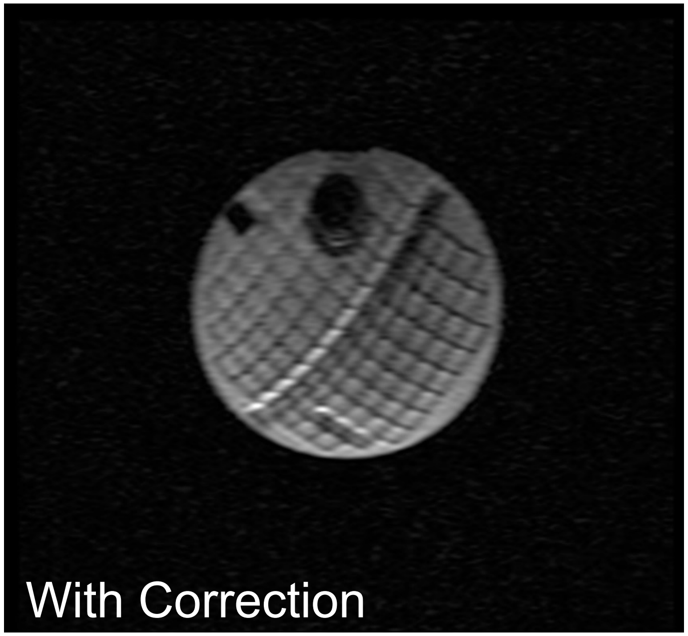
SS EPI: Odd/Even Effects Summary

- Constant phase (image or k-space)
  - coherent ghosts
  - due to eddy currents or sequence imperfections
- Linear phase in k-space
  - component images displaced (high x-freq ghosts)
  - due to off-resonance
- Delays in k-space
  - x-varying ghosts in y
  - due to eddy currents or gradient delays

EPI Phase Correction

- Turn off k_y blips and phase-encodes
- Acquire projections along k_x and FT in x
- Estimate constant and linear phase of each x line
  - Typically both alternate, but early lines may differ as eddy-currents not in steady state.

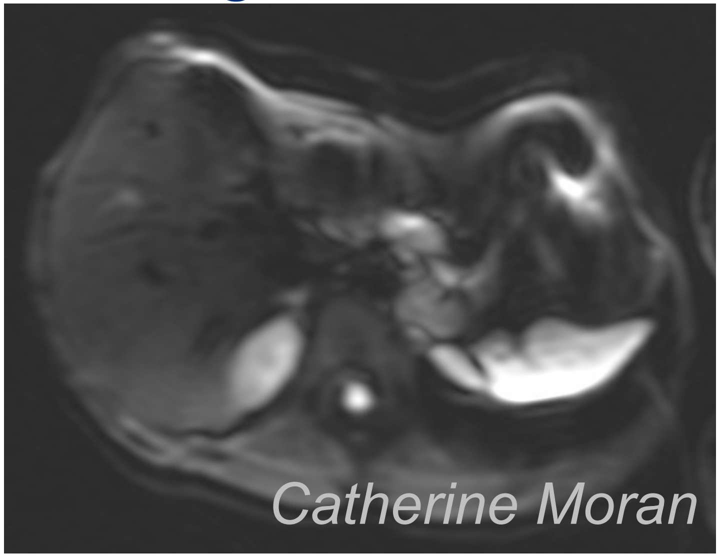




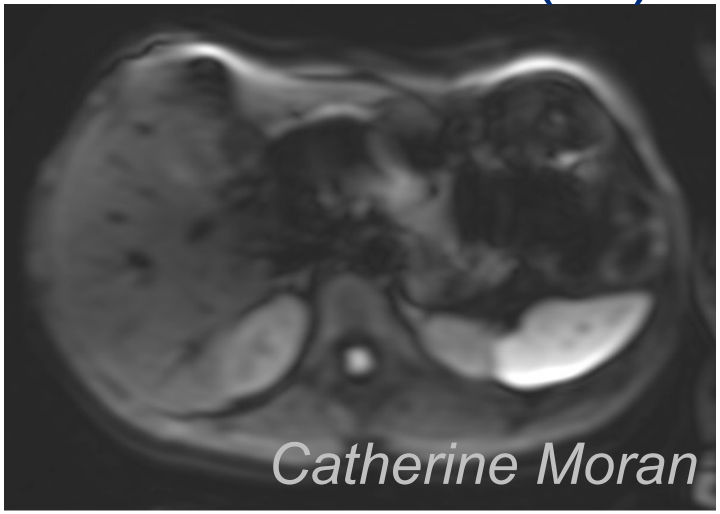
Single-Shot vs Interleaved EPI

- N/2 ghosts vs N/(2$N_{interleaves}$) ghost effects
- Phase correction is very similar
- Interleaved EPI:
  - Reduces sensitivity to T2*, off-resonance
- Single-shot EPI:
  - Faster, reduces sensitivity to motion (especially for DWI)

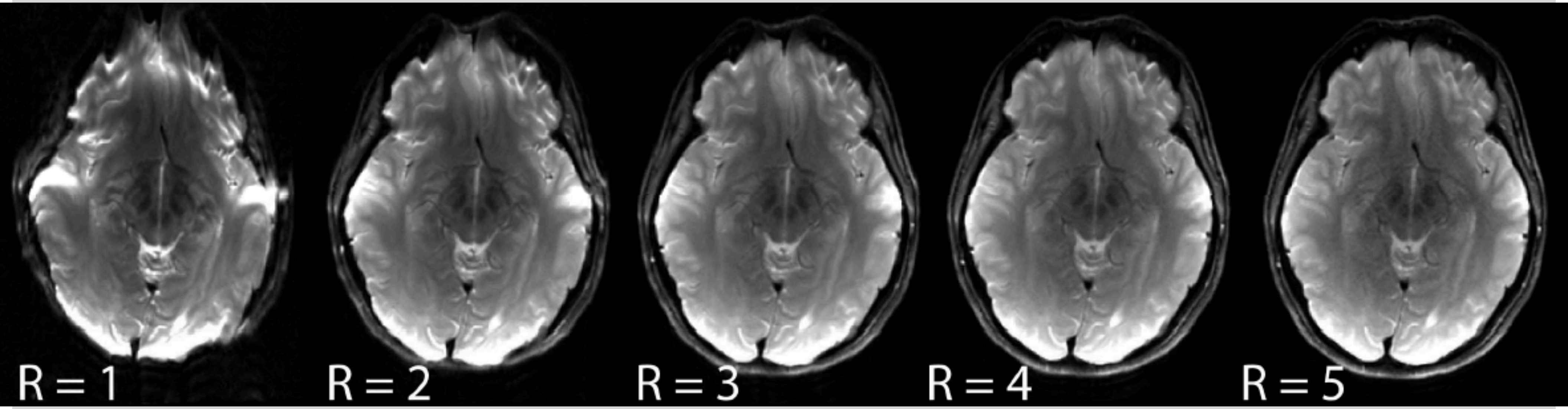
Single-Shot EPI



$N_{interleaves}$ = 2 (PI)



