Fast Imaging Trajectories: EPI and PROPELLER

M229 Advanced Topics in MRI

Holden H. Wu, Ph.D.

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UCLA

Department of Radiological Sciences
David Geffen School of Medicine at UCLA

Class Business

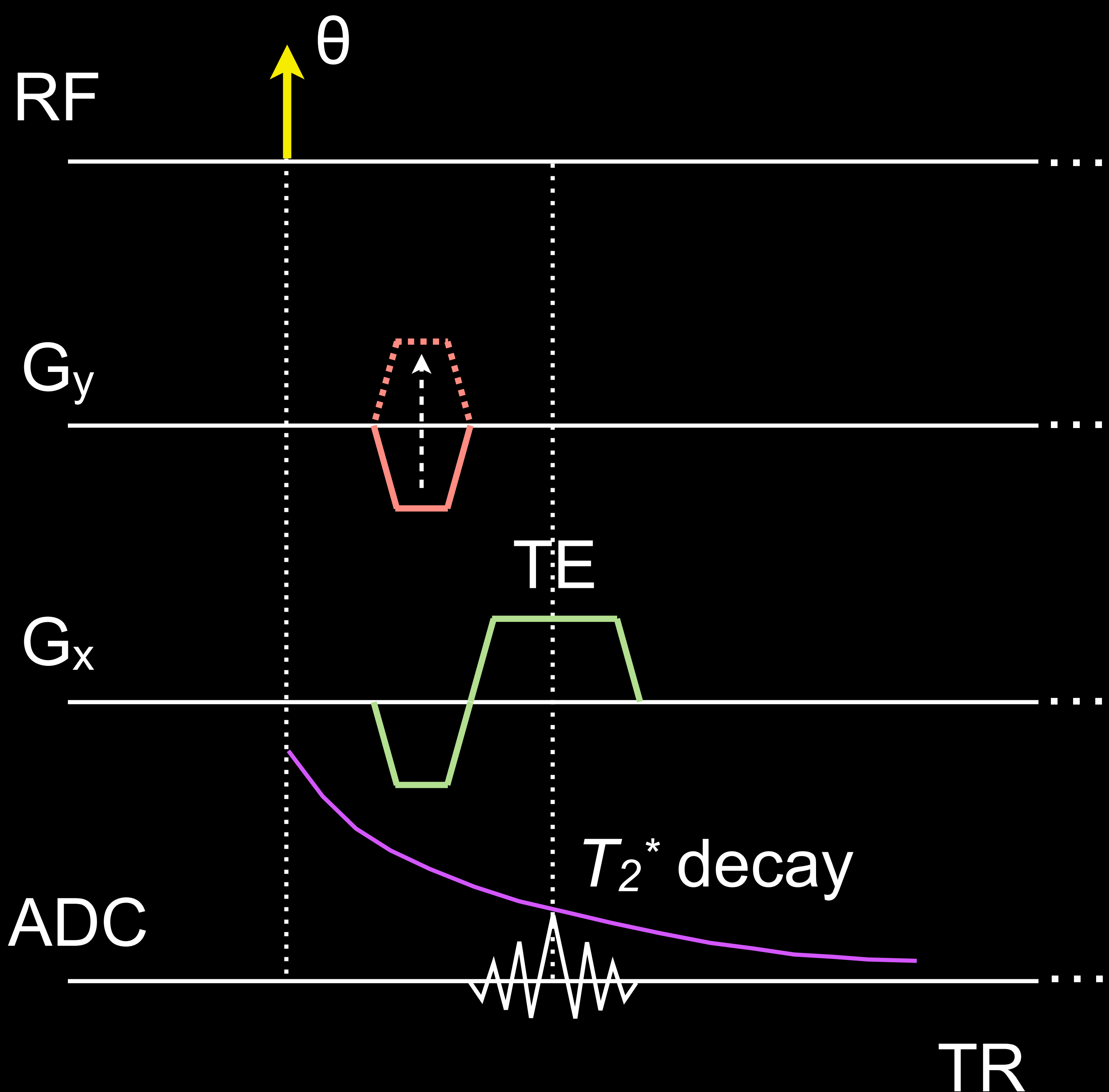
- Office hours
- Homework 1 being graded
- Homework 2 due 4/29 Mon by 5 pm
- Final project
  - Proposal due 5/10 Fri by 5 pm
  - Abstract due 6/7 Fri by 5 pm
  - Presentations and Q&A on 6/11 Tue 10-12

Outline

- EPI[1]
  - Pulse sequence and design considerations
  - Alternatives
  - Artifacts and corrections
- PROPELLER[2]
  - Applications

[1]Mansfield P, J Phys C: Solid State Phys., 1977
[2]Pipe JG, Magn. Reson. Med., 1999

Gradient Echo



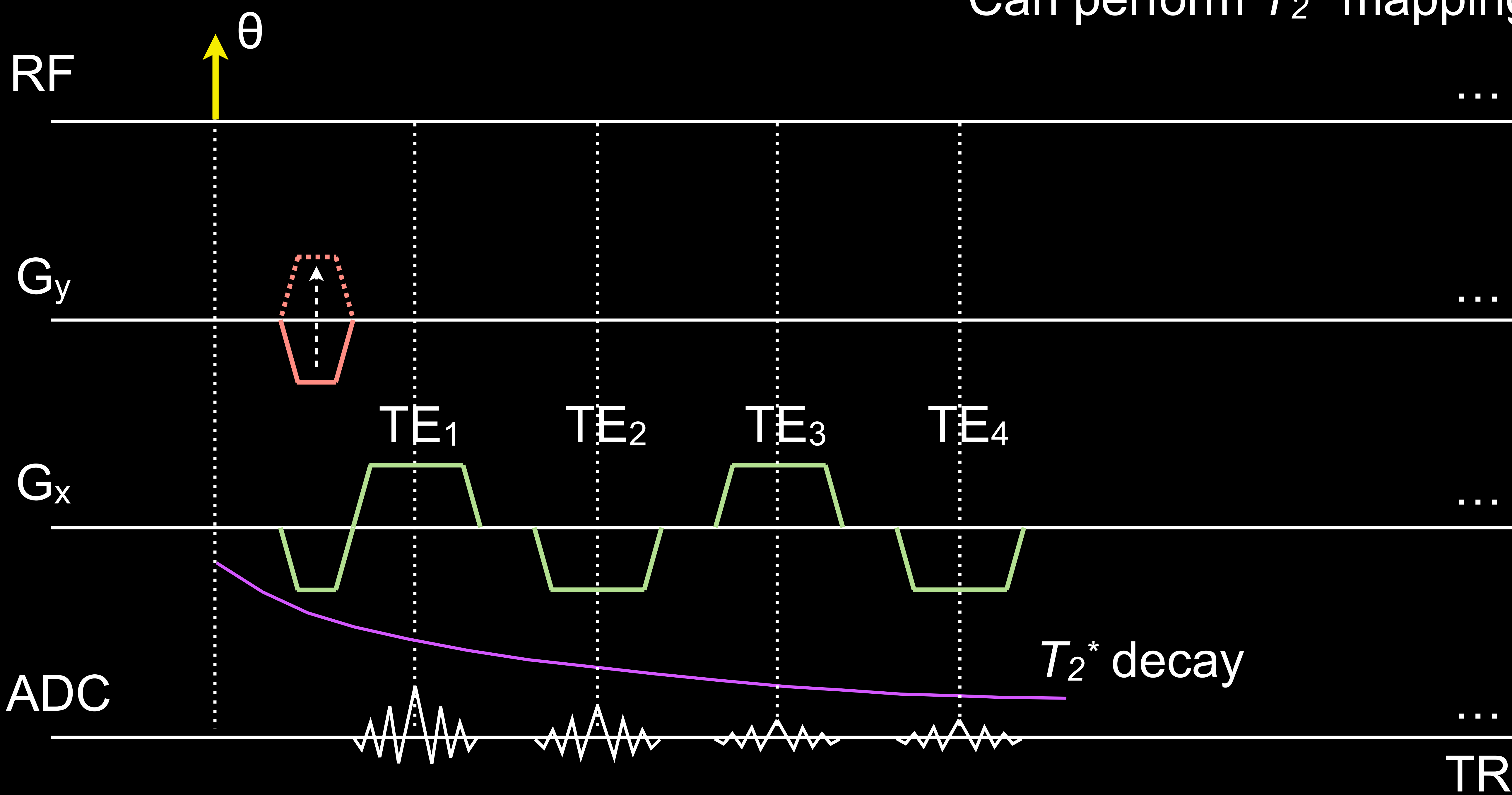
- Utilization of transverse magnetization
  - With T_s = 8 μs and N_x = 128, T_{acq} = 1.024 ms
  - <2% of T_2^* in brain at 3 T![1]
- Scan time
  - $T_{GRE} = N_{pe} \times TR$
  - TR = 10 ms, N_{pe} = 256: T_{GRE} = 2.56 sec

[1]*Peters, et al., Proc ISMRM 2006*

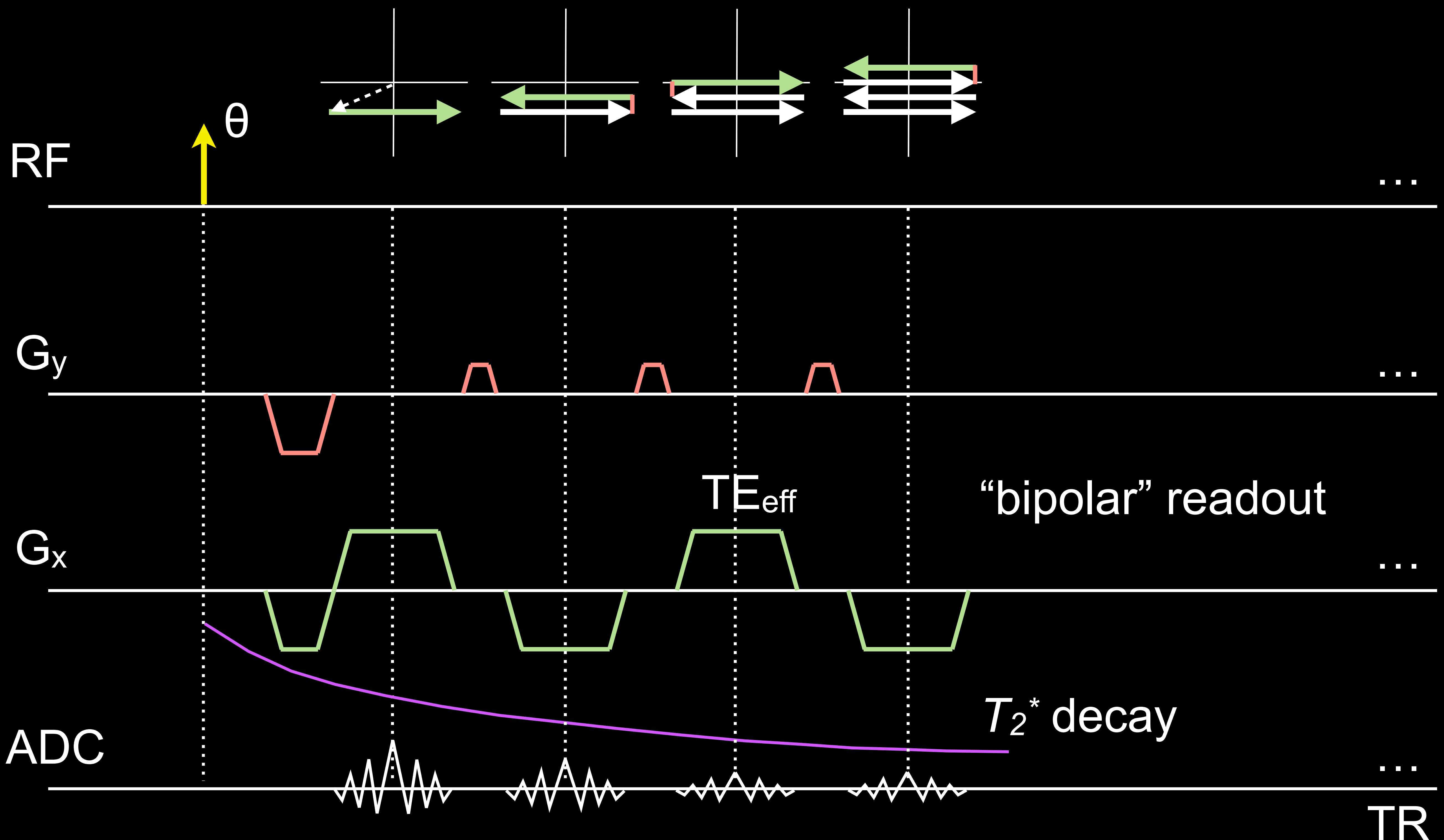
Multi-echo Gradient Echo

ΔTE can be non-uniform

Can perform T_2* mapping



Gradient-Echo EPI



Design Basics

- What species are you imaging?
  - T_2, T_2^*?
  - Utilize transverse magnetization efficiently by sampling up to, e.g., $2 \times T_2^*$ (100 ms) → *Readout gradient duration in EPI*
  - Total readout durations of up to 100 ms

readout points (N_x)

Field of view (FOV_x)

phase-encoding lines (N_y)

Readout Gradient Duration

Maximum gradient strength (G_{max})

