Chapter 19
Segmented k-space

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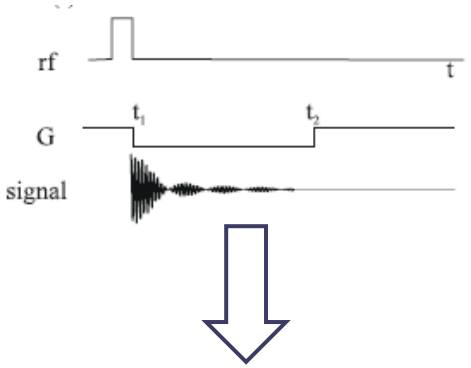
- **Previous sections:**
  - K-space (chap.9, 10,13)
  - Fourier transform (chap.11)
  - Gradient echo, spin echo (chap. 8)
- **Today's content**
  - Segmented k-space concept
  - Echo Planar Imaging
  - Related artifacts

Review

- K-space (1D, readout)



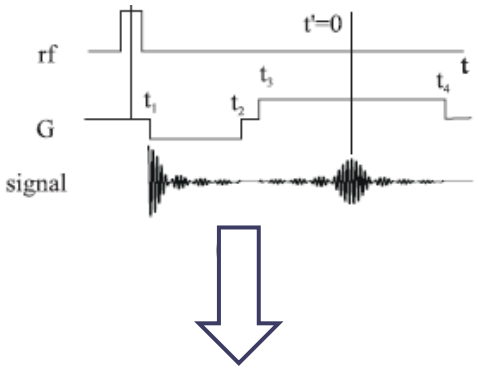


Fig.9.2

FID
(Half Fourier)

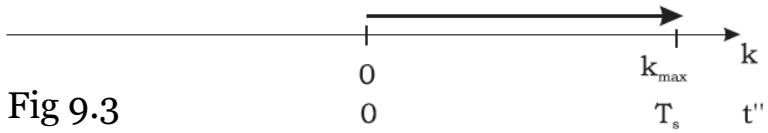


Fig 9.3

GE

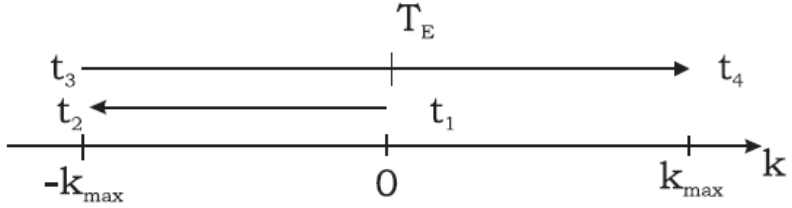
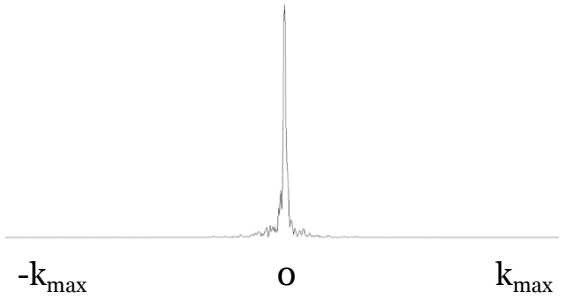


Fig 9.4

(a)

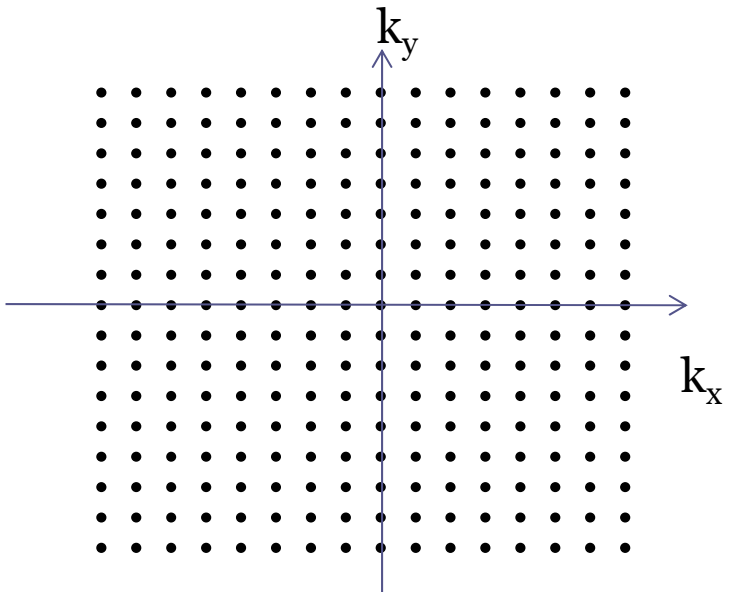
$$k(t) = \gamma \int_0^t dt' G(t')$$

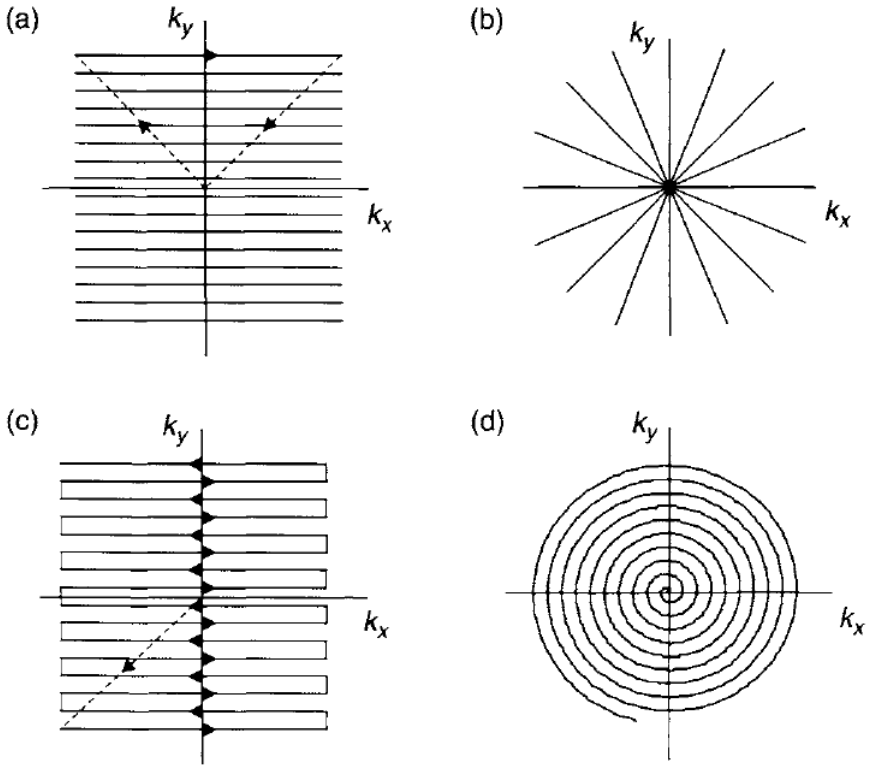
$$-k_{max} < k < k_{max}$$



Review

- K-space (2D)