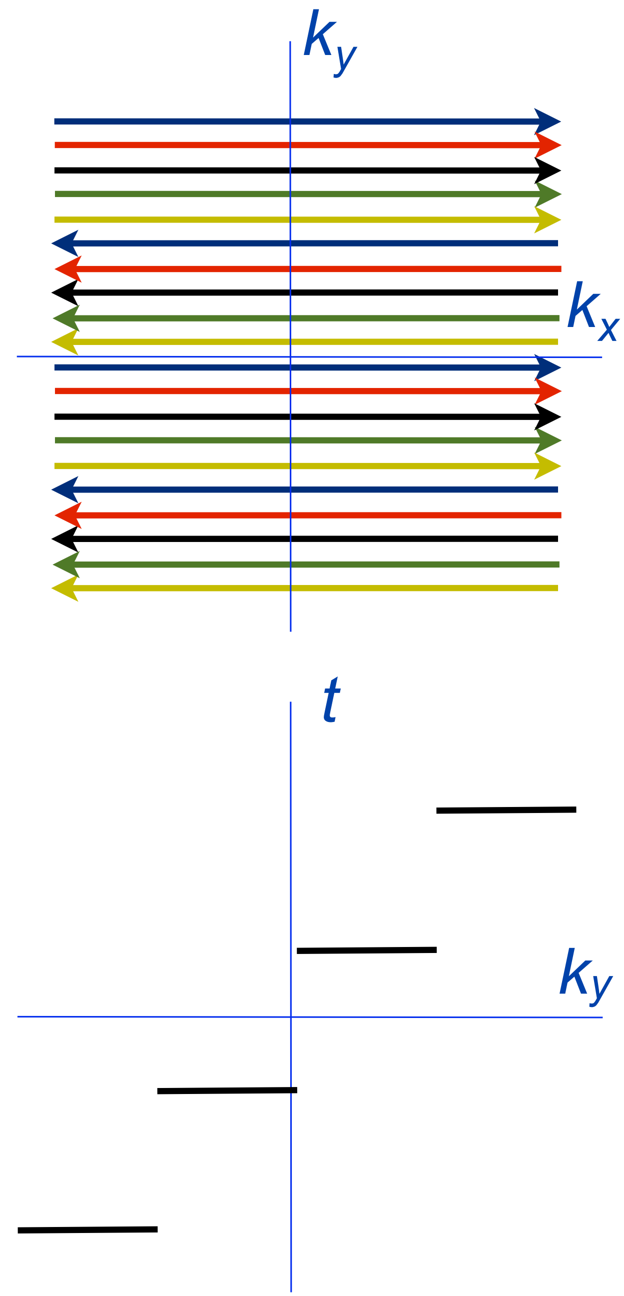
Example of EPI with parallel imaging



(Different parallel imaging acceleration factors. T2-weighted image. Same target resolution. Scan time matched)

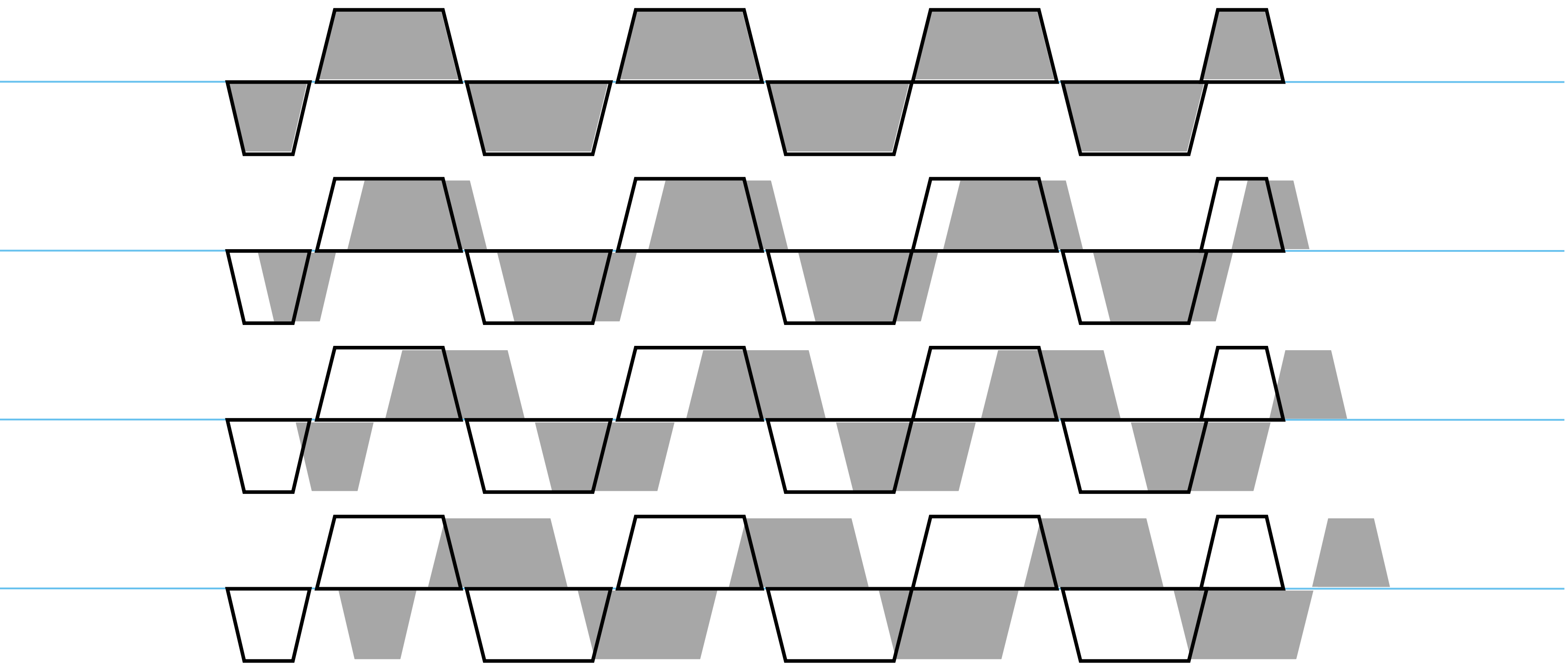
Stair-step Modulation in Interleaved EPI

- Lines in a Segment of k-space all acquired at similar time
- Boundaries have a discontinuity in time, thus amplitude and phase
- What might this cause in the image?