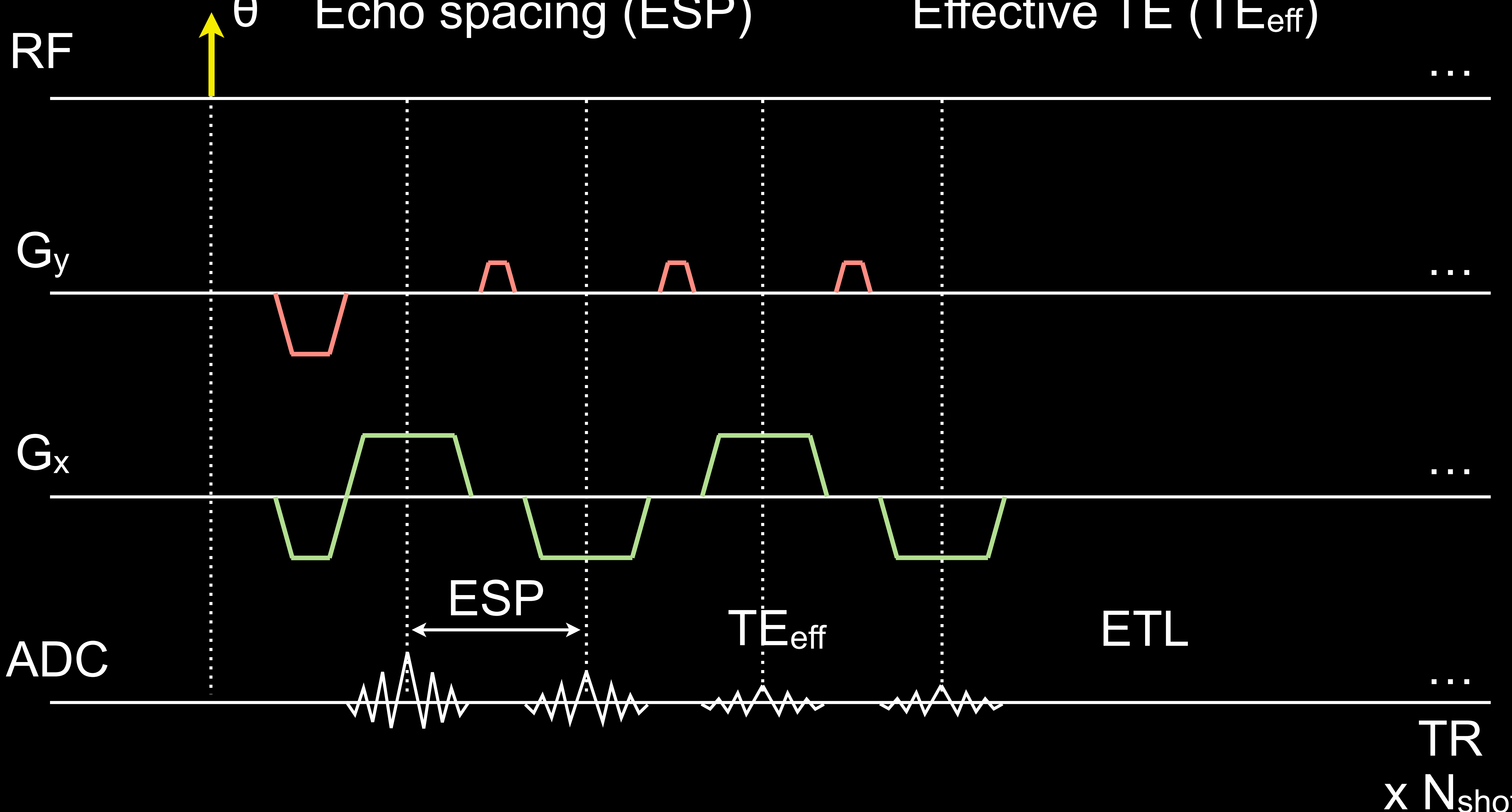
Readout bandwidth (BW)

Maximum gradient slew rate (S_{max})

EPI Sequence Parameters

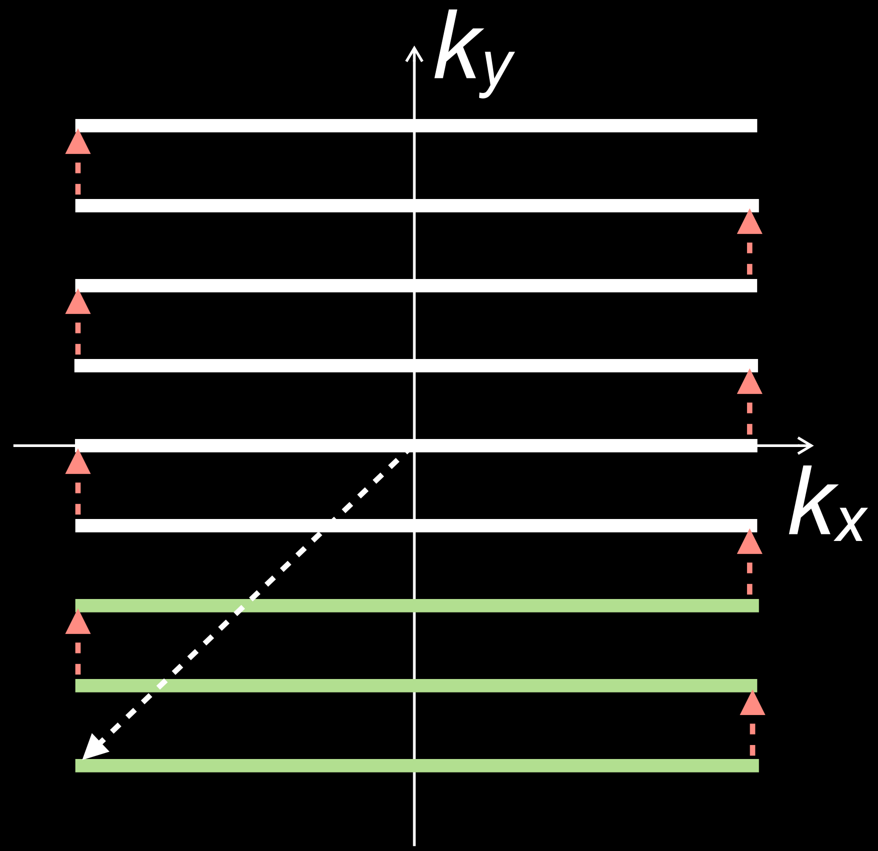
Echo train length (ETL) Number of shots (N_{shot})

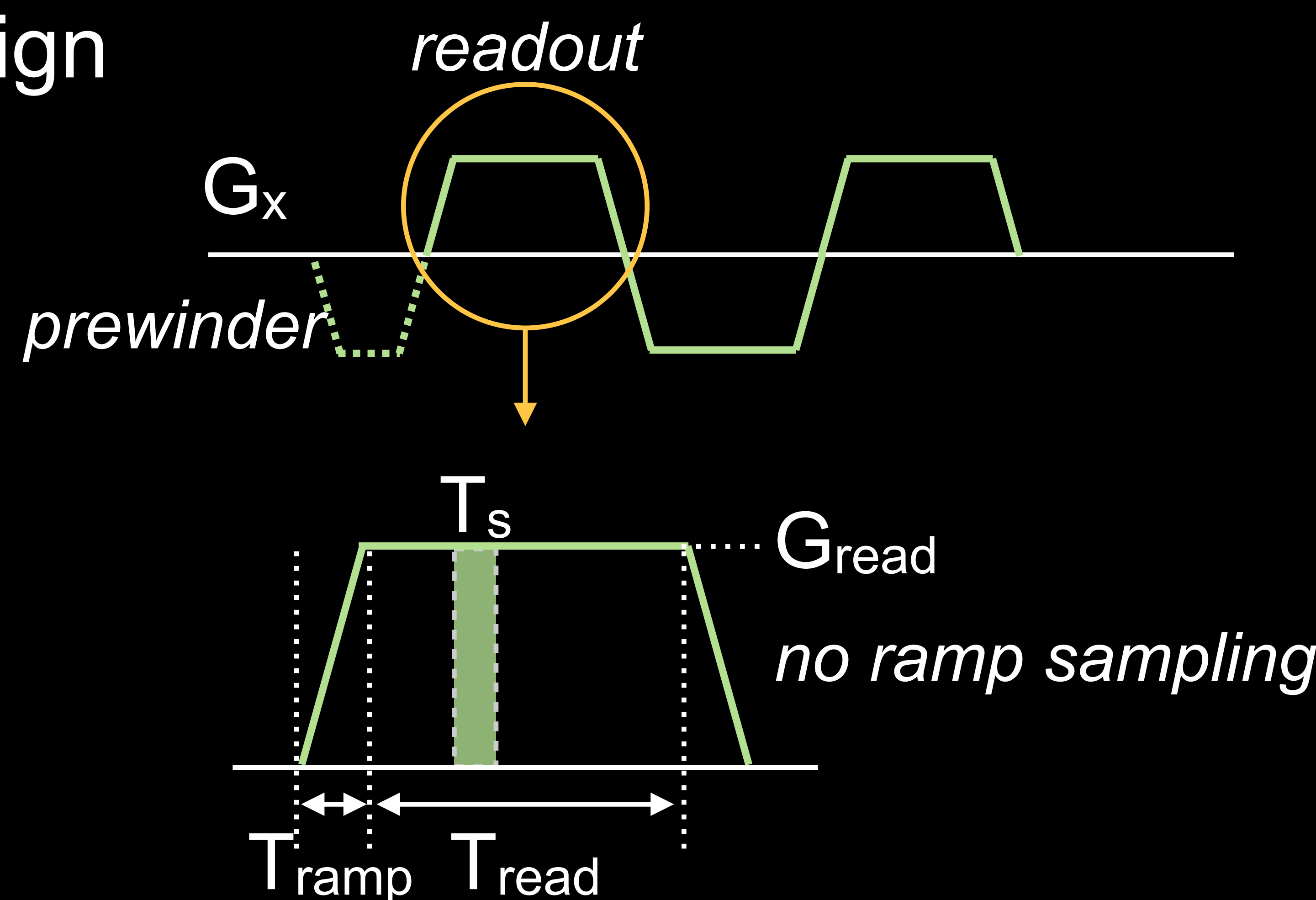
Echo spacing (ESP) Effective TE (TE_{eff})



EPI Sequence Parameters

Readout Gradient Design





$(\gamma/2\pi)\cdot G_{read}\cdot T_s = \Delta k_x \leq 1/FOV_x$

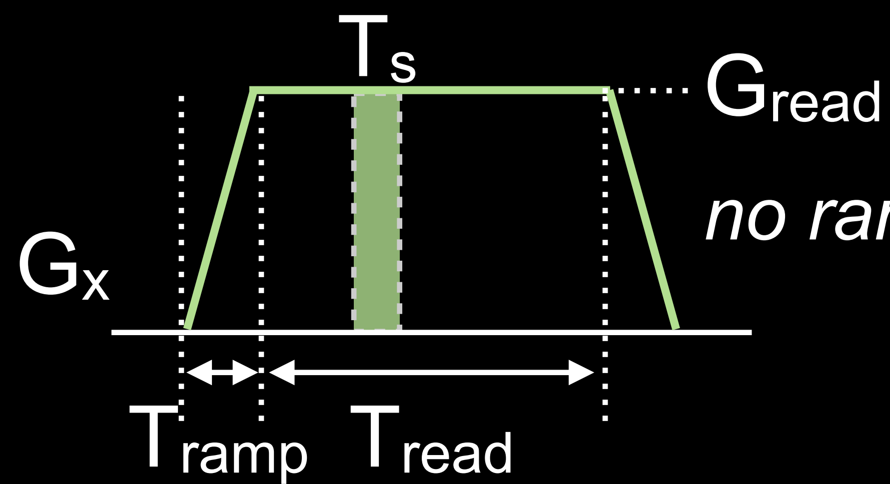
$G_{read} \leq G_{max}$ $\quad$ $SR \leq S_{max}$

$T_{read} = T_s \cdot N_x$ $\quad$ $T_{ramp} = G_{read}/SR$

$ESP \geq T_{read} + 2\cdot T_{ramp}$

EPI Sequence Parameters

Readout Gradient Design Example:



no ramp sampling

$(\gamma/2\pi)\cdot G_{read}\cdot T_s = 1/FOV_x$

$ESP = (T_s \cdot N_x) + 2\cdot(G_{read}/SR)$

$T_s = 8\ \mu s$; $N_x = 128$;
$FOV_x = 22$ cm; SR = 120 T/m/s

$G_{read} = 13.3$ mT/m

ESP = 1.246 ms

If $T_s = 4\ \mu s$

ESP = 0.955 ms

If $T_s = 8\ \mu s$ and SR = 20 T/m/s

ESP = 2.354 ms

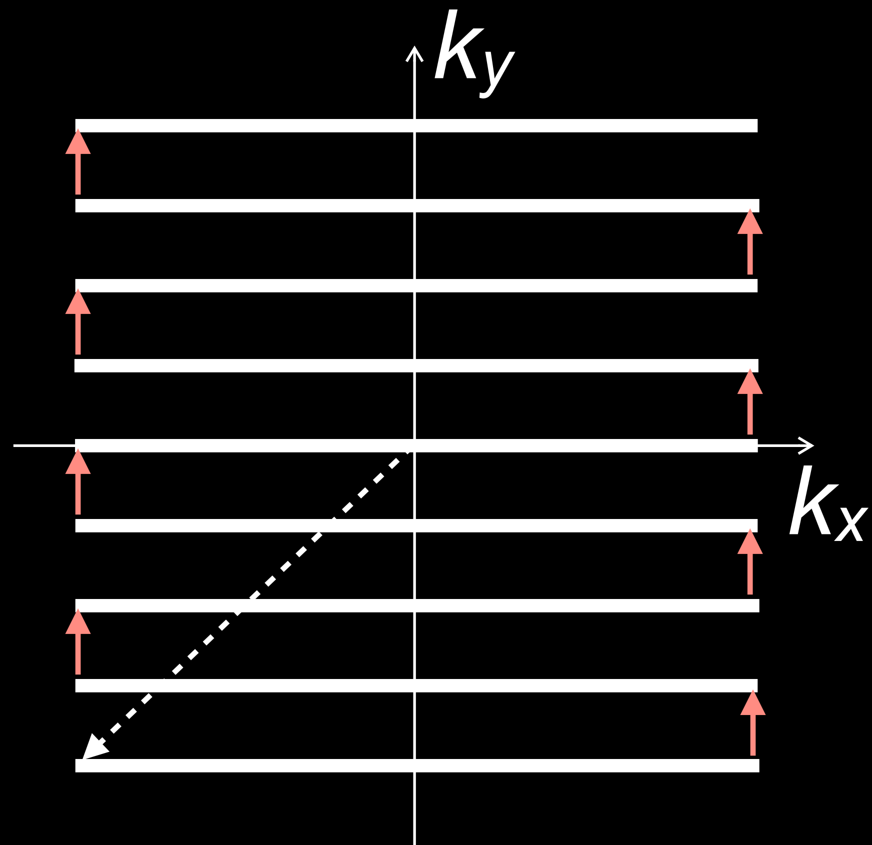
If $T_s = 4\ \mu s$ and SR = 20 T/m/s

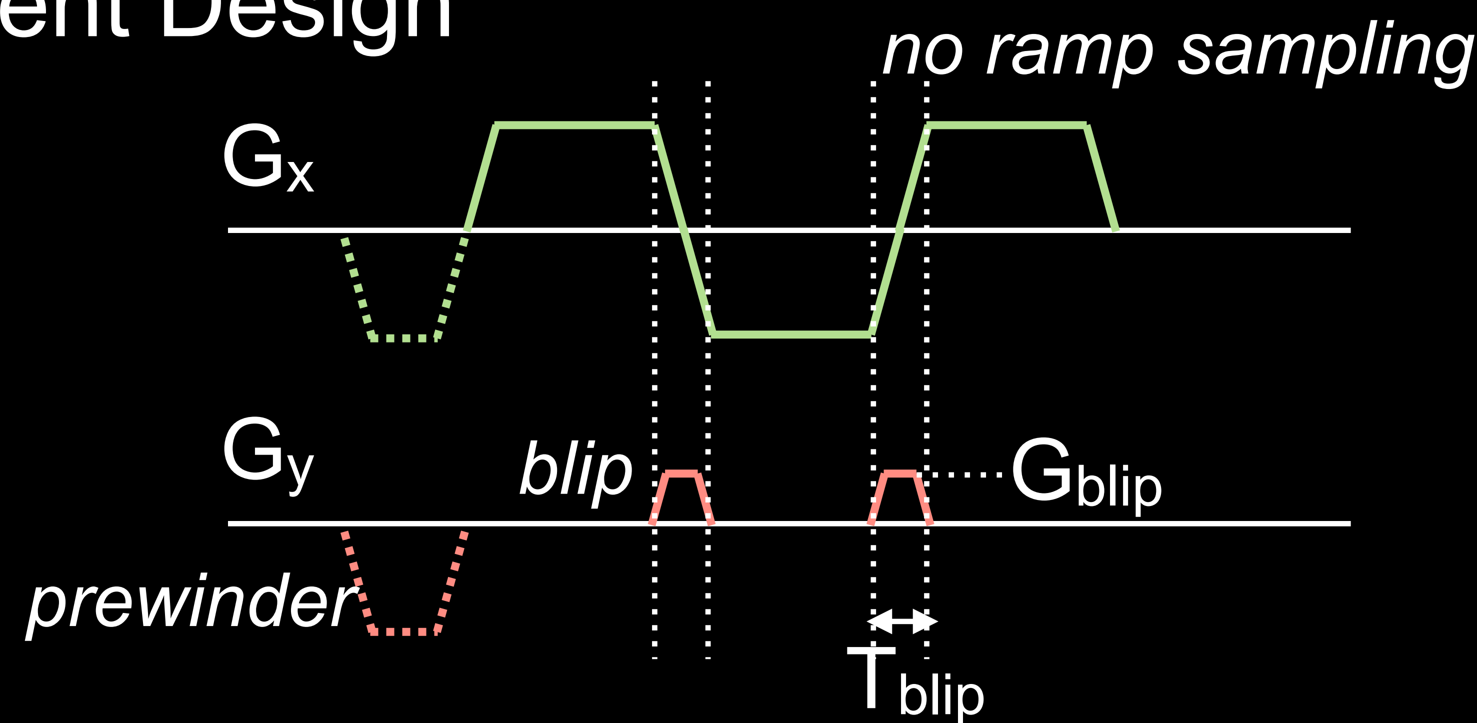
ESP = 3.172 ms

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.1

EPI Sequence Parameters

Phase Encoding Gradient Design





$$(\gamma/2\pi)\cdot\text{Area}(G_{blip}, T_{blip}) = \Delta k_y \le 1/FOV_y$$

Phase Encoding Bandwidth

PEbw = 1/ESP ~ 1 kHz; more off-resonance artifacts

cf. *RObw* up to 500 kHz (T_s = 2 μs)

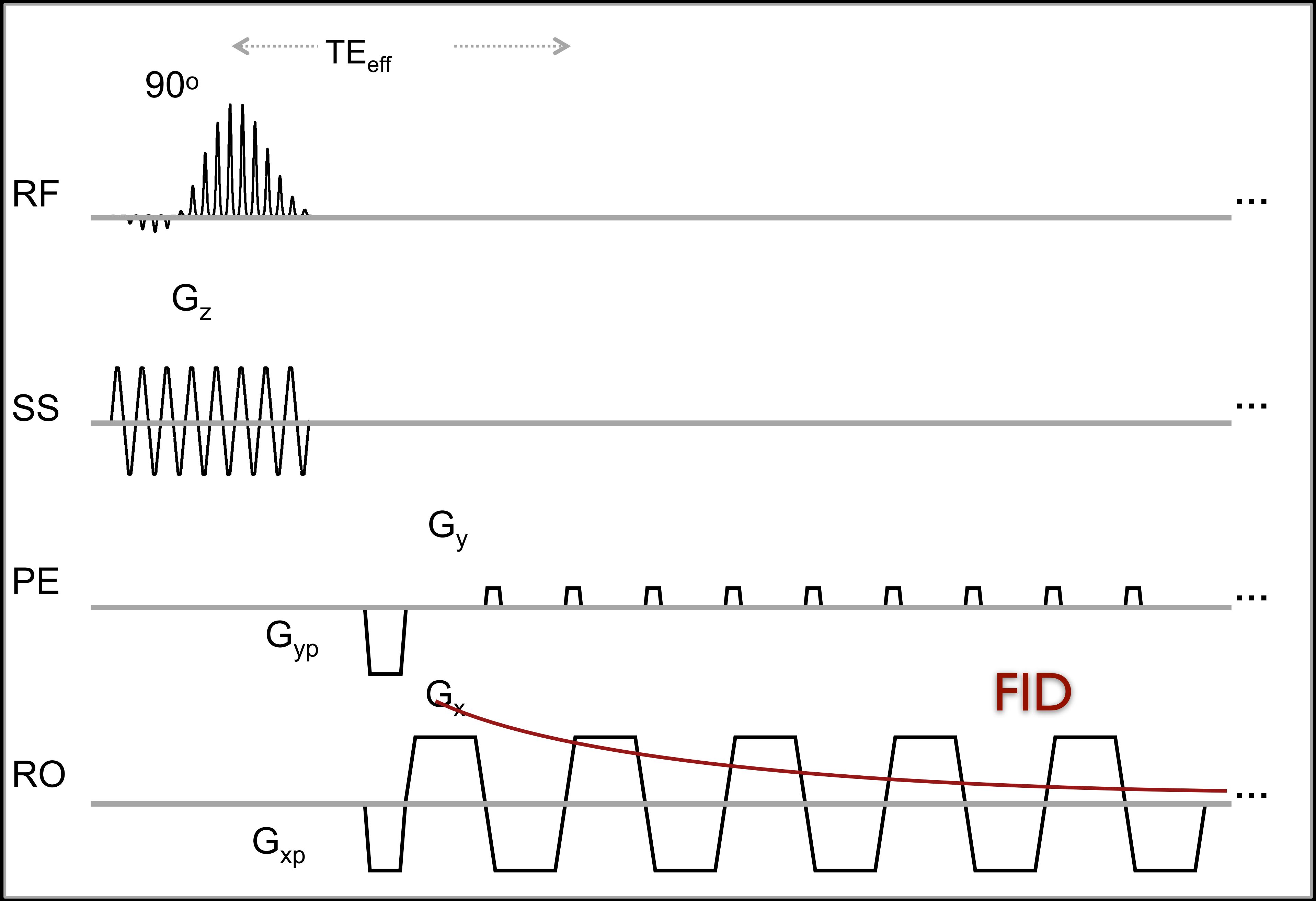
EPI Sequence Parameters

- ETL can be 4-64 or higher
  - Limited by T_2* decay, off-resonance effects
  - aka "EPI factor"
- ESP typically ~1 ms
  - Must accommodate gradients and ADC
  - Short ESP facilitates high ETL
- ***Example:*** readout until $S = 0.2\ S_0$
  - $S = S_0 * \exp(-t/T_2^*)$; assume $T_2^* = 60$ ms
  - $t = 96.6$ ms
  - ESP = 1 ms; ETL = 96

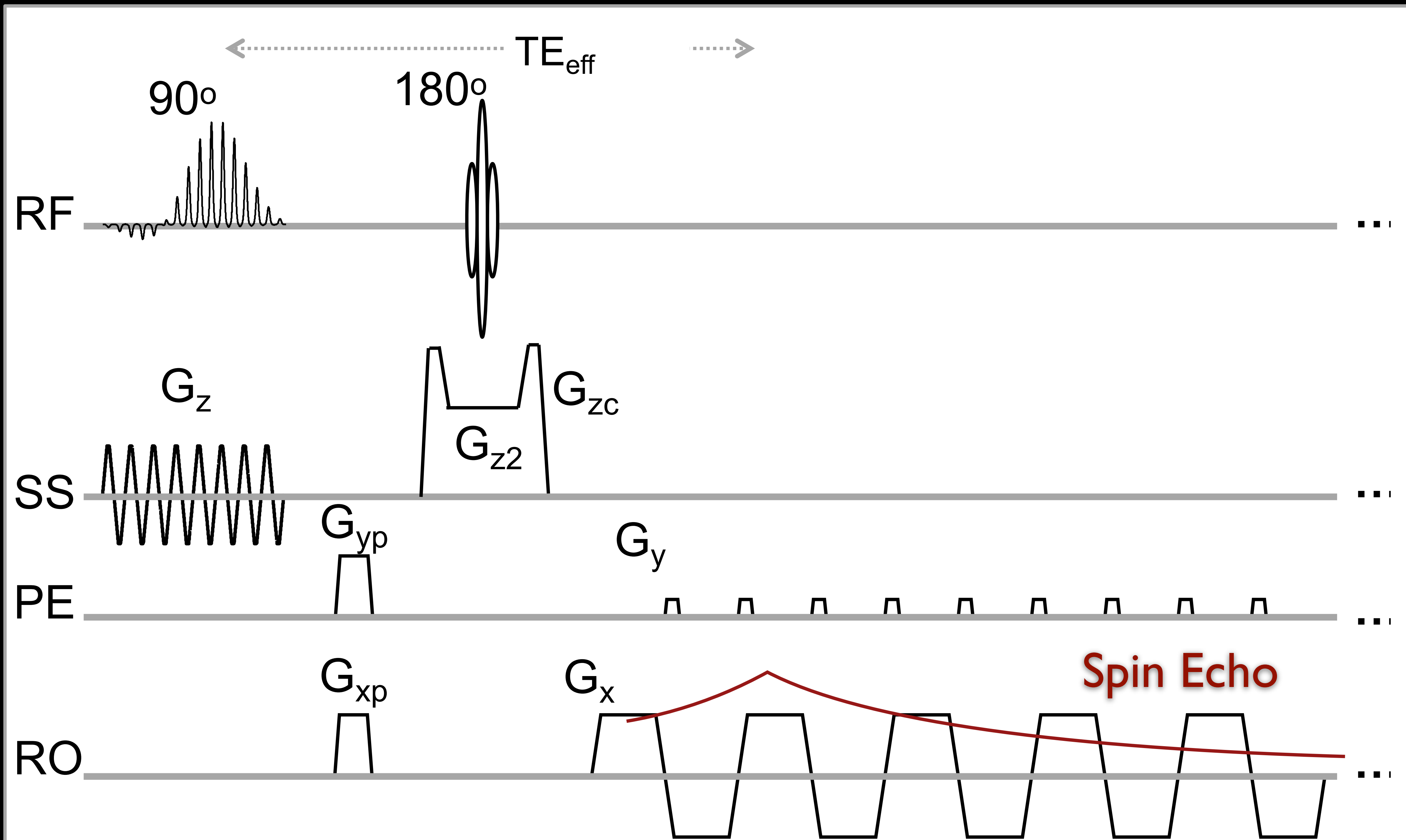
Minimizing Readout Duration / ESP

- Higher gradient amplitudes and slew rates
- Higher readout bandwidths
- Sampling along the ramps
- Partial k-space acquisition
  - in x: “partial Fourier” < 1
  - in y: phase FOV can be < 1
- Parallel imaging
- Inner volume imaging