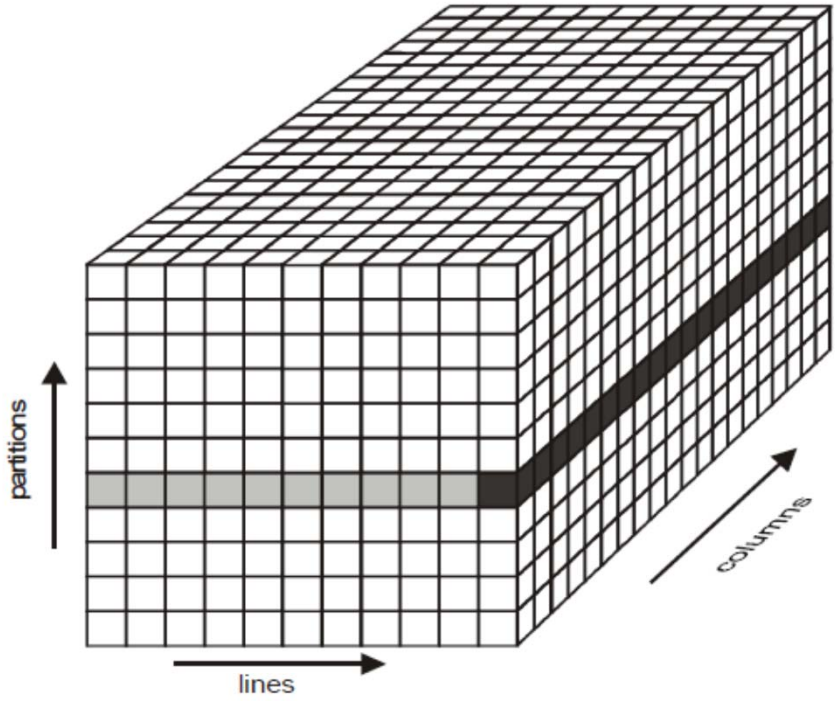


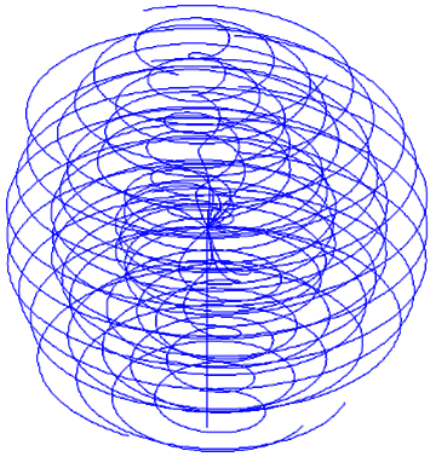


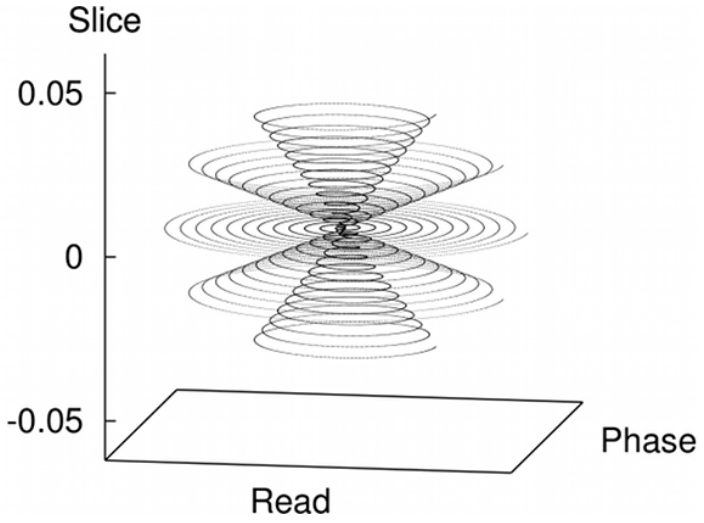
(Bernstein et al, Handbook of MRI Pulse Sequences, Fig.11.6)

Review

- K-space (3D)