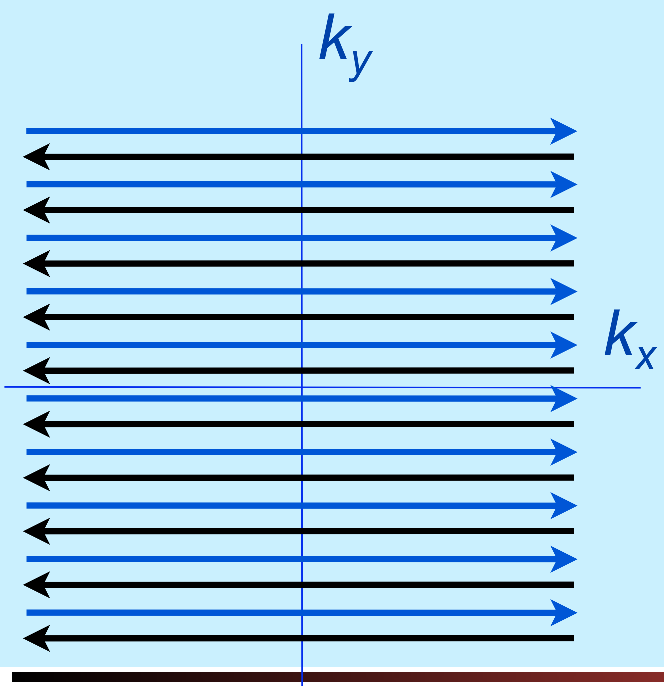
Interleaved EPI: Smoothing Phase

- Time T between echo n and n+1
- Desire smooth $k_y(t)$ overall
- Delay m^{th} interleaf by (m/N)T (N=4 here)



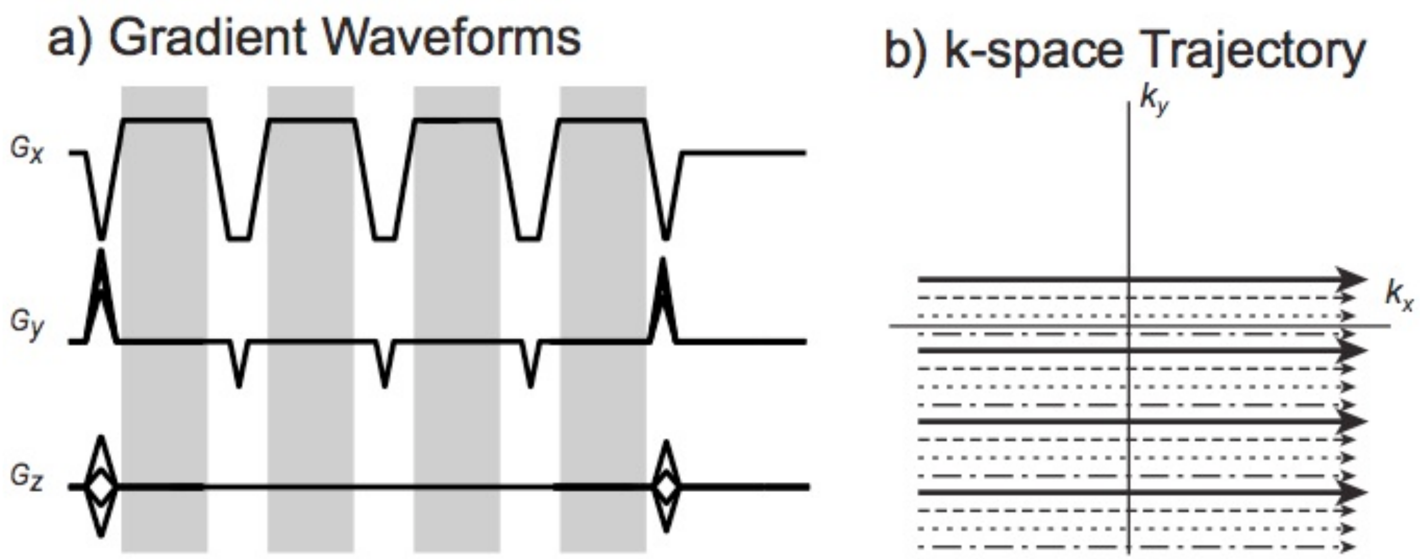
EPI Design Example

- We want to sample a 30cm FOV at 1mm resolution as fast as possible using EPI with less than 1cm displacement between fat and water at 3T