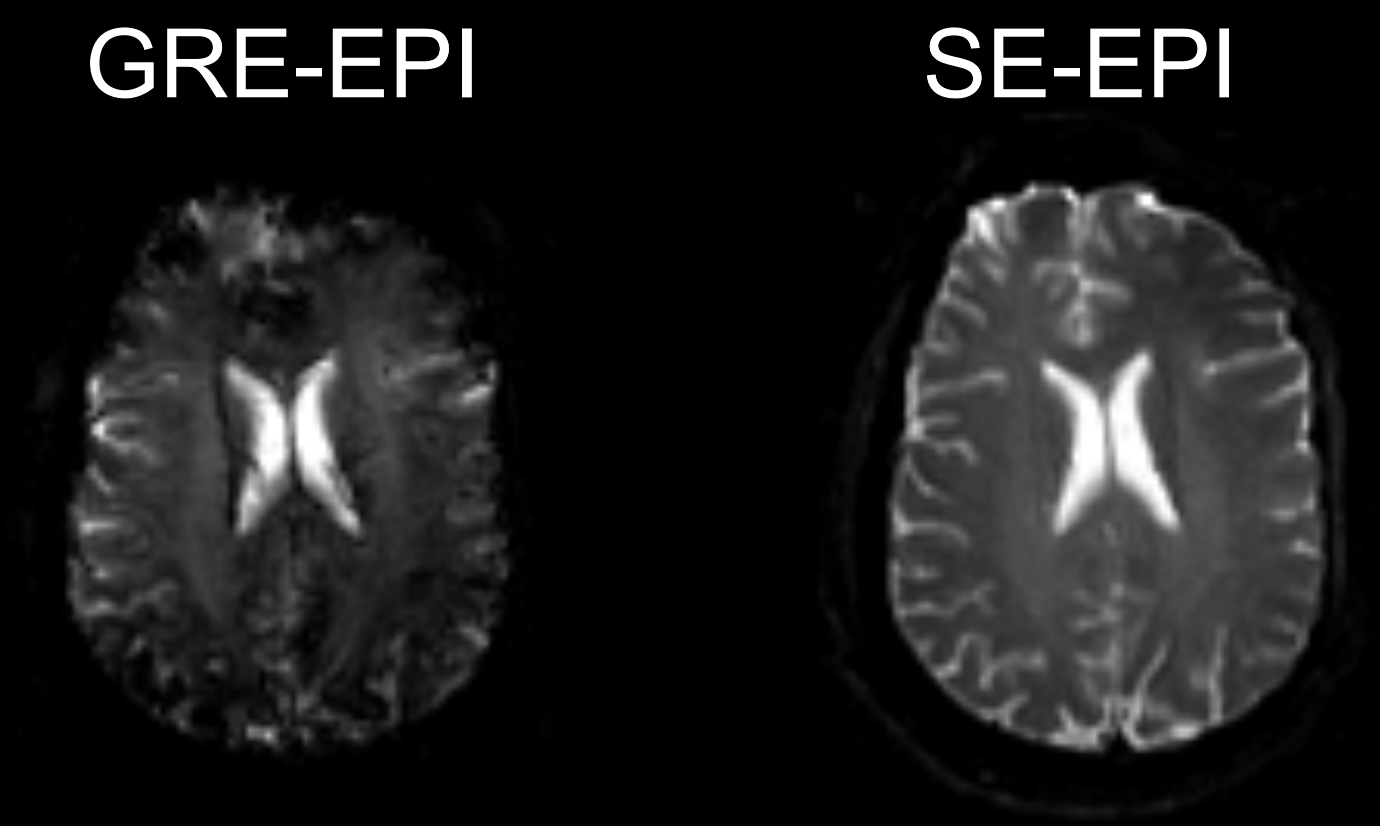
Gradient-Echo EPI



Spin-Echo EPI



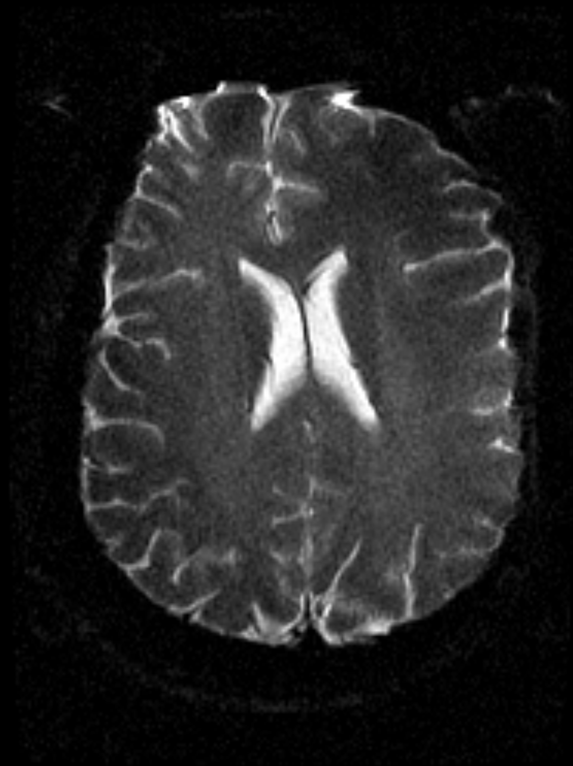
Comparison



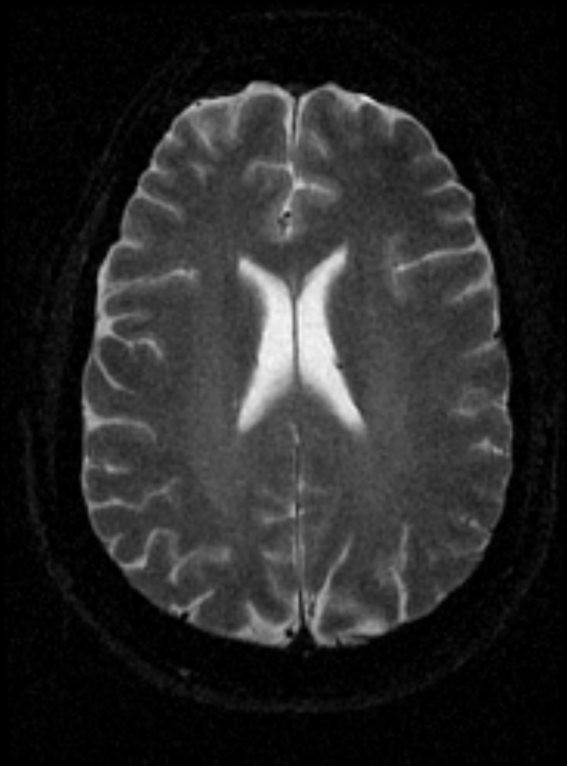
- GRE-EPI More signal dropouts, distortion
- GRE-EPI: More susceptibility effects, better for functional MRI acquisition

Managing EPI distortion

SE-EPI



???

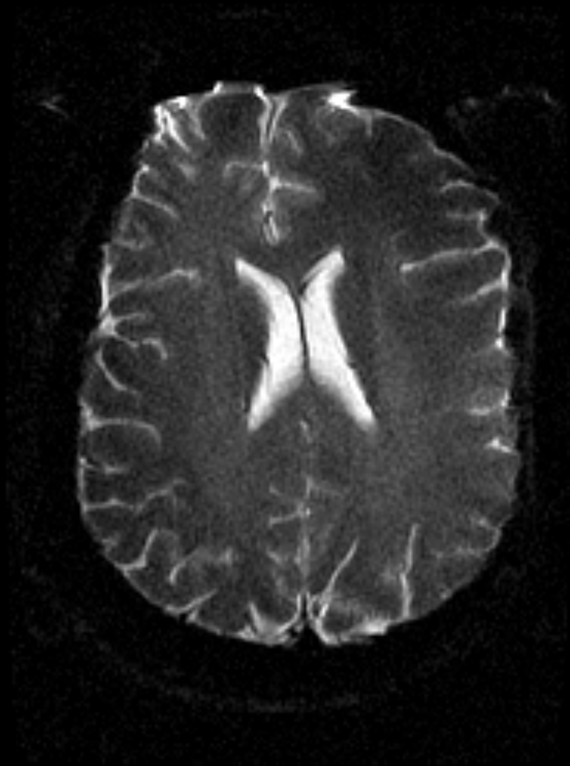


Multi-shot EPI

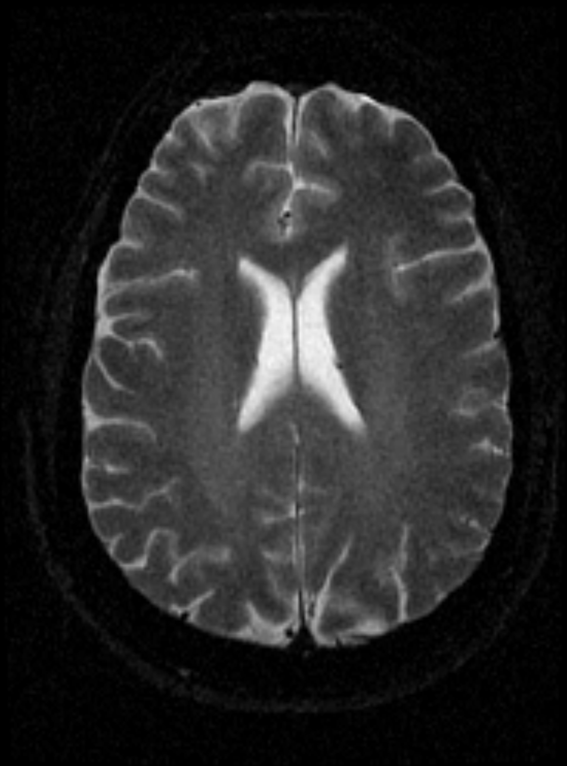
- Single-shot EPI (ssEPI)
  - minimal motion artifacts
  - low resolution
  - geometric distortion and signal loss
- Multi-shot EPI (msEPI)
  - aka interleaved or segmented EPI
  - higher resolution
  - less distortion & signal loss (improve PEbw)
  - need to address motion and phase inconsistencies

Comparison

ssEPI



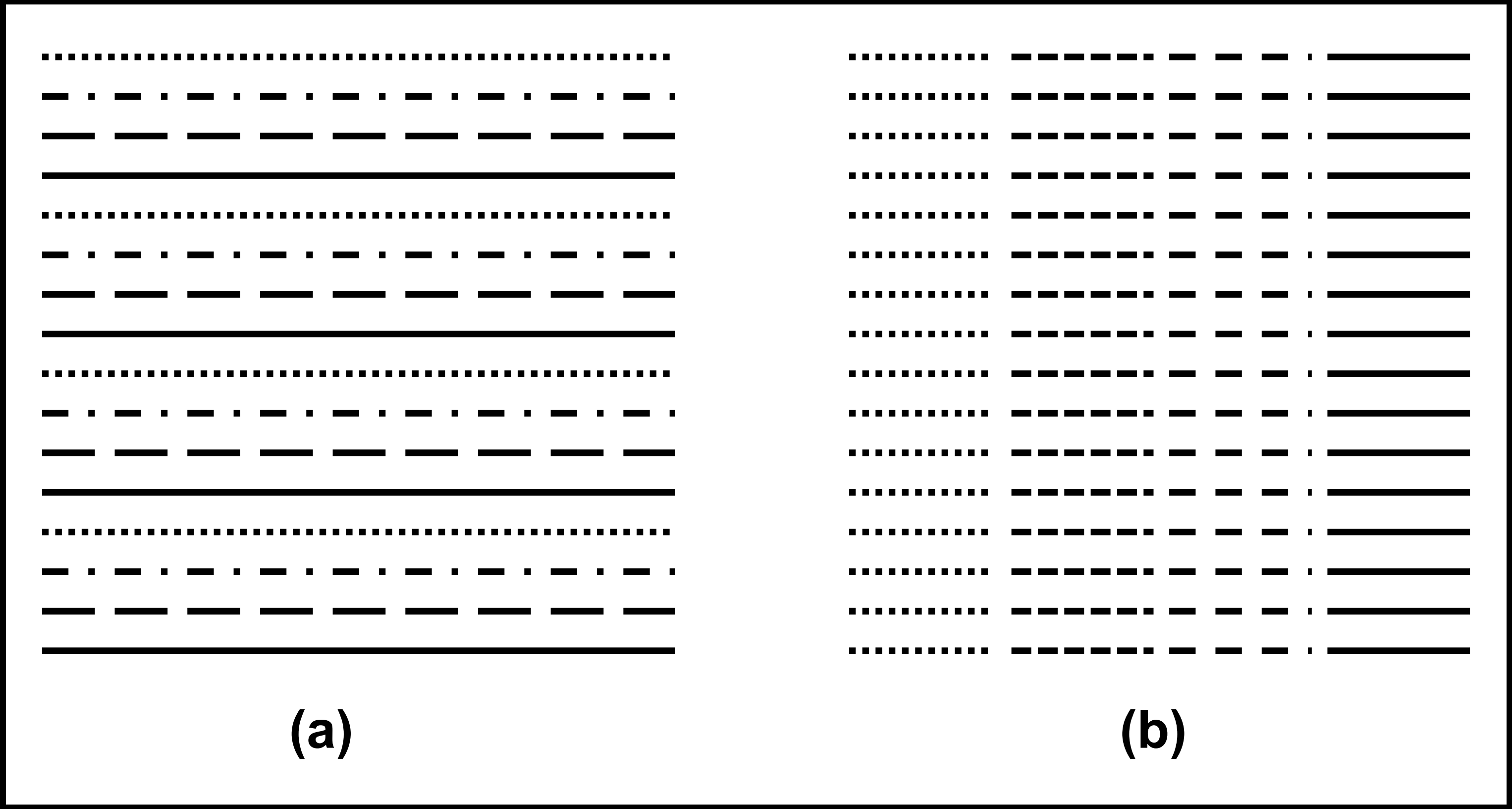
msEPI



Multi-shot EPI

Interleaved

Readout Segmented

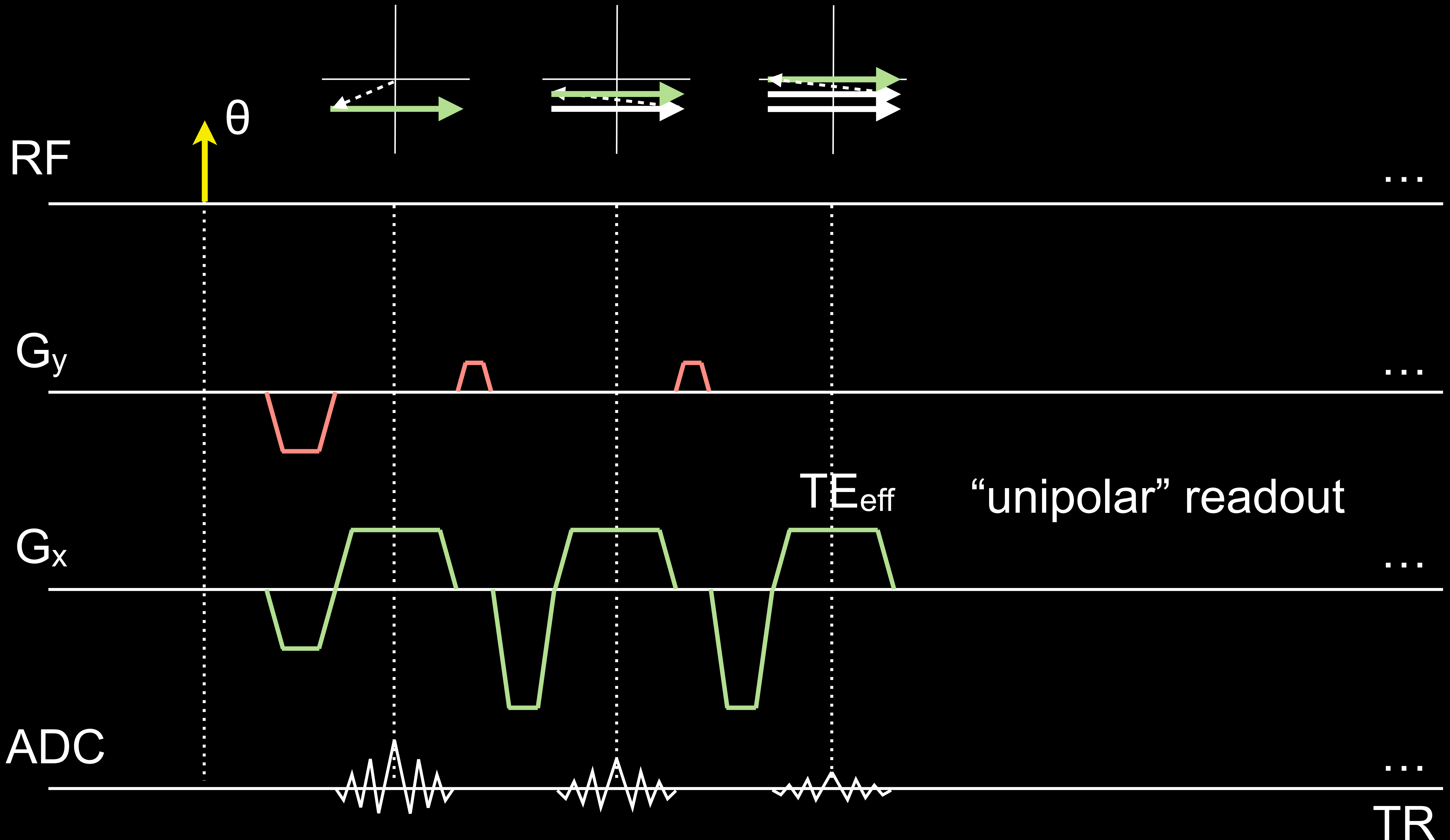


Courtesy of Dr. Novena Rangwala

EPI Scan Time

- Scan time
  - Recall $T_{GRE} = N_{pe} \times TR_{GRE}$
  - $N_{shot} = N_{pe} / ETL$
  - $T_{EPI} = N_{shot} \times TR_{EPI} = (T_{GRE} / ETL) \times (TR_{EPI}/TR_{GRE})$
- ***Example 1***
  - $N_{pe} = 256$; $ETL = 16$; $N_{shot} = 16$
  - $TR = 30$ ms: $T_{EPI} = 480$ ms
- ***Example 2***
  - $N_{pe} = 64$; $ETL = 64$; $N_{shot} = 1$
  - $TR = 100$ ms: $T_{EPI} = 100$ ms

Fly-Back GRE-EPI



Fly-Back GRE-EPI

- “Fly-back” gradients
  - No data sampling
  - Use max gradient amplitude/slew rate
- Advantages
  - All readouts in the same direction, minimal artifacts
- Disadvantages
  - Longer ESP than bipolar EPI