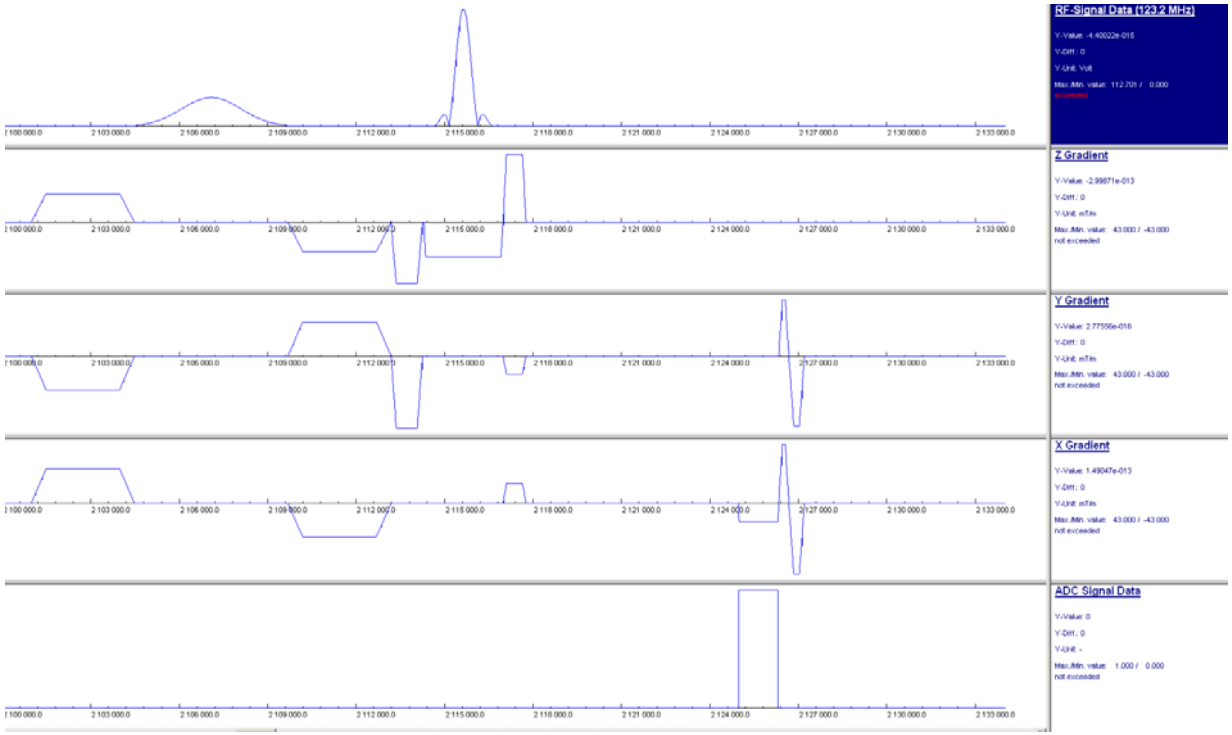
Reducing scan time (Cartesian)

$$T_T = N_{acq} N_y N_z TR$$

- Reduce TR
- Reduce Ny, Nz
  - Partial Fourier
  - Parallel imaging
  - Compress sensing
- Increase data acquisition efficiency
  - K-space segmentation (or multi-line collection)
  - Compact sequence design using ‘dead’ times
  - Multi-band excitation

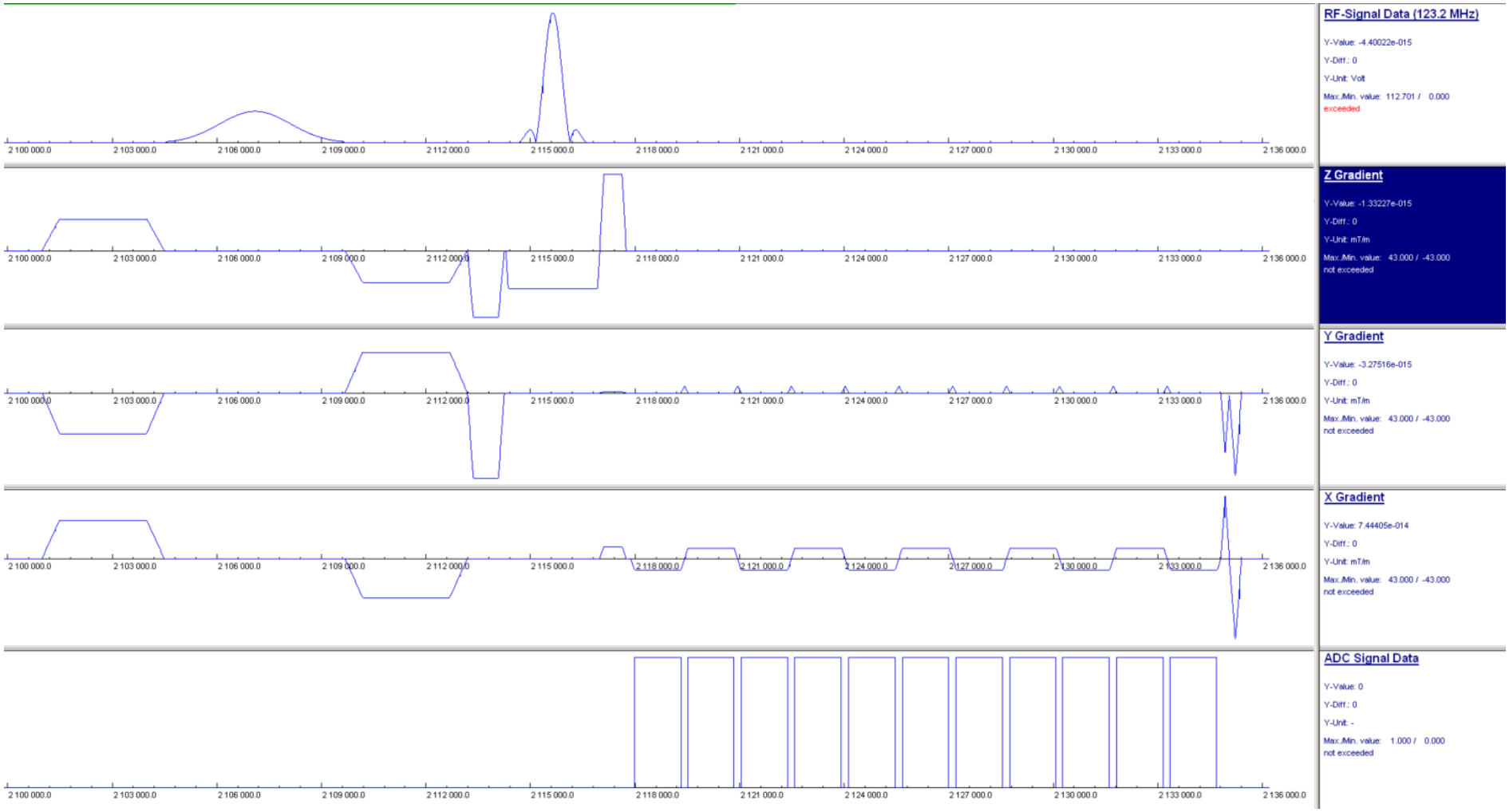
Filling k-space

- MR sequence functionalities
  - Signal excitation
  - Signal manipulation (IR, FS, SE, FC, Spoiler…)
  - Signal readout
- Single PE line per RF (max segmentation)