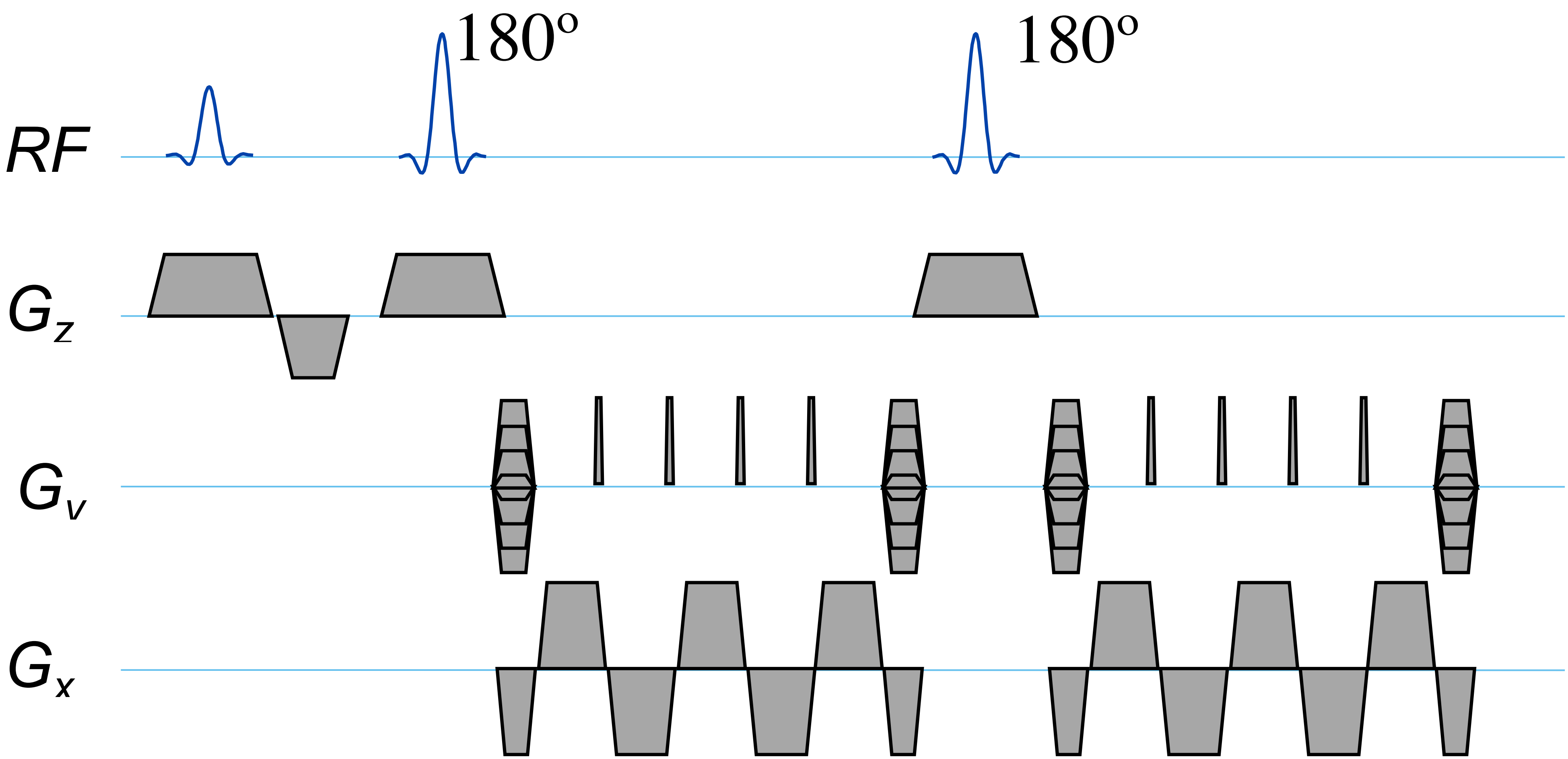
Flyback EPI

- Readout in only one direction
- Completely avoids odd/even line sensitivity
- Slower, but useful when flyback is fast
- Still sensitive to off-resonance



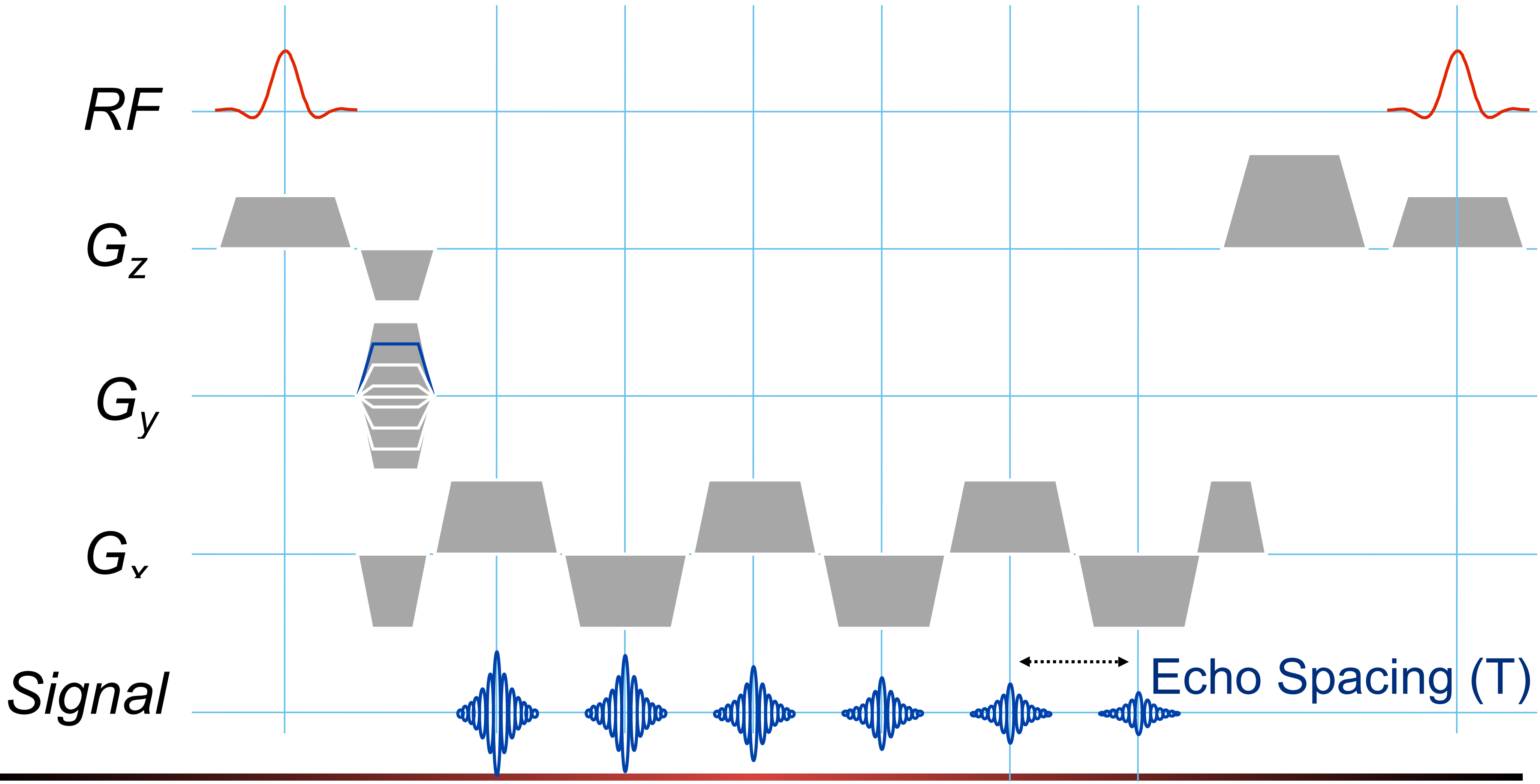
GRASE (Gradient and Spin Echo)