Related Sequences

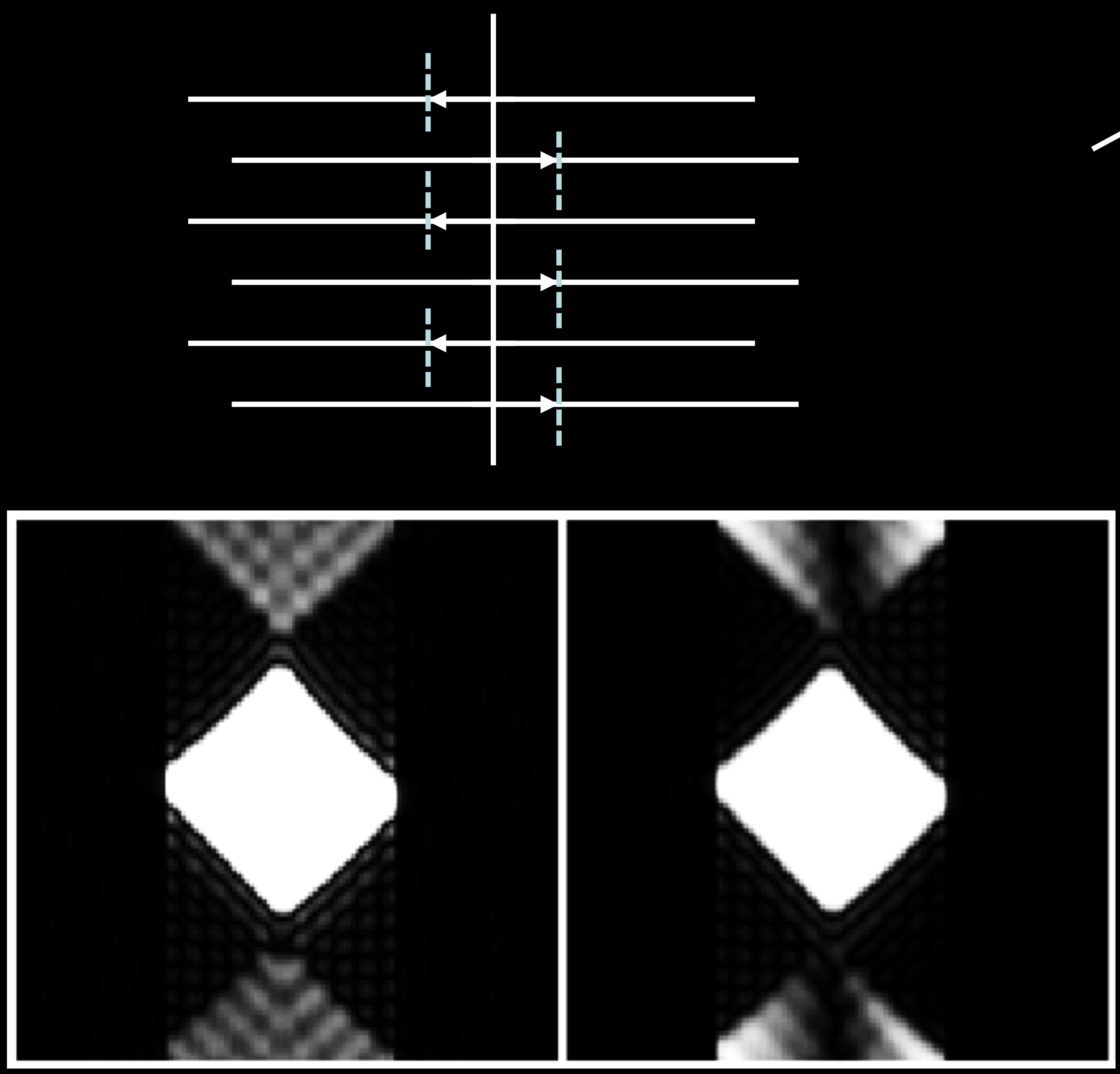
- 3D echo-volume imaging (EVI)
- Hybrid EPI + non-Cartesian (e.g., PROPELLER, EPI in a circular plane)
- Multi-echo chemical shift imaging
- Echo-planar spectroscopic imaging (EPSI), 2D and 3D

EPI Artifacts

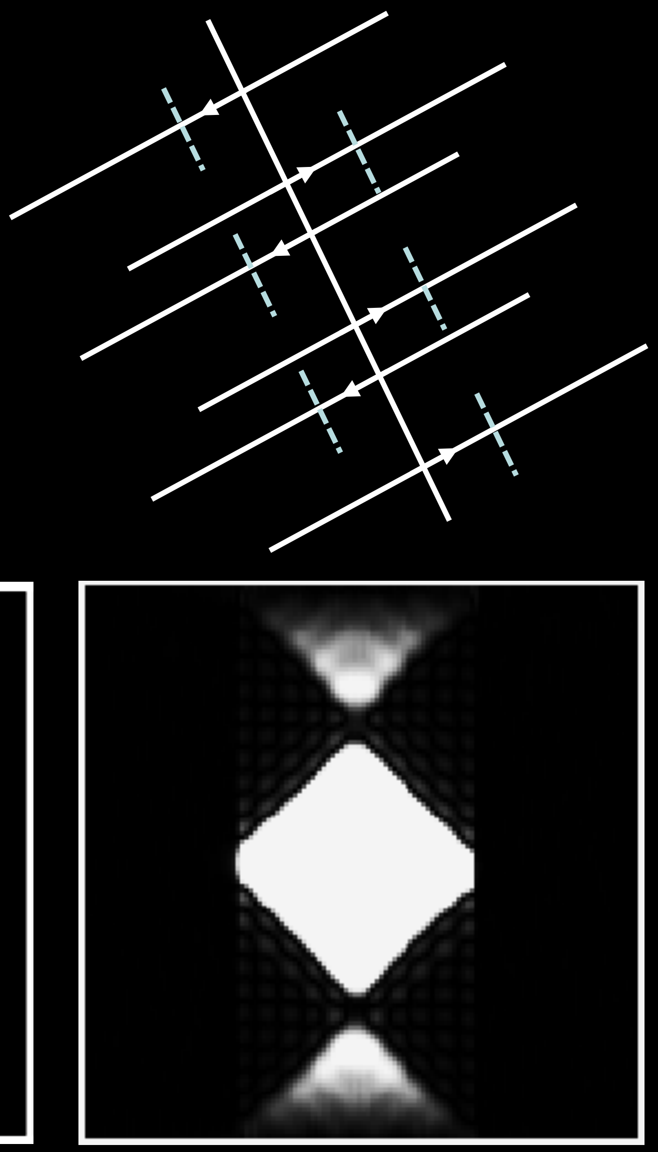
- Nyquist ghosting artifacts
- Chemical-shift artifacts, e.g., fat
- Signal drop-out
- Geometric distortion

EPI Ghosting Artifacts

'Orthogonal' Plane



'Oblique' Plane



EPI Ghosting Artifacts

- Inconsistencies between even/odd echoes due to:
  - Spatially independent (constant): B_0 eddy currents, off-center freq mismatch
  - Linear and oblique phase errors: k-space shifts from gradient / timing errors
  - Higher order eddy current effects
  - Concomitant magnetic fields

EPI Chemical Shift Artifacts

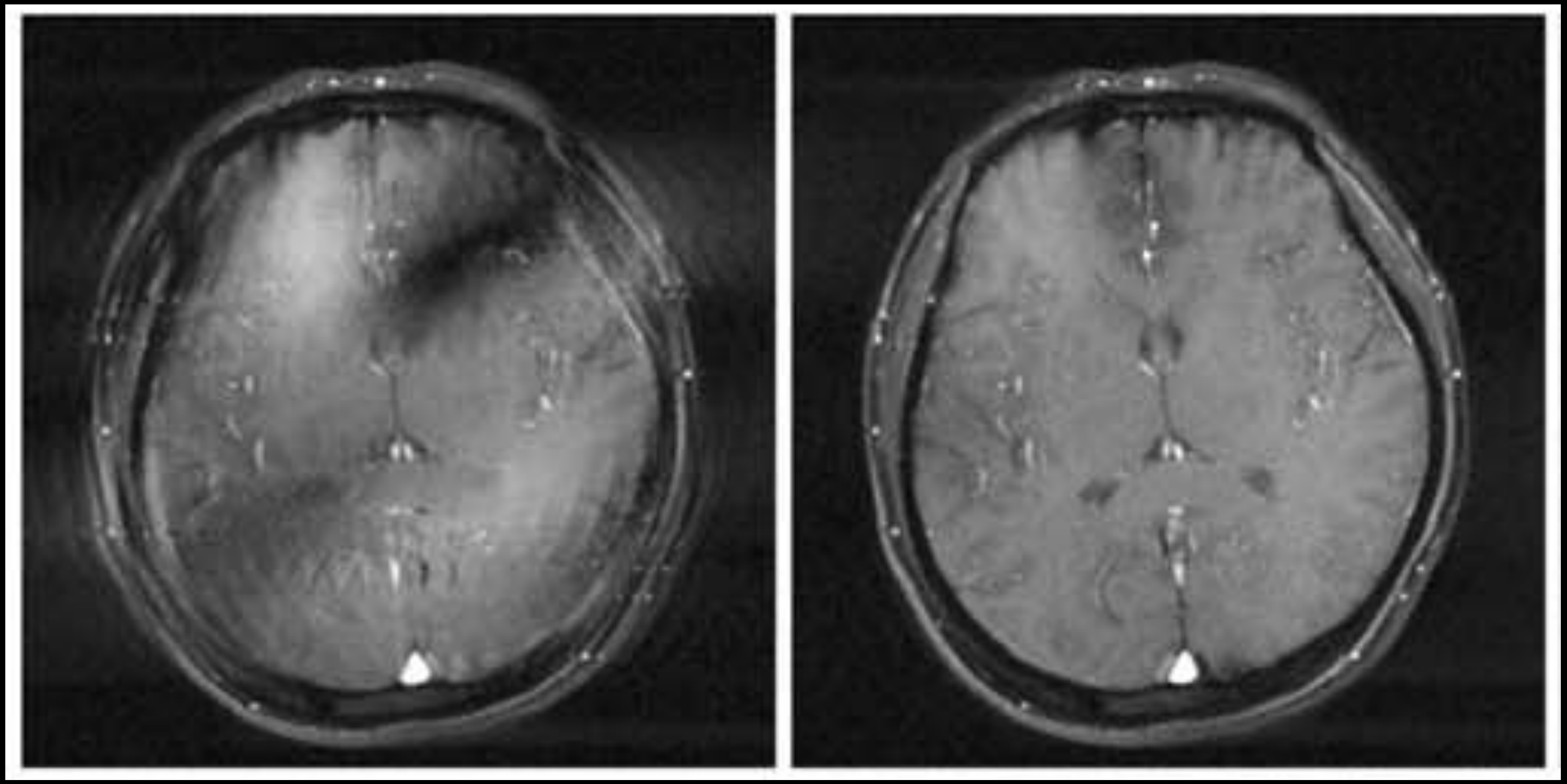
- Along readout
  - $\Delta x_{cs} = \Delta f_{cs} \cdot (FOV_x / RObw)$
  - At 1.5 T, $\Delta f_{WF} \sim 210$ Hz
    for FOVx = 32 cm and RObw = 250 kHz,
    $\Delta x_{cs} = 0.027$ cm
- Along phase encode
  - $\Delta y_{cs} = \Delta f_{cs} \cdot (FOV_y / PEbw)$,
    PEbw = 1 / ESP
  - for ESP = 1 ms, $\Delta y_{cs} = 6.72$ cm

EPI Considerations

- Minimize ESP (covered earlier)
- Spatial-spectral excitation for fat signal suppression
- Reconstruction steps
  - Row flipping and phase correction
  - Ramp sampling correction
  - Fourier transformation
  - (Possible) B_0 inhomogeneity correction
  - (Possible) Gradient trajectory corrections

EPI Considerations

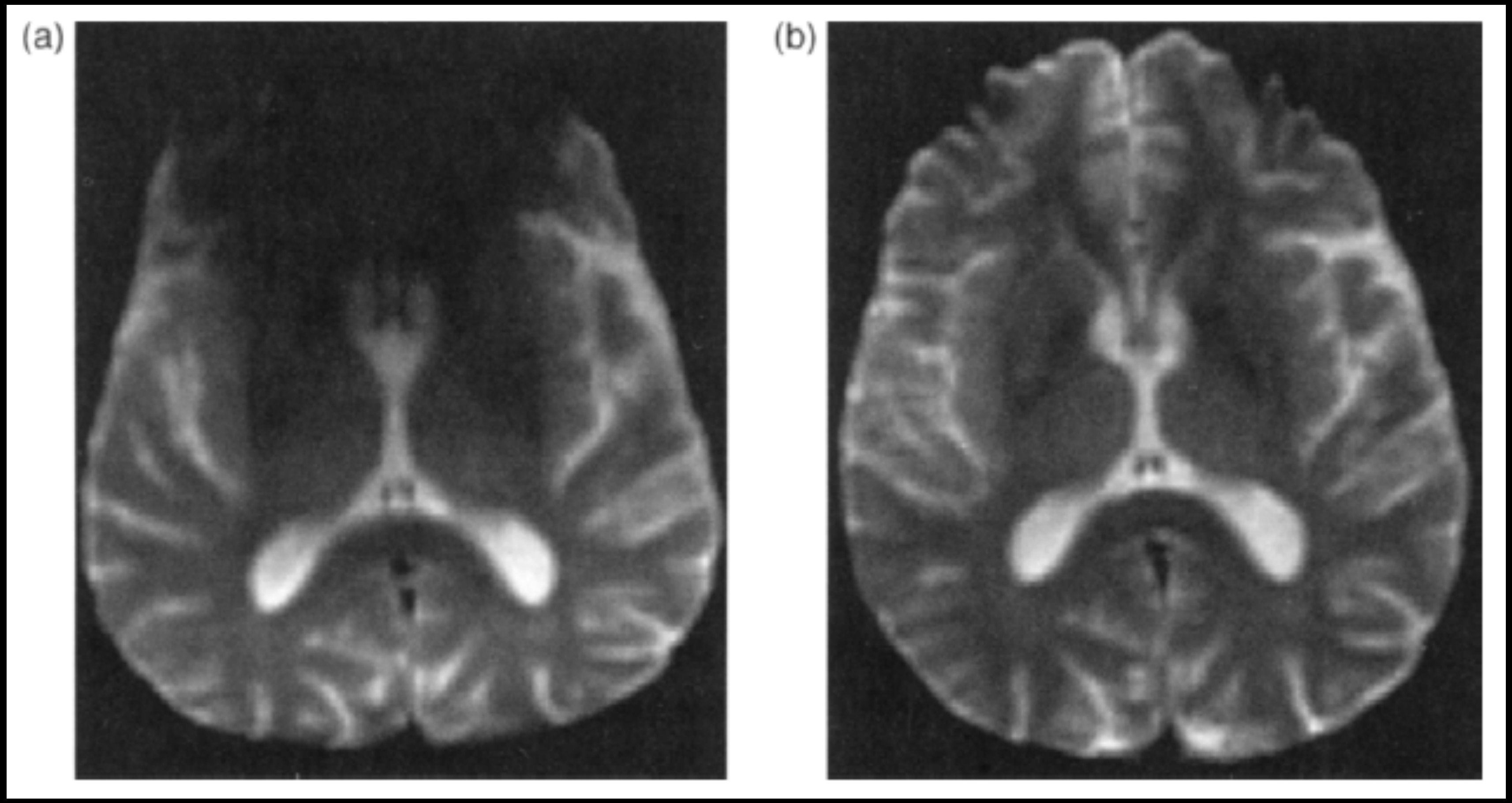
Axial EPI, before & after trajectory correction