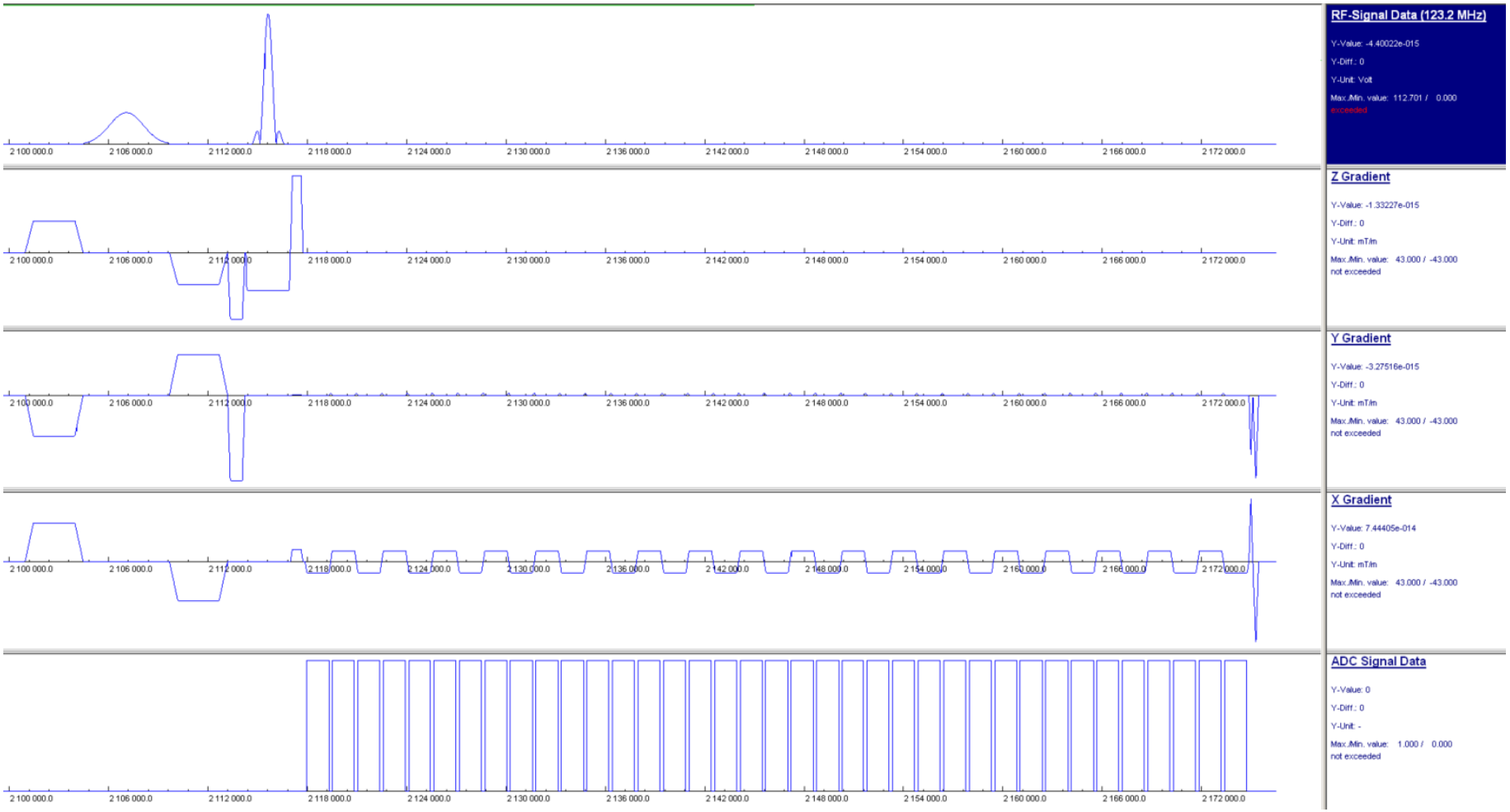
Filling k-space

- Multiple PE lines per RF (multiple segments/shots)



Filling k-space

- All PE lines per RF (‘single shot’, one segment, e.g. EPI)