- Helps improve efficiency of spin echo
- Both T2 and T2* modulation! (3D can spread over y and z)



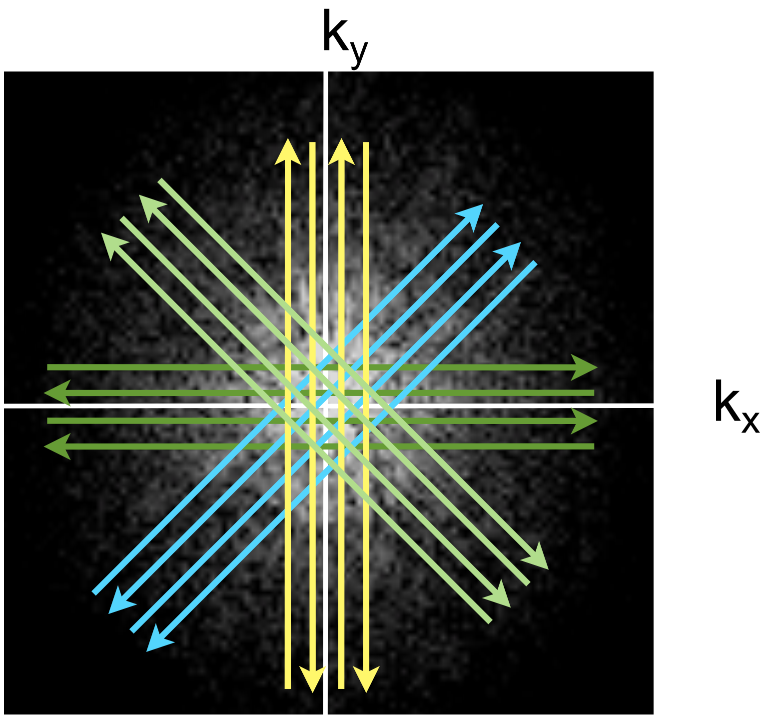
EPSI (Echo-planar Spectroscopic Imaging)

- No k_y blips, or repeat k_y pattern every N echoes
- Spectral FOV of 1/T or 1/(NT)

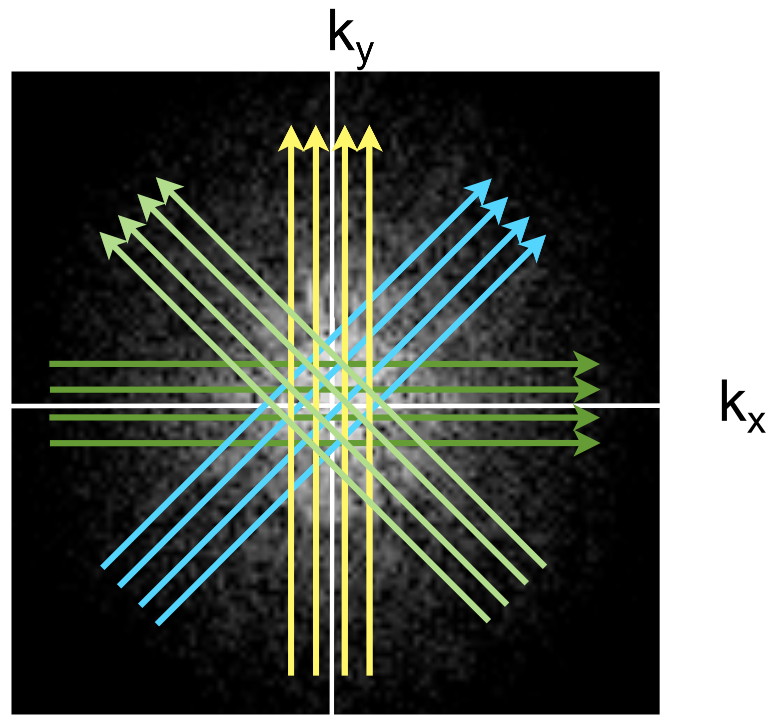


Propellor (EPI or FSE)

- Rotated low-ky-res acquisitions (“blades”)
- Self-navigating (low-res image every blade)
- Individual blades corrected for phase, delays and gridded
- Robust to motion