Addy NO et al., MRM 2012

EPI Considerations

Image distortion and signal loss from dentures



w/ dentures

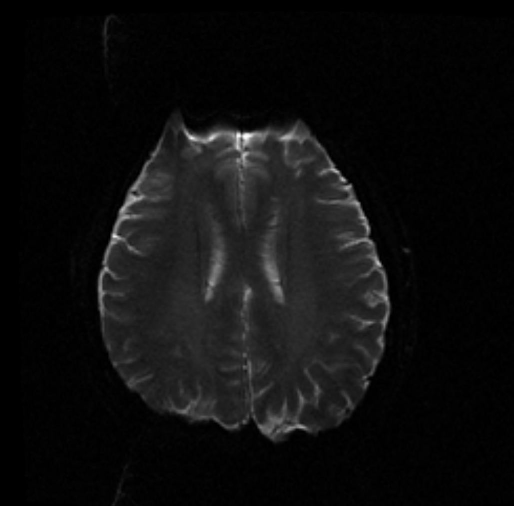
Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.1

Summary

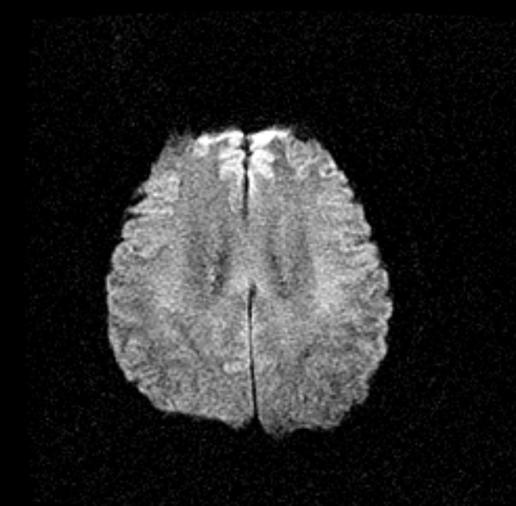
- Strengths
  - very fast
- Challenges
  - T_2^* decay
  - high demand on slew rate
  - artifacts

Clinical Applications

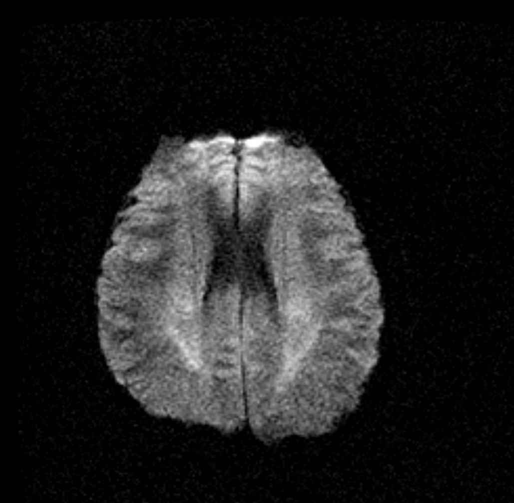
- BOLD fMRI
- ASL
- DWI (see figure)
- Real-time MRI
- MRSI
- *and more ...*



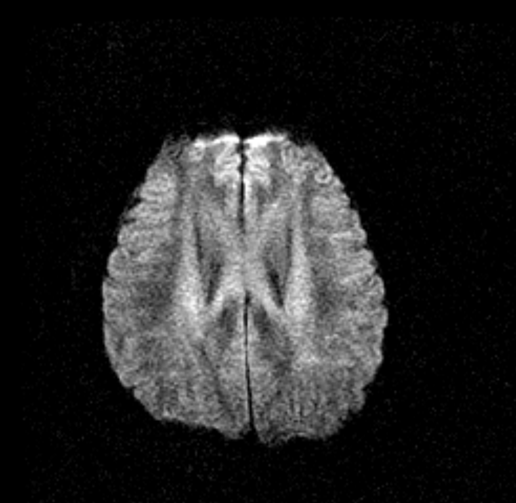
b = 0 s/mm²



b = 750 s/mm², S/I



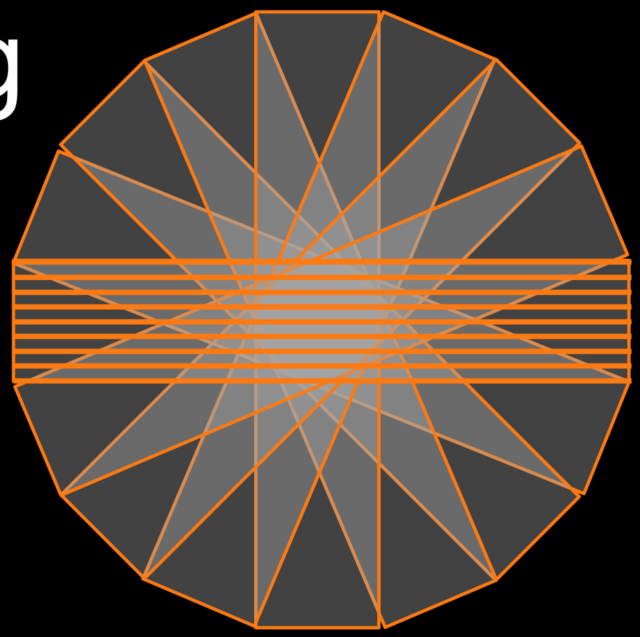
b = 750 s/mm², R/L



b = 750 s/mm², A/P

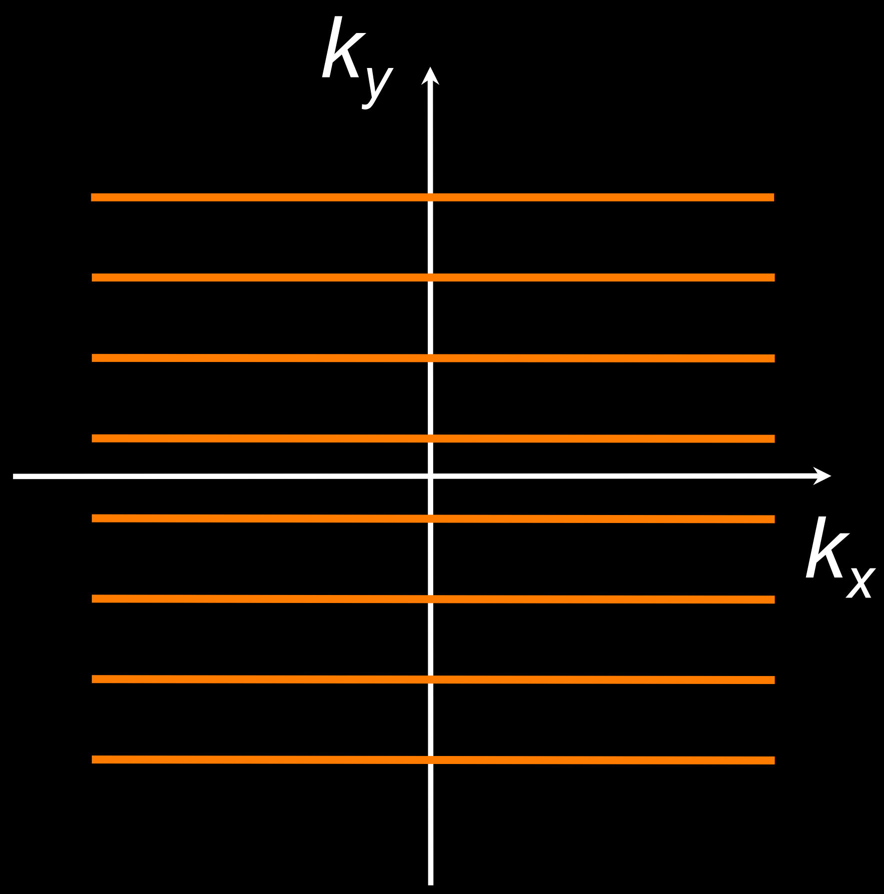
PROPELLER

- Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction[1], aka BLADE
- Radial and Cartesian hybrid
- Oversampling at the center of k-space
  - correct inconsistencies between strips
  - reject data with through-plane motion
  - weigh strip contributions w.r.t. motion
  - average to decrease motion artifacts

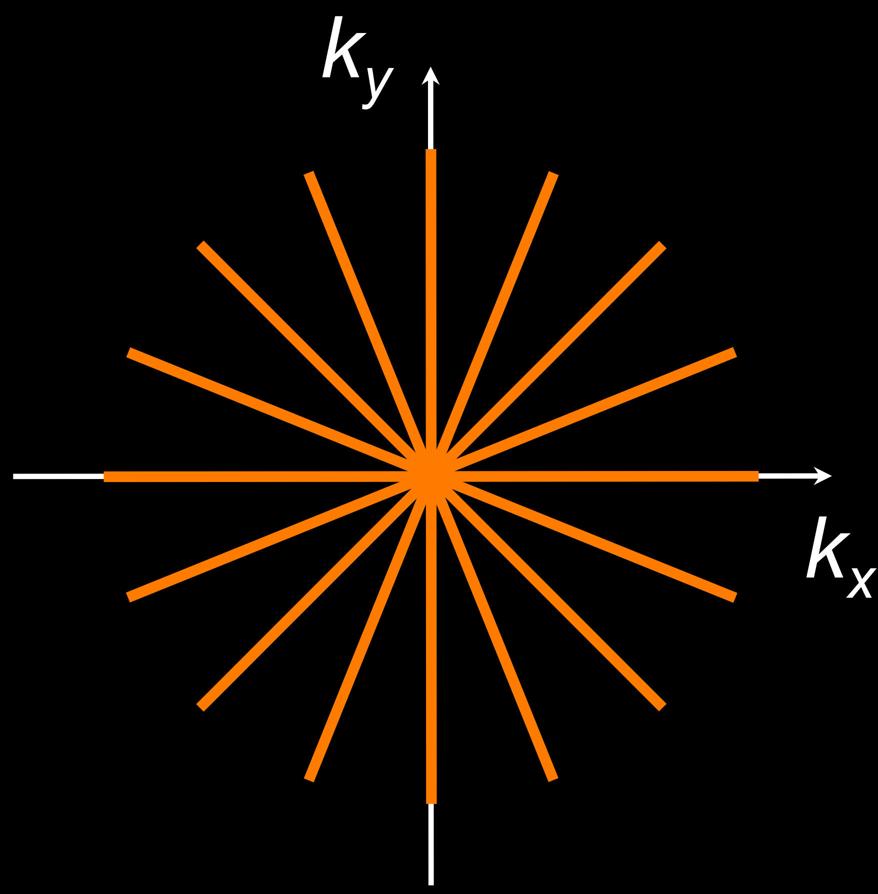


[1] *Pipe, MRM 1999; 42: 963-969*

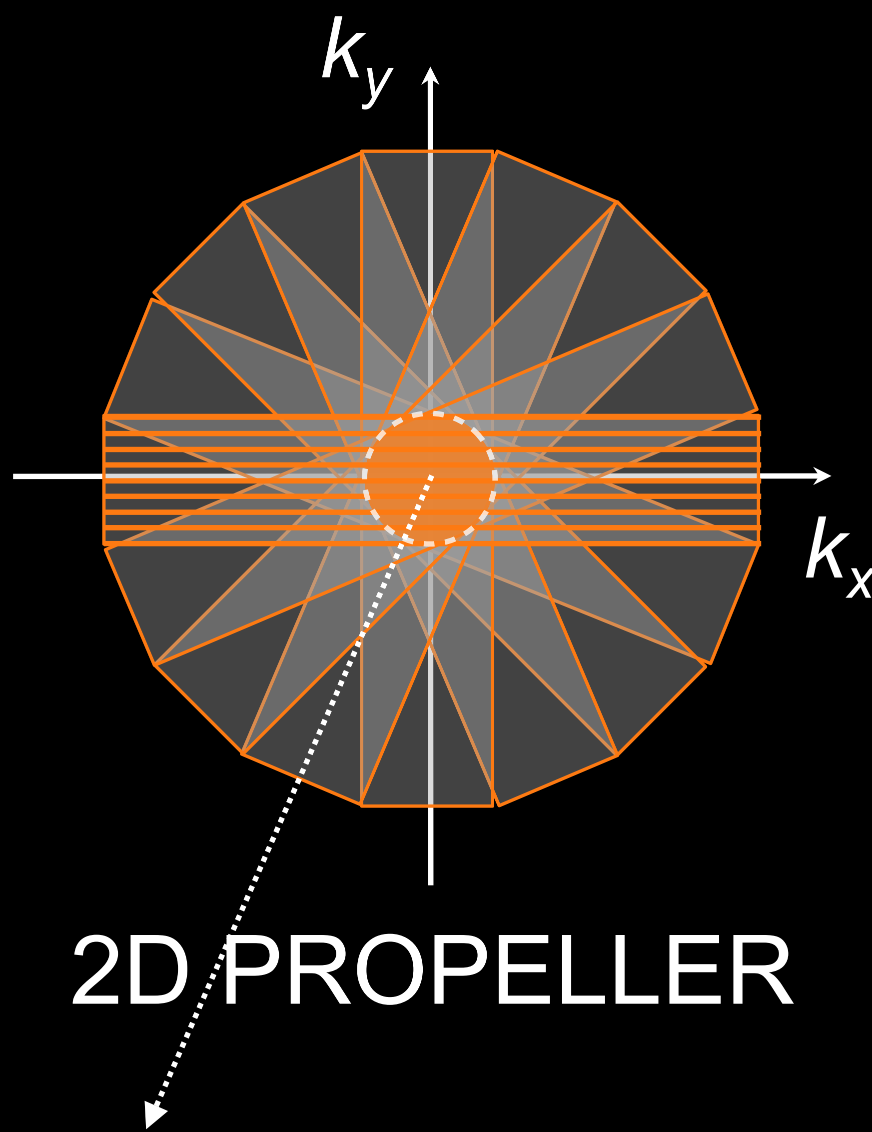
PROPELLER



2D Cartesian



2D Radial

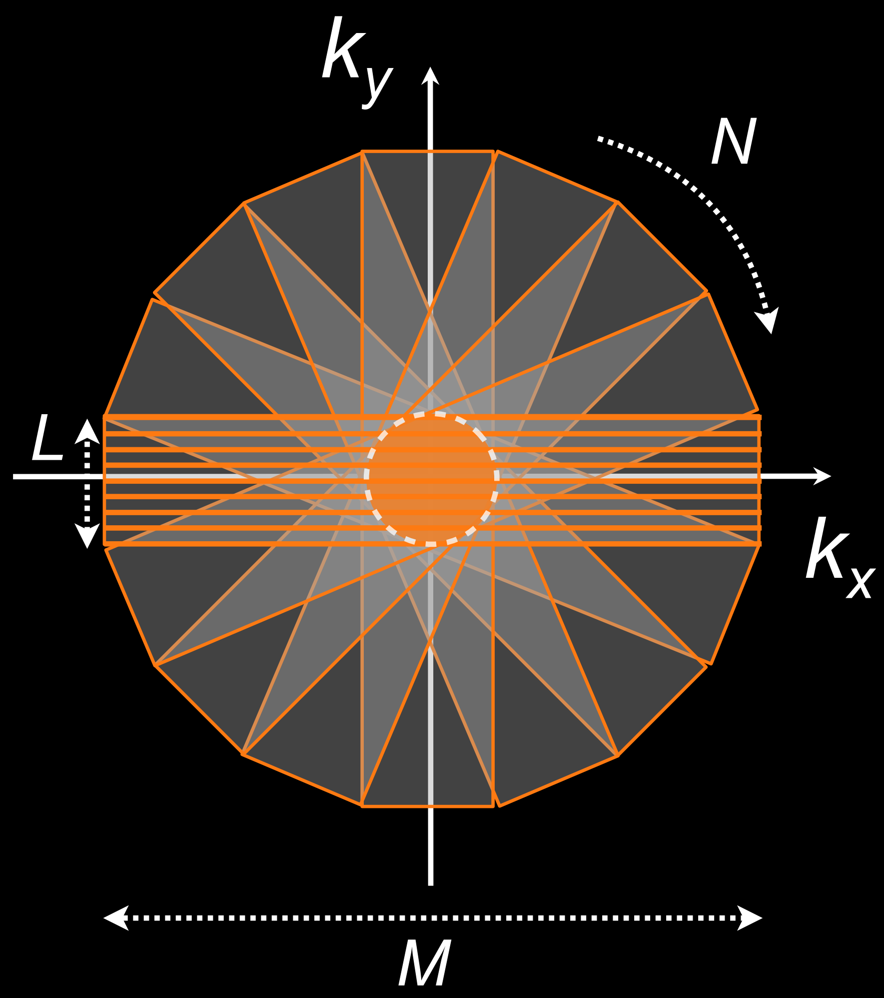


2D PROPELLER

always sampled

PROPELLER

Trajectory Design:



N strips, successively rotated by $d\alpha = \pi/N$

L lines per strip, *M* points per line

For an *M* x *M* image, need $L \cdot N = M \cdot (\pi/2)$

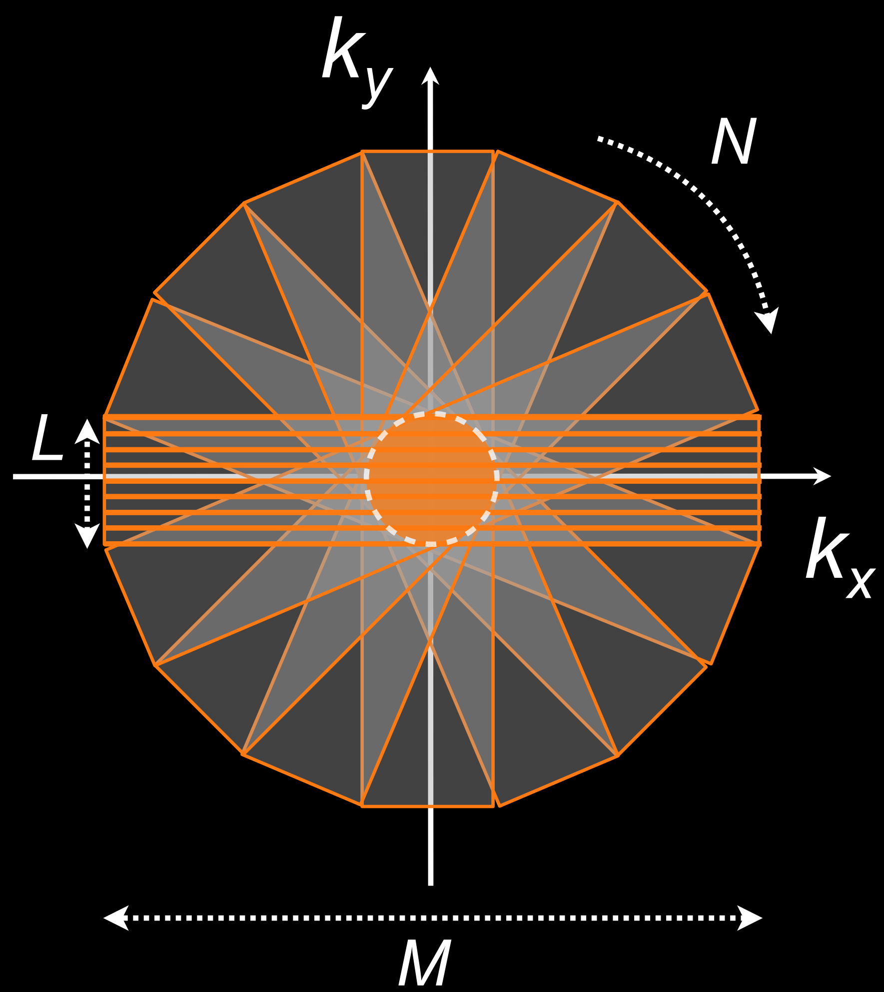
central oversampled circle of diameter *L*

Scan time trade-offs based on *L* and *N*

Asymmetric FOV also possible

PROPELLER

Trajectory Design Example:



24-cm FOV; 0.5 mm in-plan resln; L = 28

M = FOV/resln = 480

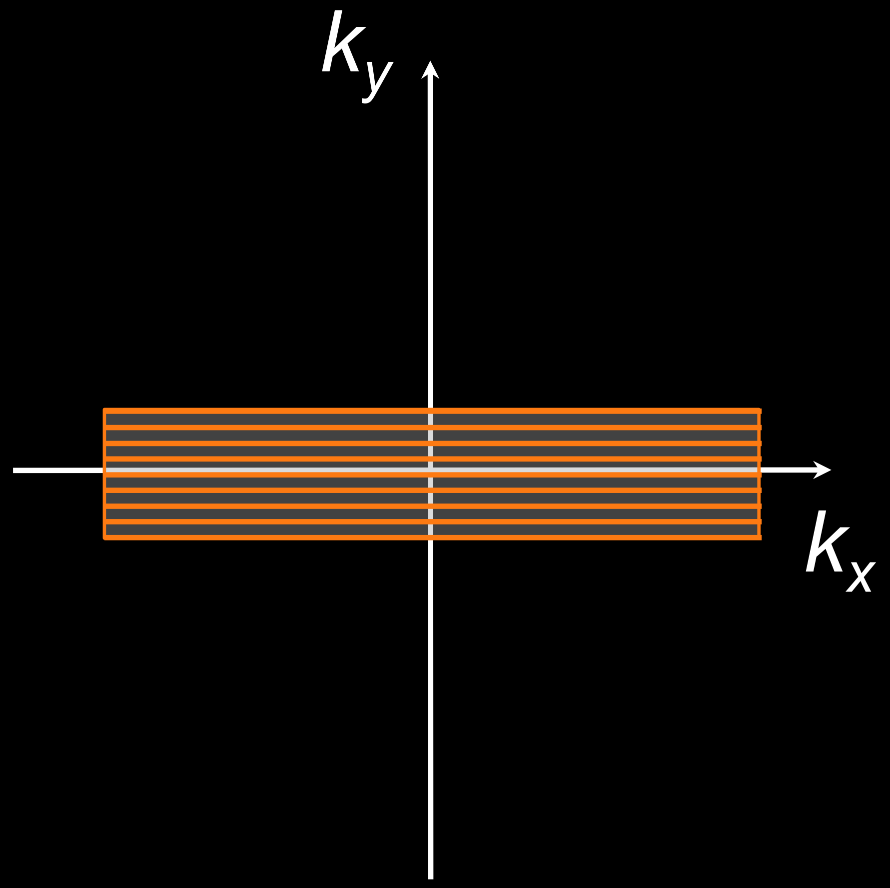
$N = (M/L)\cdot(\pi/2) \sim 27$

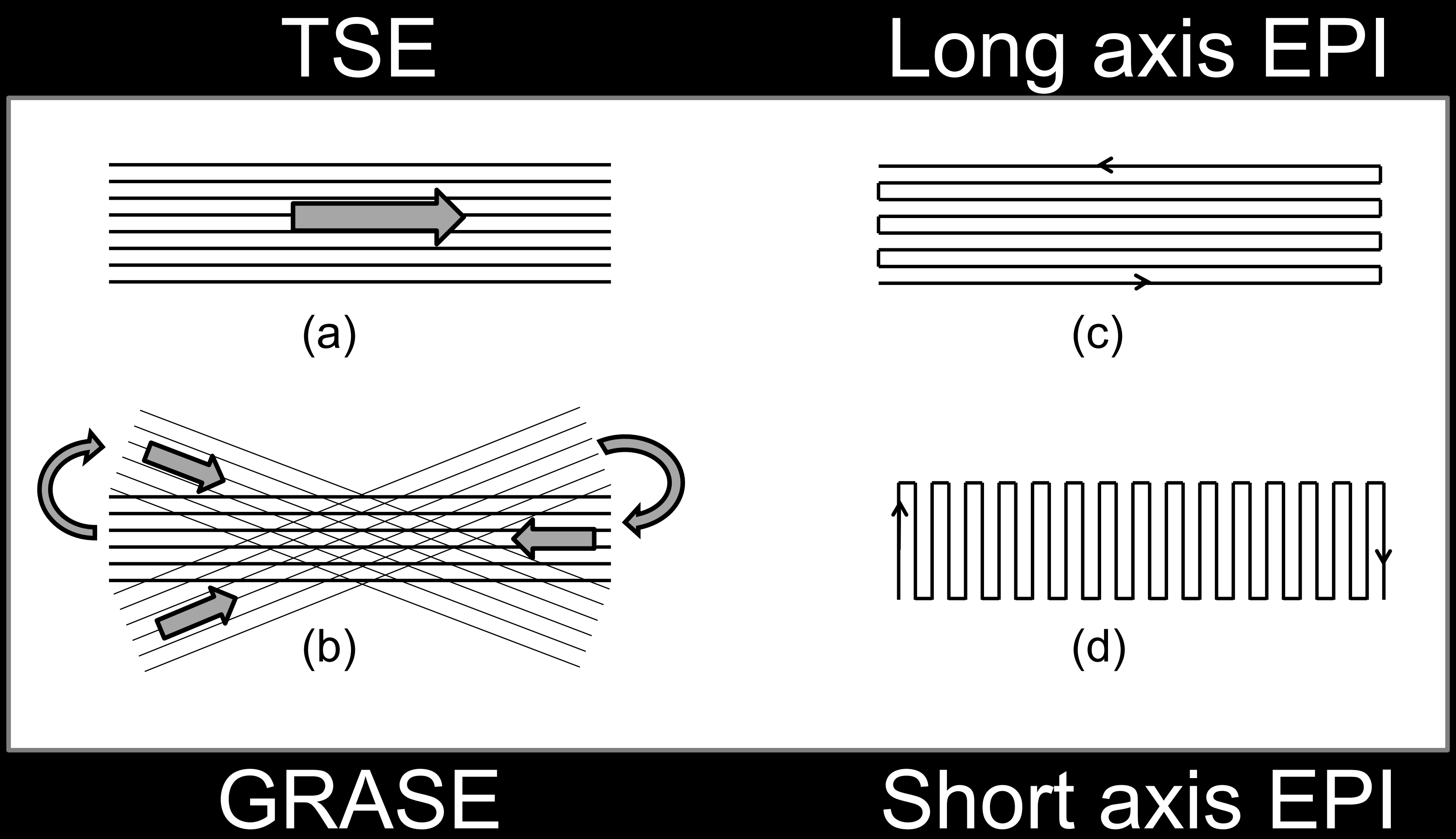
TR = 4000 ms, $T_{scan} = N\cdot\mathrm{TR}$ = 1 min 48 s

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 17.5

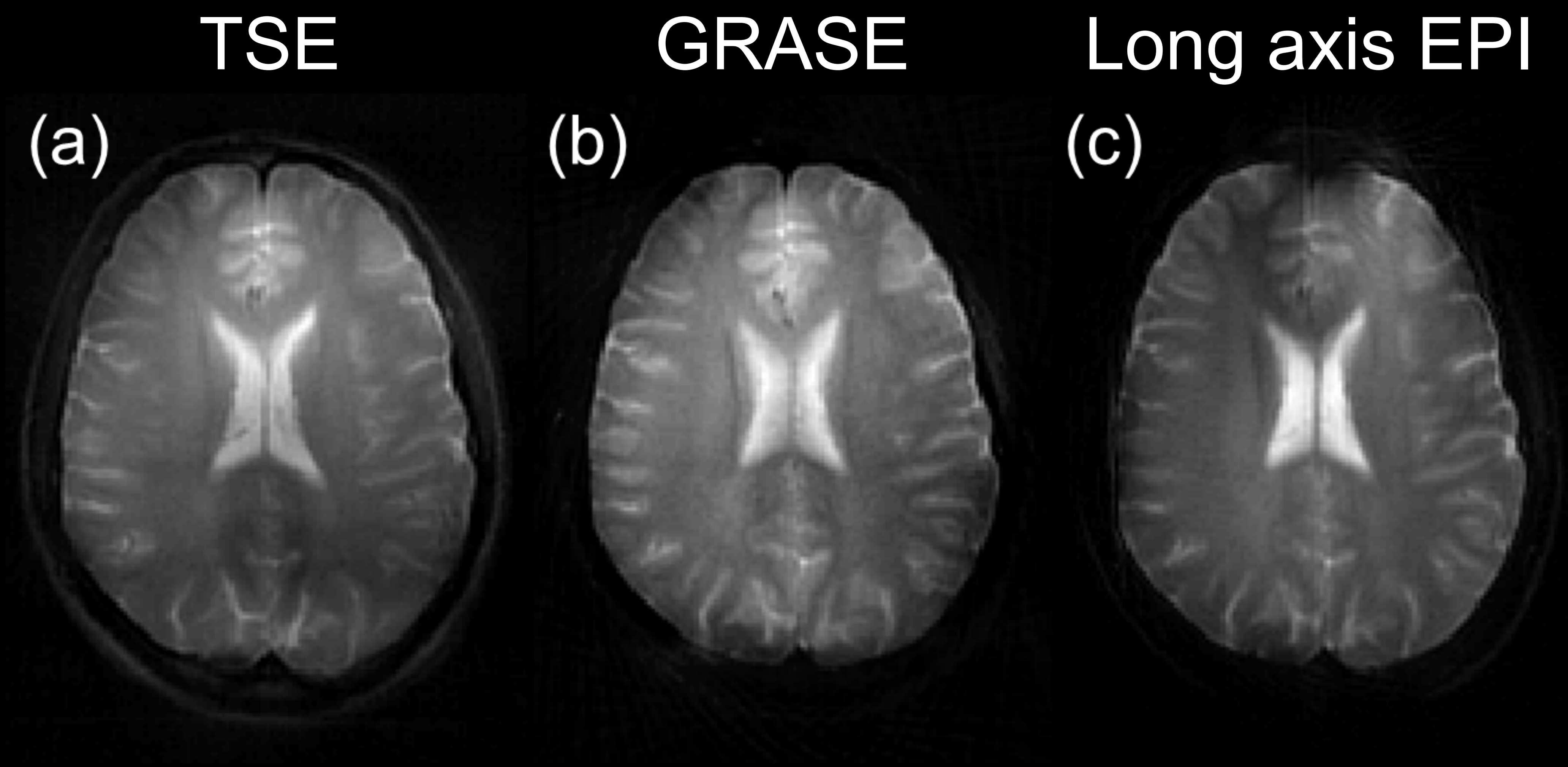
PROPELLER

Trajectory Design:





PROPELLER



PROPELLER

Motion correction:

Rotation in image space $\longleftrightarrow$ rotation in k-space

Compare k-space magnitude between strips

Translation in image space $\longleftrightarrow$ linear phase in k-space

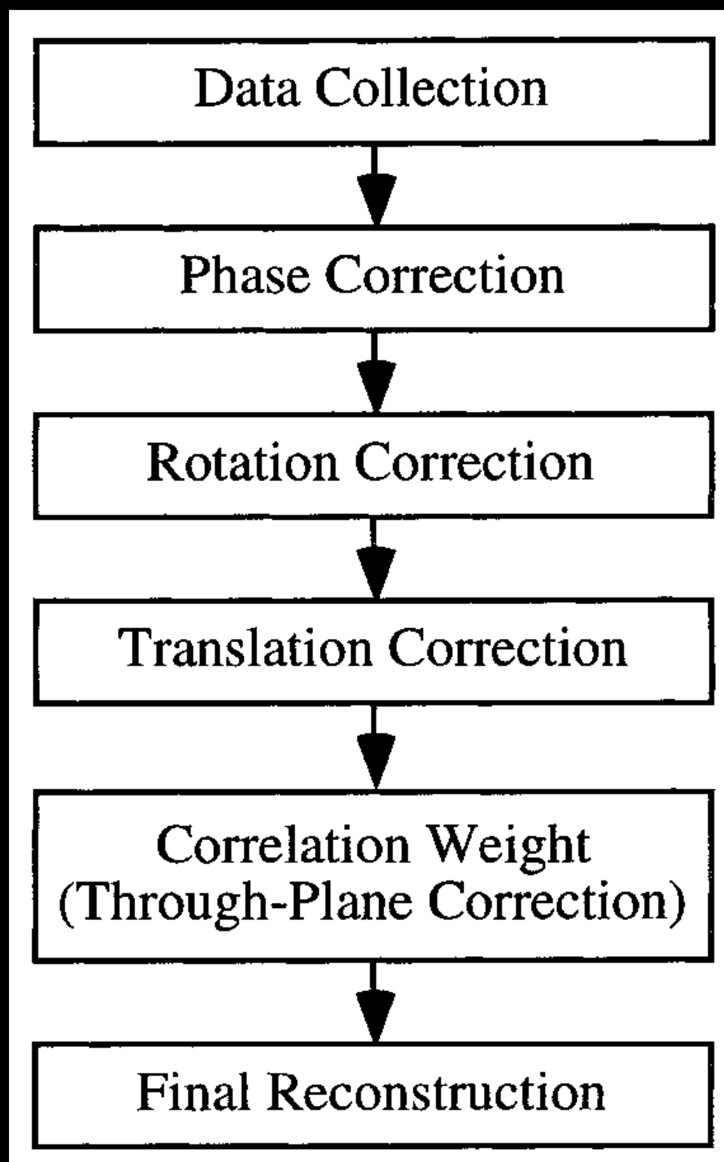
Compare k-space phase between strips

Other motion in image space $\longleftrightarrow$ k-space mag/phase

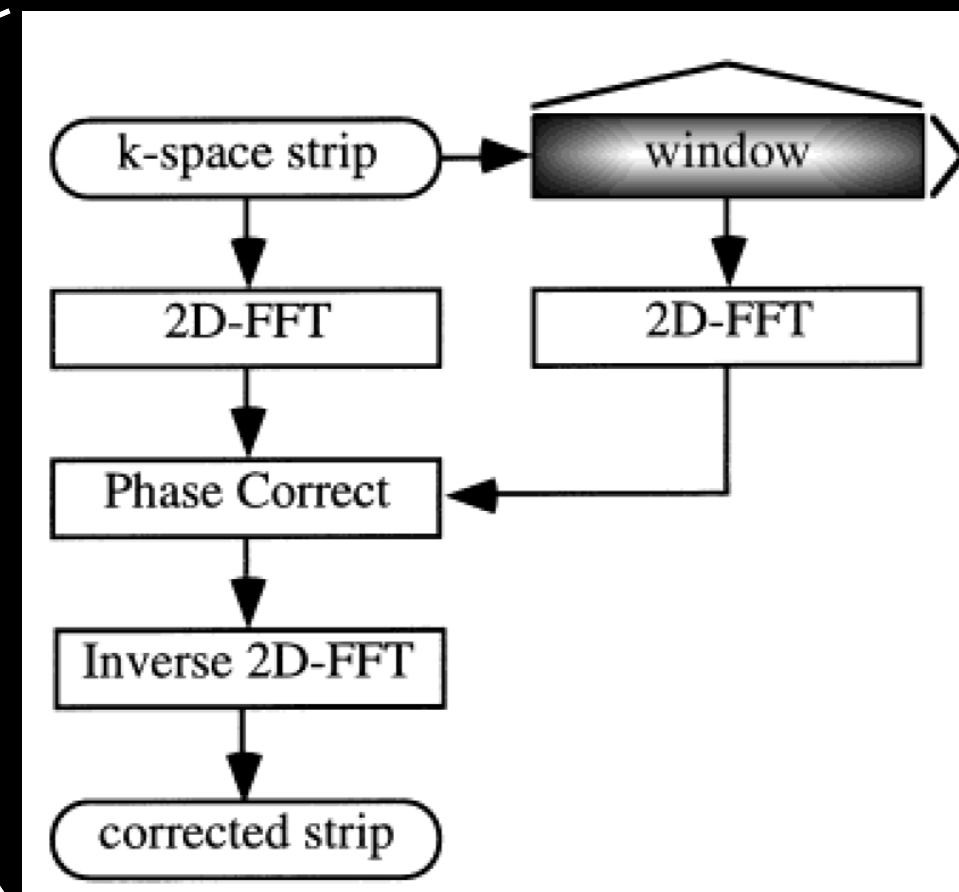
Compare and weigh importance of strips

PROPELLER

Reconstruction:



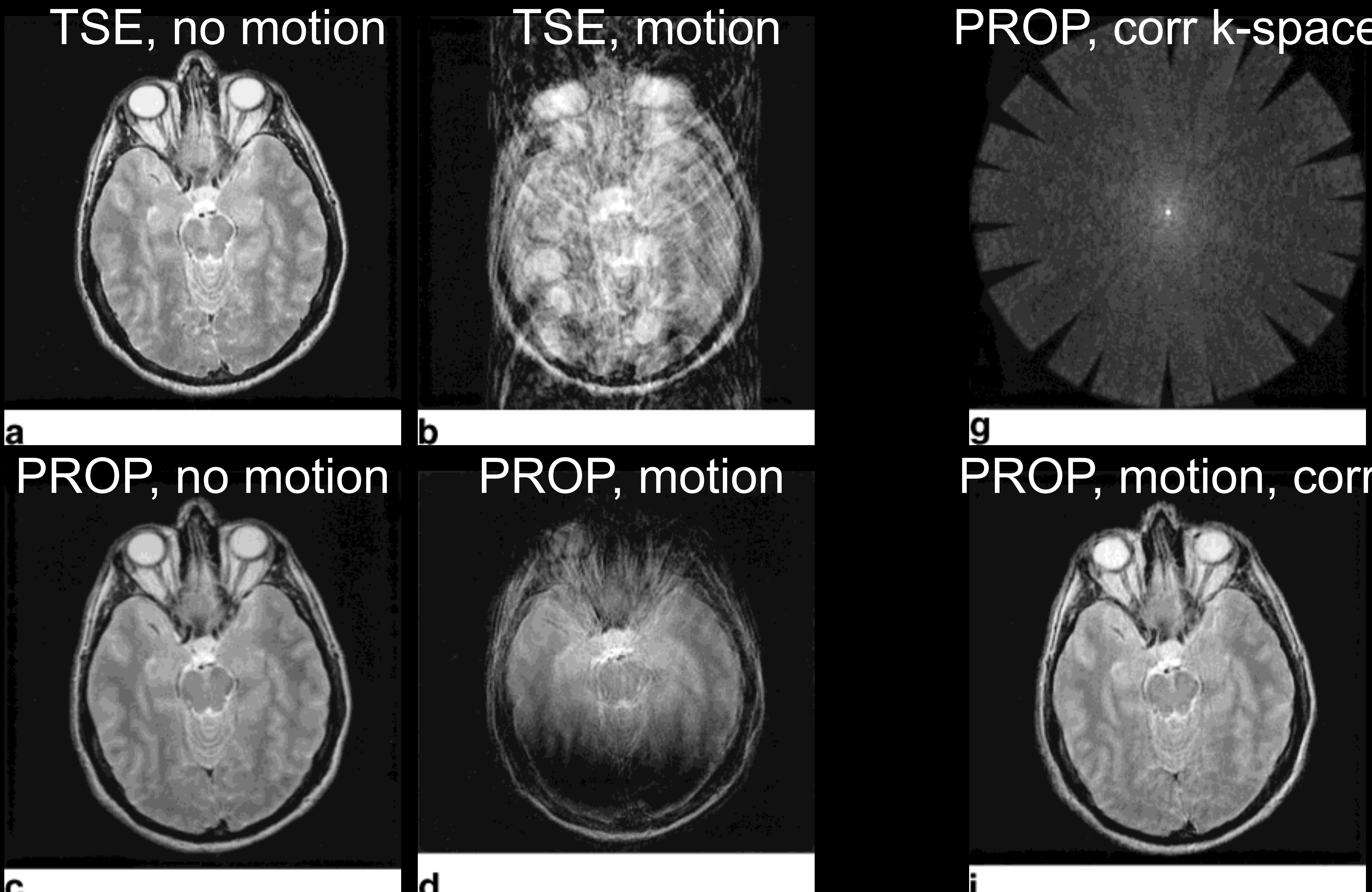
For each strip:



density compensation

Pipe, MRM 1999; 42: 963-969

PROPELLER

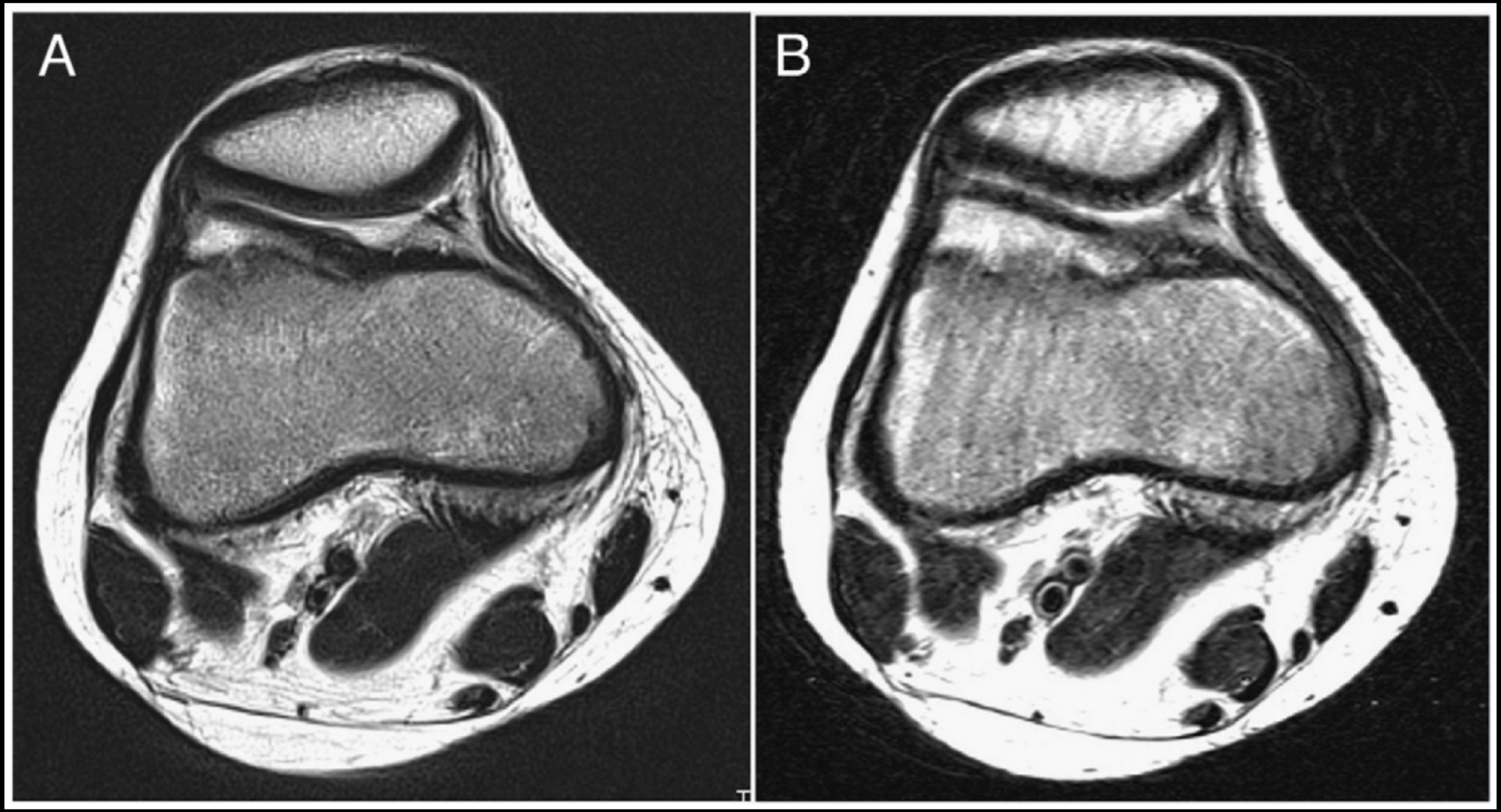


Pipe, MRM 1999; 42: 963-969

PROPELLER

T2 TSE BLADE

T2 TSE



Lavdas E, et al., MRI 2012; 30: 1099-1110

PROPELLER

- Advantages
  - robust to motion
- Disadvantages
  - increased scan time
- Extensions
  - 3D blocks; 3D rods (TORQ)

Clinical Applications

- Brain
- Abdomen/Pelvis
- MSK
- Diffusion-weighted imaging (high-resolution)

Summary

- EPI
  - very popular for fast MRI!
  - design, recon, corr drives a lot of research
- PROPELLER
  - very robust to motion
  - philosophy can be adapted to other seq
- Next: Non-Cartesian sampling

Thanks!

- Further reading
  - Bernstein et al., Handbook of MRI Sequences
  - pubmed.org
- Acknowledgments
  - Novena Rangwala

Holden H. Wu, Ph.D.

HoldenWu@mednet.ucla.edu

http://mrrl.ucla.edu/wulab