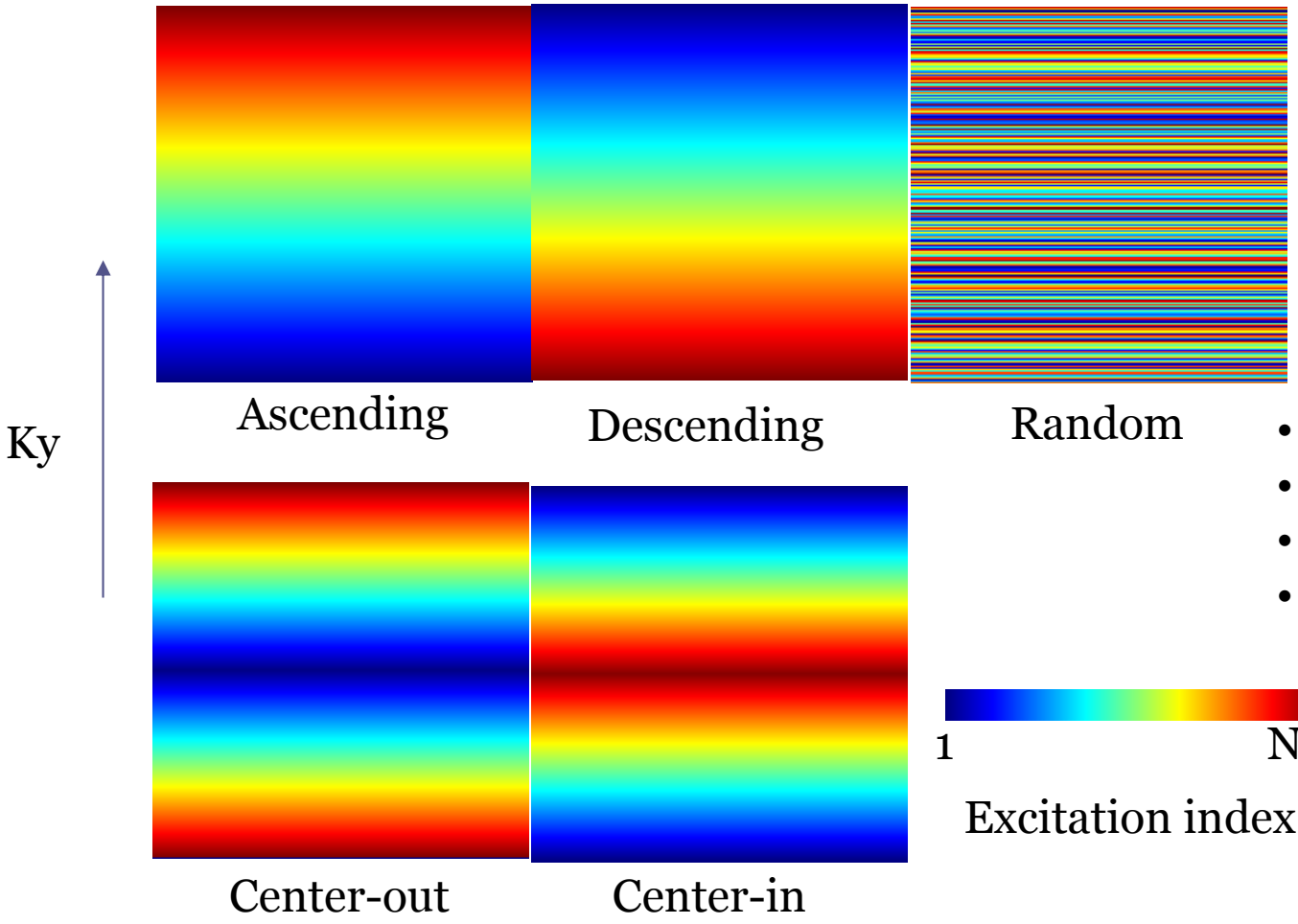
Nomenclature

- Single echo
- Multi-echo (multi-TE?)
- Single shot
- Multi-shot
- Segmented

- Pros and Cons in a nut shell
  - Faster scan for high resolution imaging
  - Higher resolution for fast scans
  - Compromise or improvement?

Filling segmented k-space

- Single echo acquisition

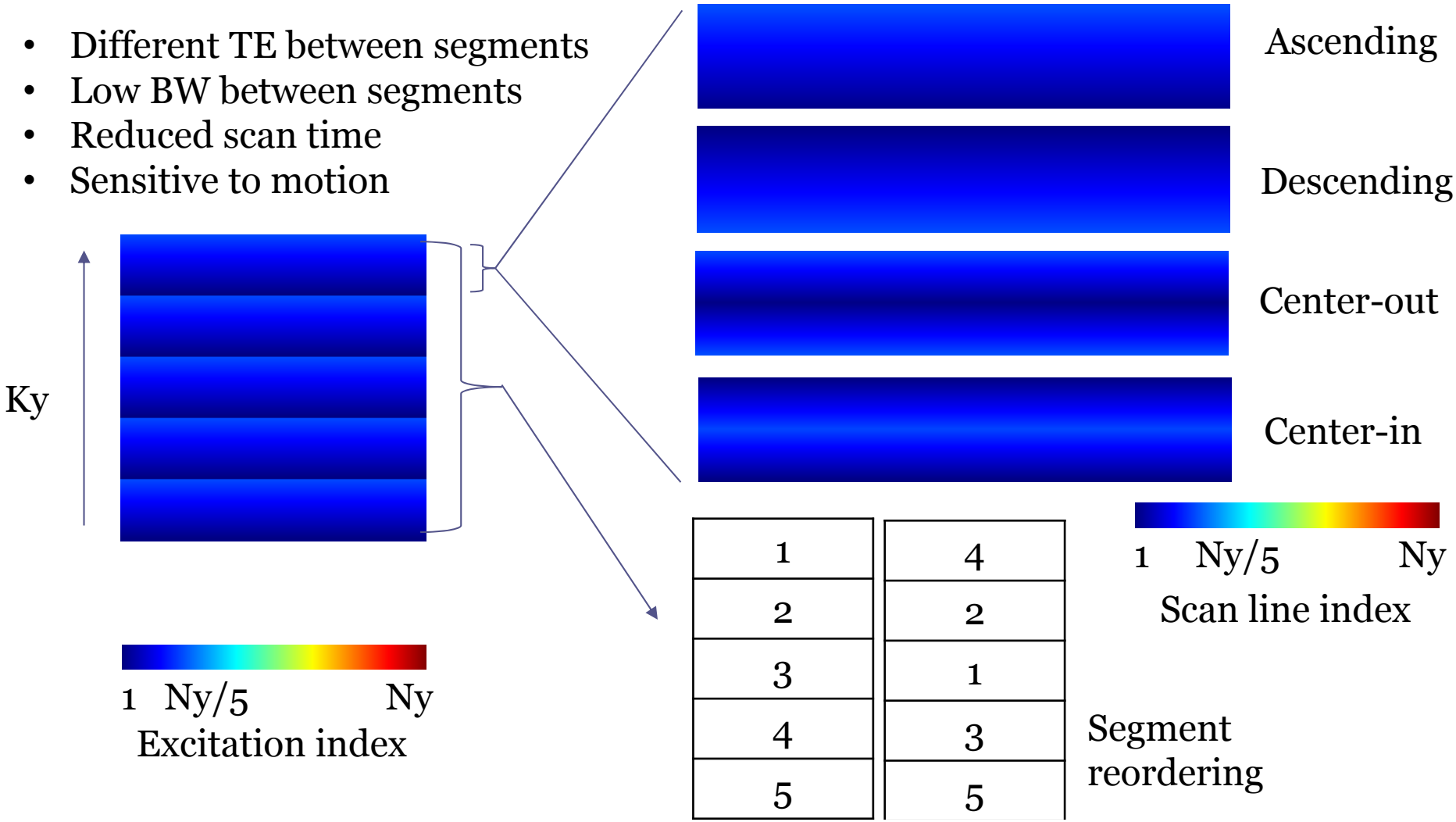


- Same TE for all lines
- Infinite BW along PE
- Long scan time
- Flexible PE reordering