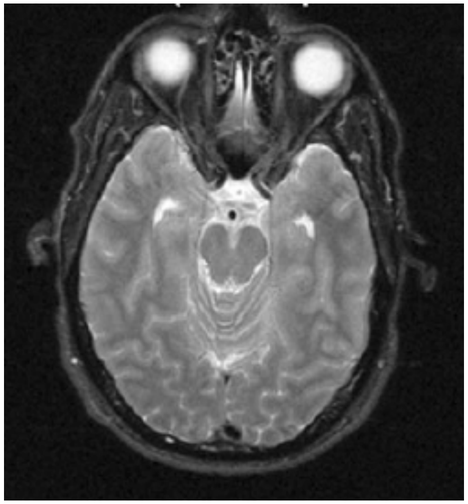


EPI Propellor

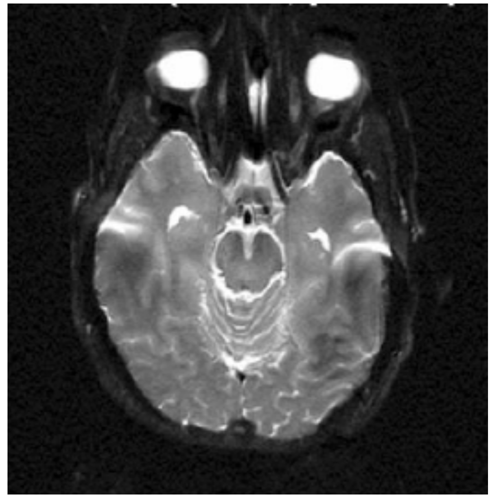


FSE Propellor

Propeller EPI

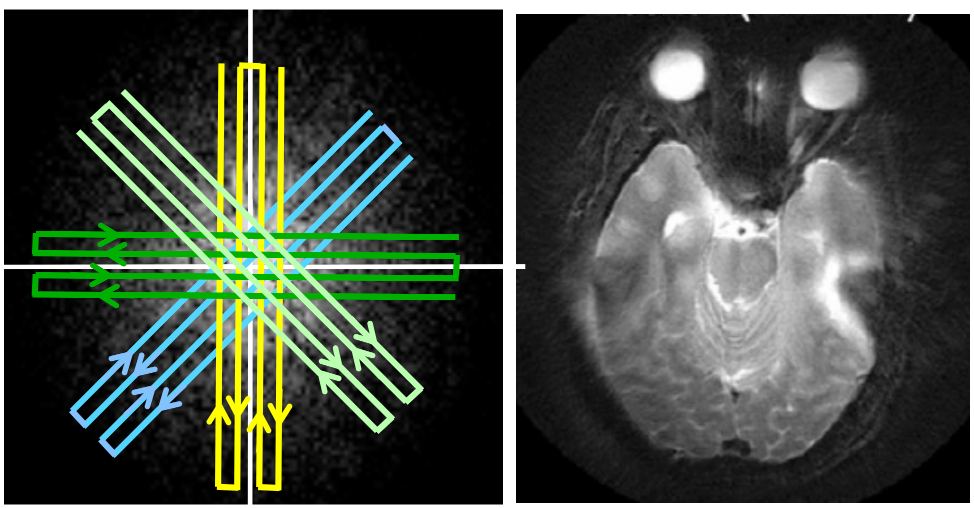


FSE

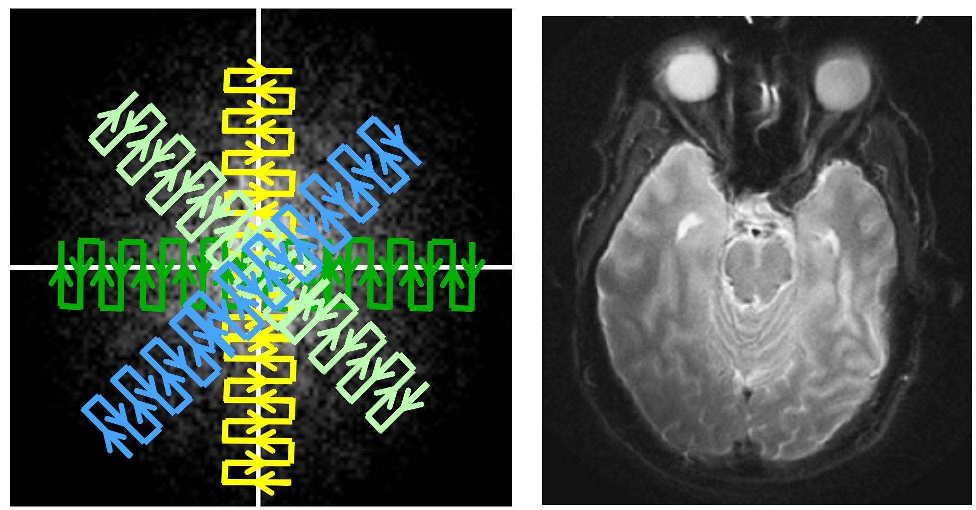


EPI – positive k_y blips

EPI – negative k_y blips



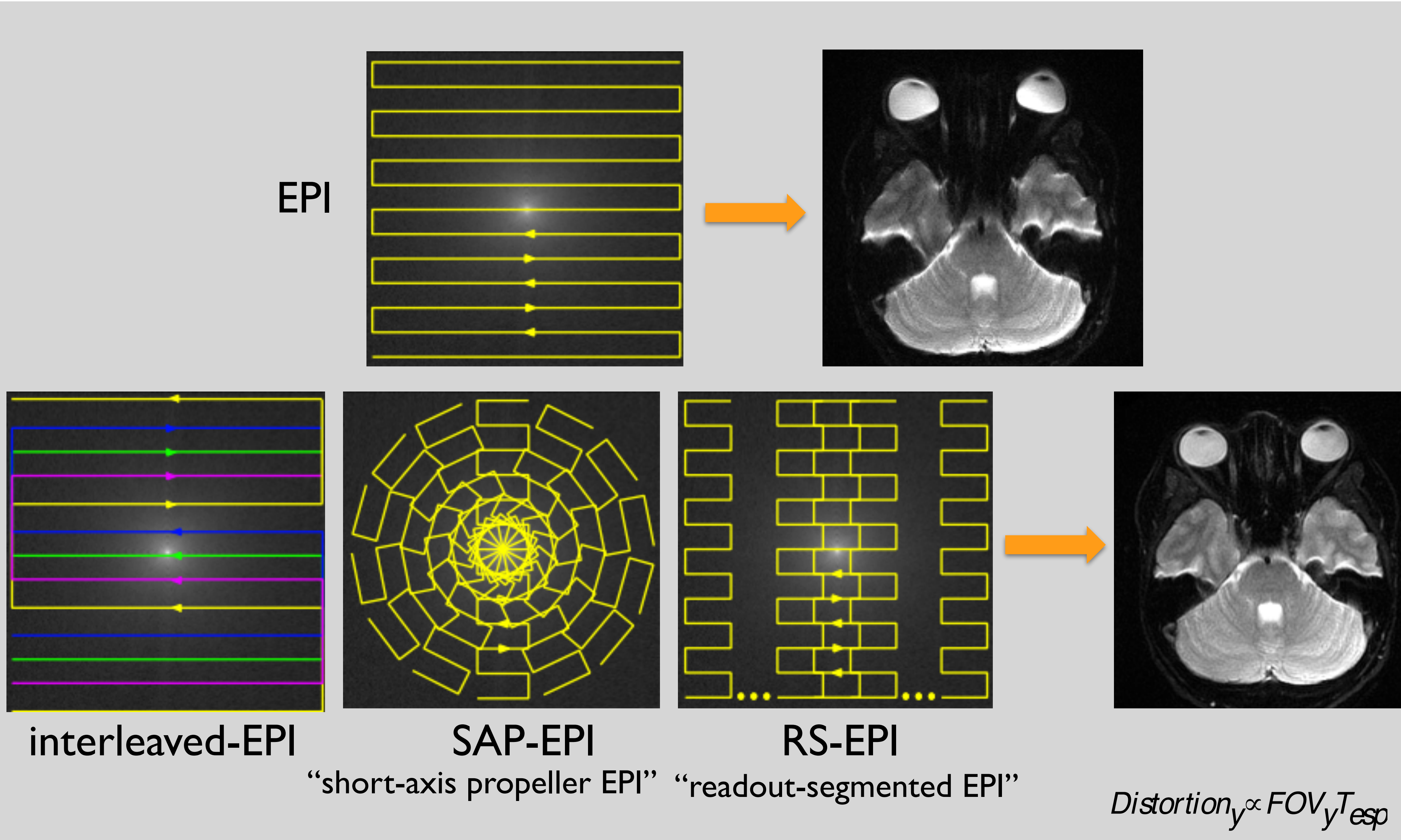
EPI Propeller



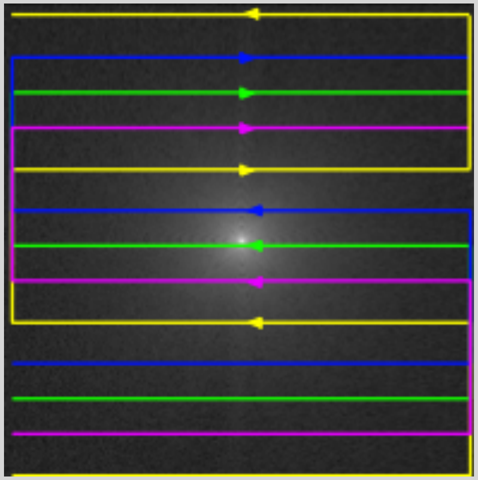