Filling segmented k-space

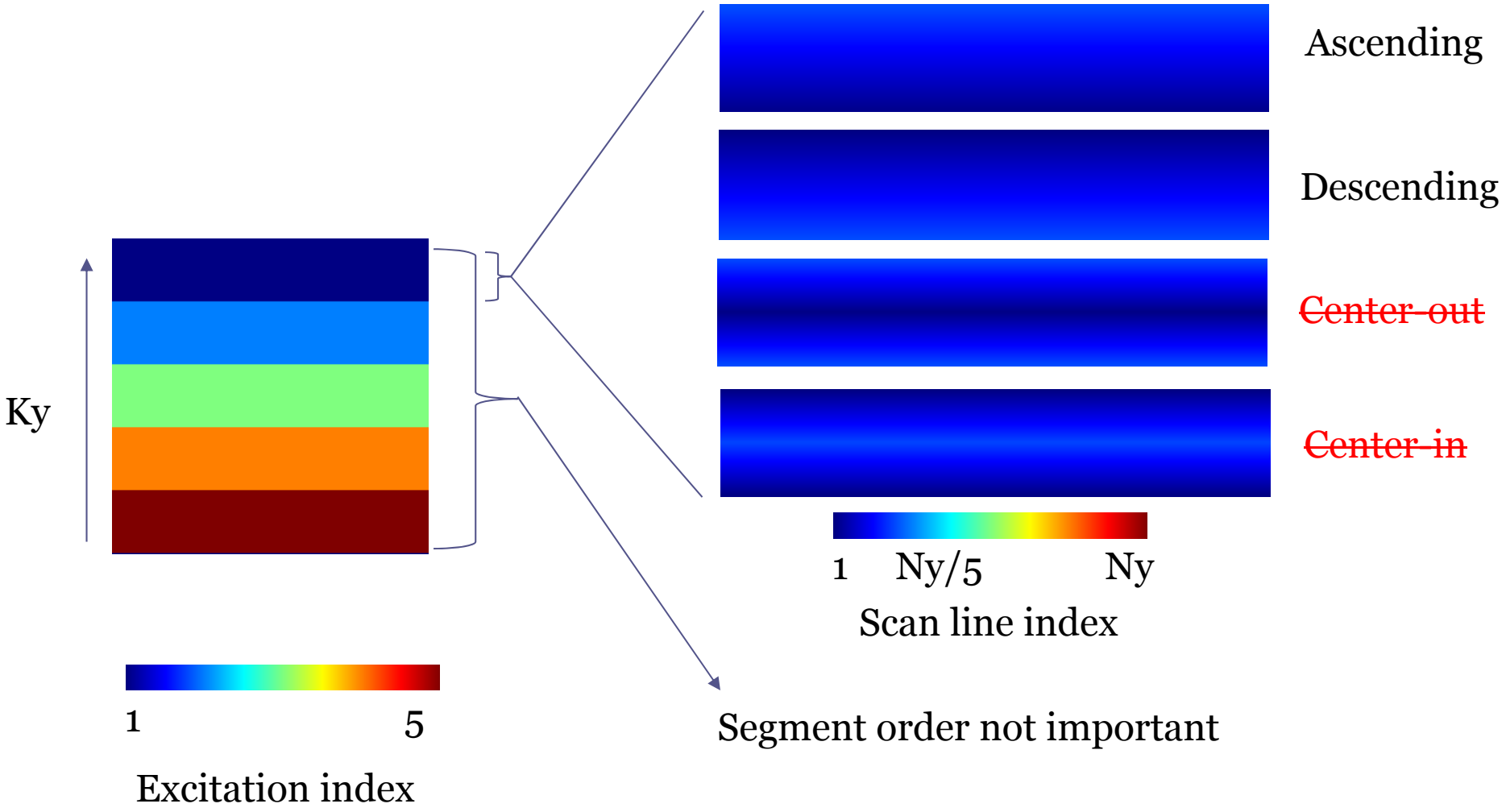
- Multi-echo acquisition (interleaved segments)

- Different TE between segments
- Low BW between segments
- Reduced scan time
- Sensitive to motion



Filling segmented k-space

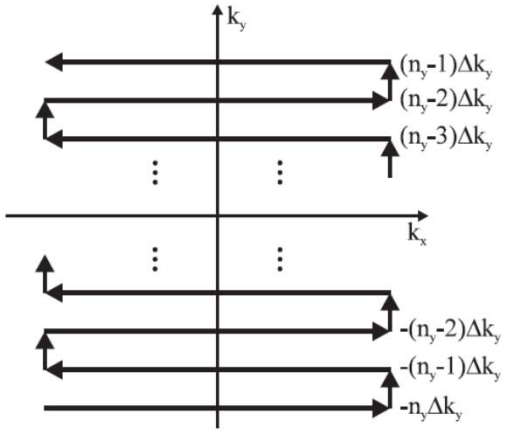
- Multi-echo acquisition (simple offset segments)

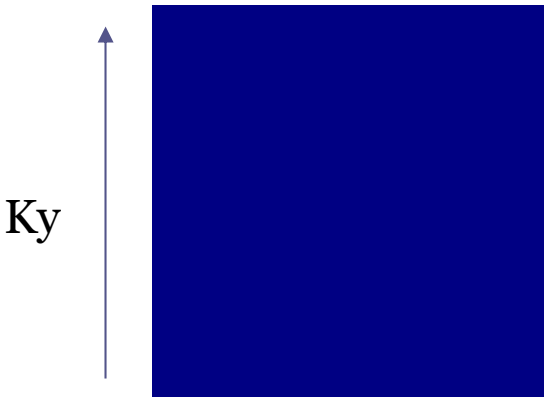


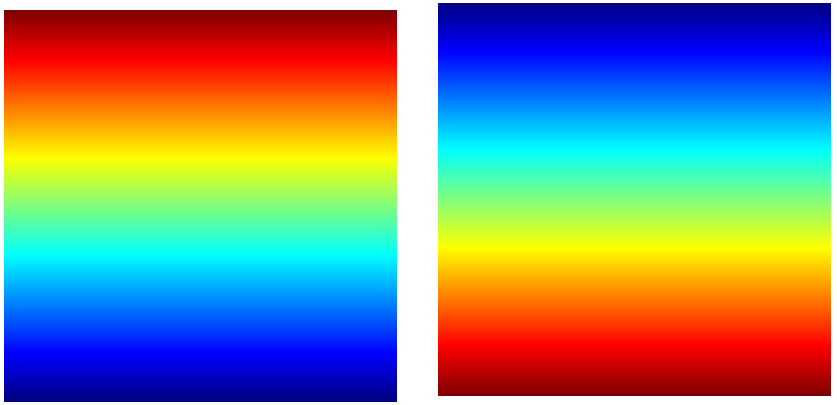
Filling segmented k-space

- Single shot acquisition

- Different TE between lines
- Low BW along PE
- Very short scan time
- Insensitive to motion







1 Ny

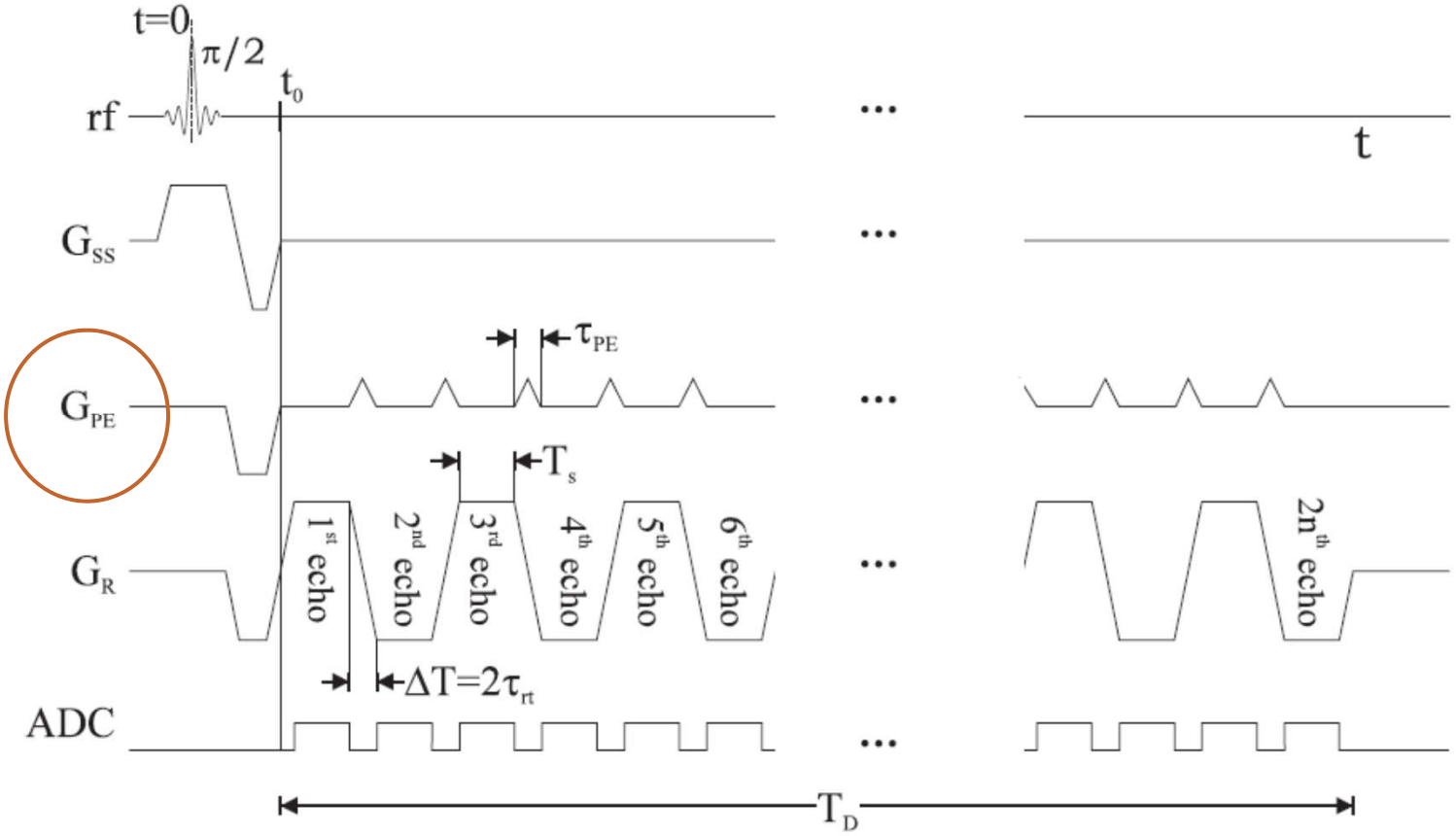
Excitation index

1 Ny

Scan line index

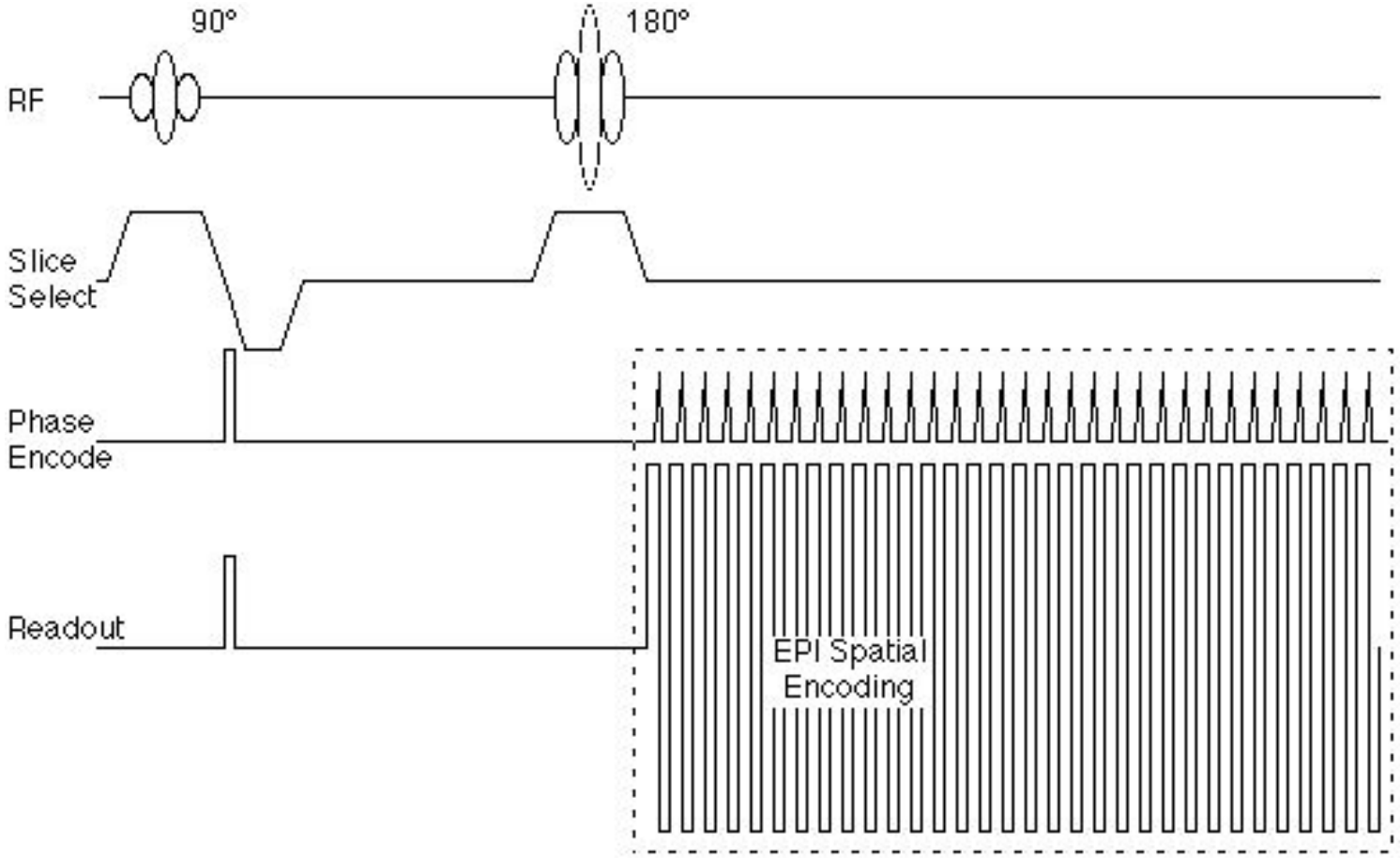
Echo Planar Imaging (EPI)

Gradient echo EPI



Echo Planar Imaging (EPI)

Spin echo EPI



EPI

- 'Blipped' phase encoding