Short-Axis EPI Propeller

Skare et al. MRM (2006)

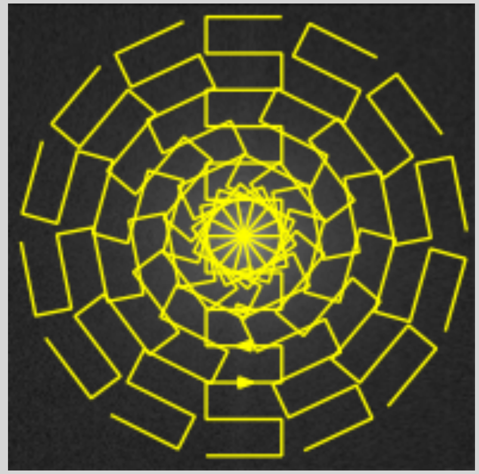
Interleaved EPI and other pseudo-EPI approaches



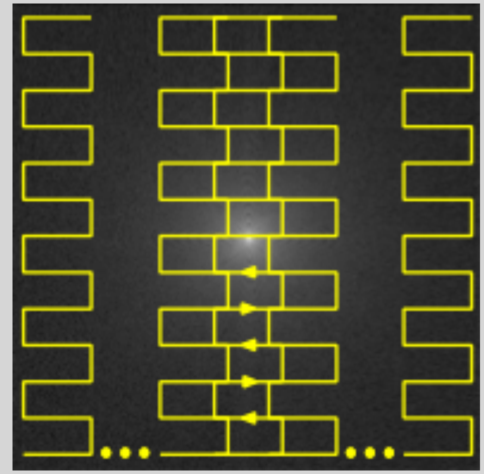
Important differences between interleaved EPI and other pseudo-EPI approaches



interleaved-EPI



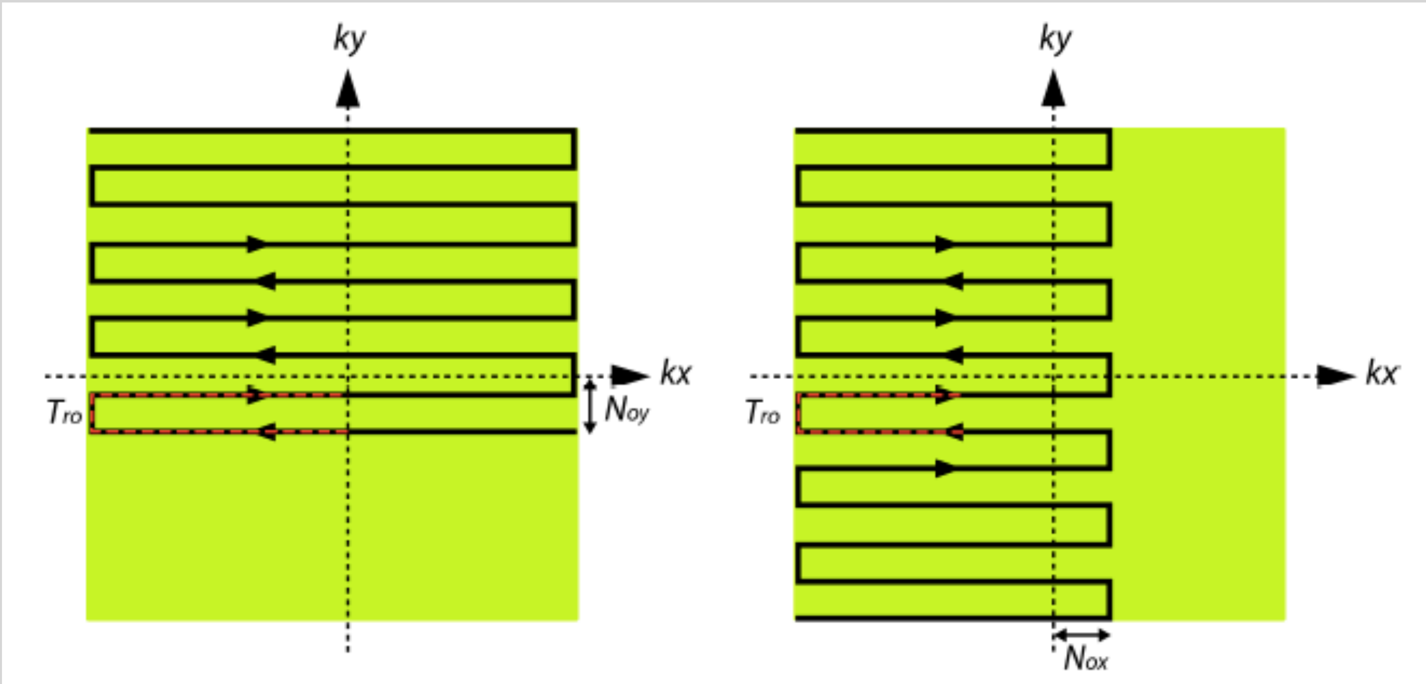
SAP-EPI
"short-axis propeller EPI"



RS-EPI
"readout-segmented EPI"

	Advantages	Disadvantages
Interleaved EPI	*Easier to implement/ reconstruct, not slewing all the time (more efficient)*	*Motion between interleaves causes ghosting – harder to correct*
SAP-EPI and RS-EPI	*Each 'segment' acquired at full FOV -> can correct for motion between segments*	*Slewing a lot. Residual distortion for each "SAP-EPI segment" combines to give overall image blurring.*

Half-Fourier EPI approaches



Half-Fourier in k_y

Compared with full-Fourier:

- Reduced T2* effects
- Reduced minimum TE

(most common)

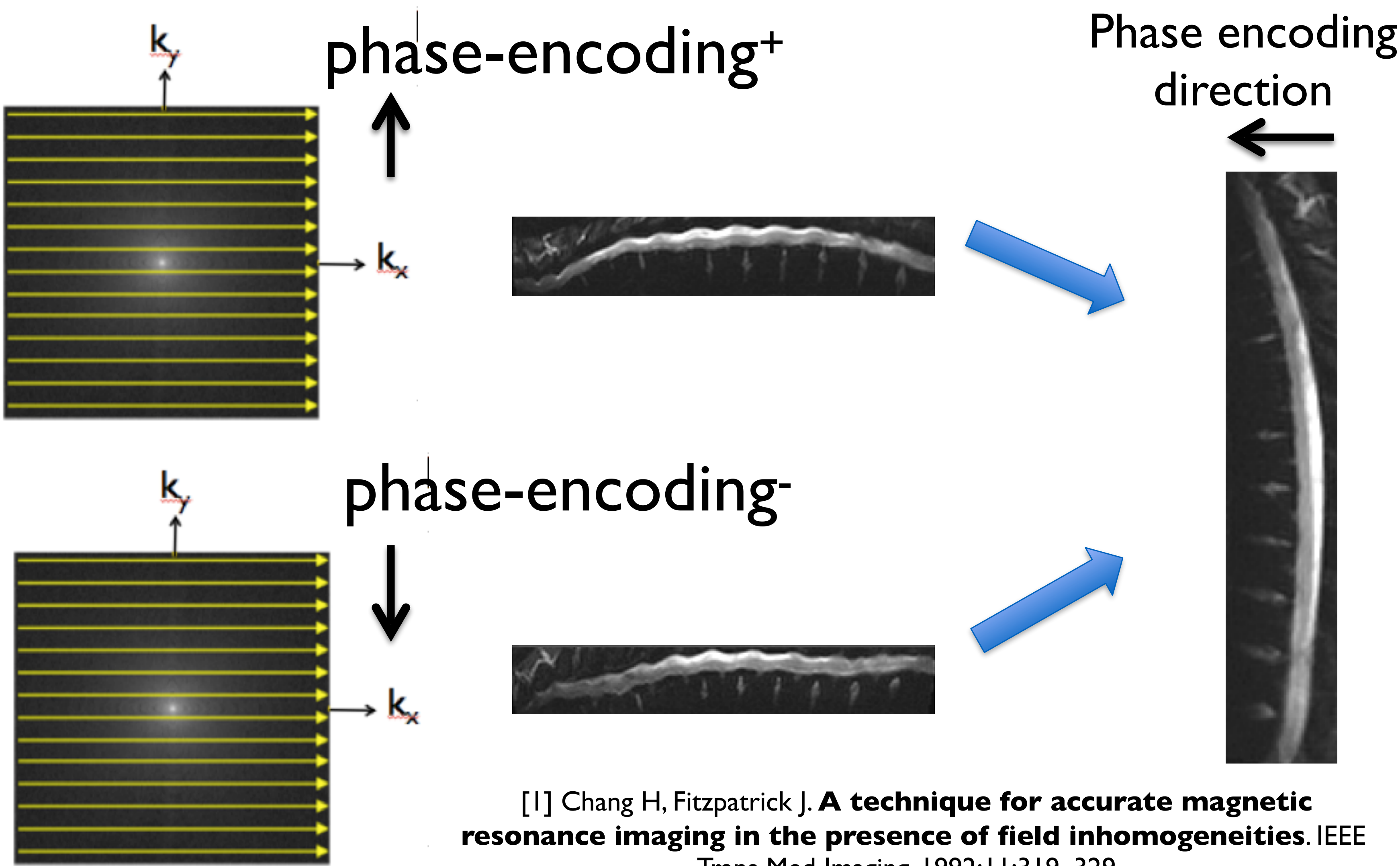
Half-Fourier in k_x

Compared with full-Fourier:

- Reduced distortion
- Slightly reduced T2* effects
- Slightly reduced minimum TE

Other distortion reduction strategies

Reversed Gradient Polarity Method (RGPM[1])



[1] Chang H, Fitzpatrick J. **A technique for accurate magnetic resonance imaging in the presence of field inhomogeneities**. IEEE Trans Med Imaging. 1992;11:319–329. .

EPI Other Considerations

- Readouts: Trapezoid gradients
- Phase encode/Blips: Consider quantization to avoid boundary artifacts
- May sample on ramps
  - Regrid data, slight sensitivity to off-resonance
- Parallel imaging: How to calibrate?
- Partial k_x to reduce echo spacing
- Partial k_y to reduce T2* effects (not off-resonance)
- Off-resonance correction in reconstruction may help

EPI Summary

- Very fast imaging trajectory
- Single-shot, Interleaved or Segmented
- Bidirectional EPI requires phase correction
- Sensitive to T2* and Off-resonance (blur and distortion)
- Much more widely used than spiral (currently)
- Variations: Flyback, GRASE, Propellor