- PE lines reordering
  - N/2 Ghosting
- T2* Weighting
- T2* filtering effects

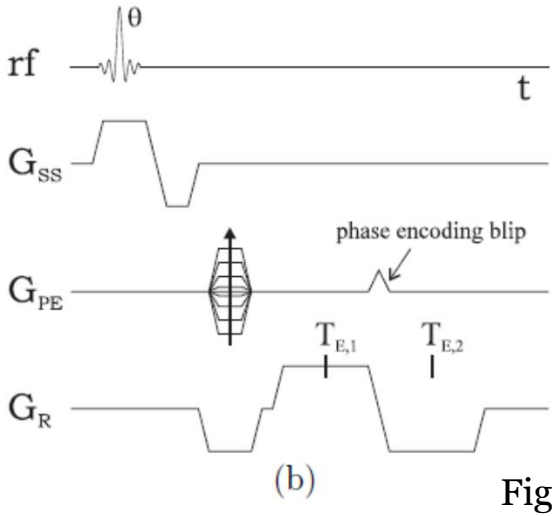


Fig 19.2

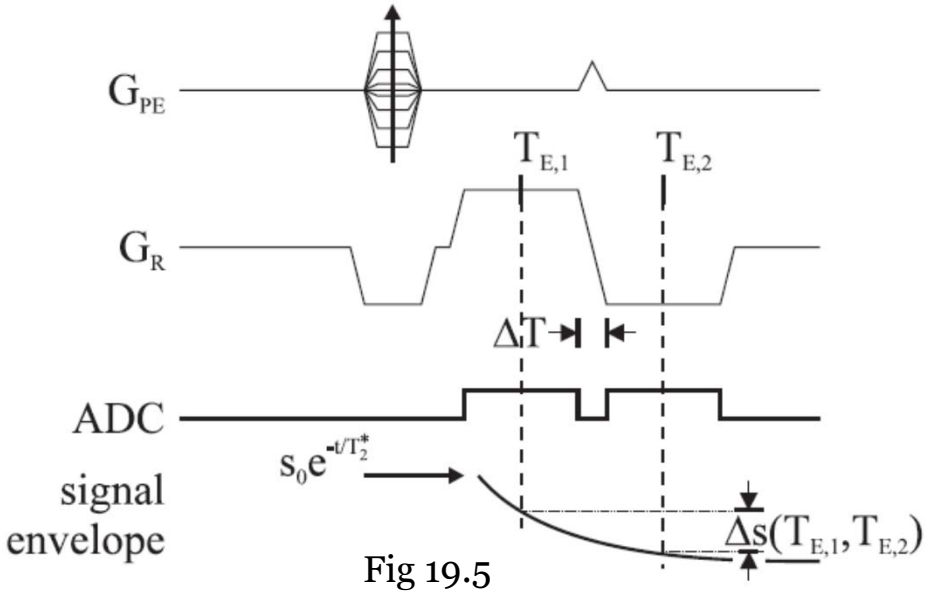
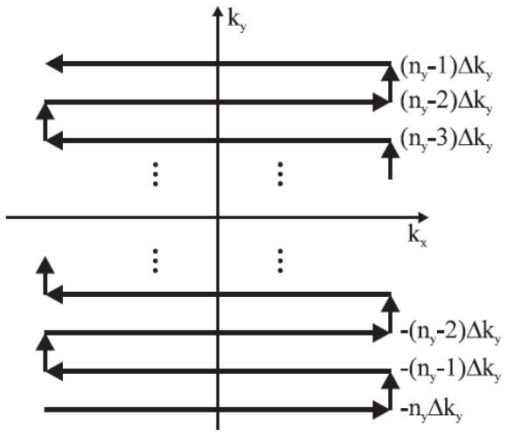


Fig 19.5



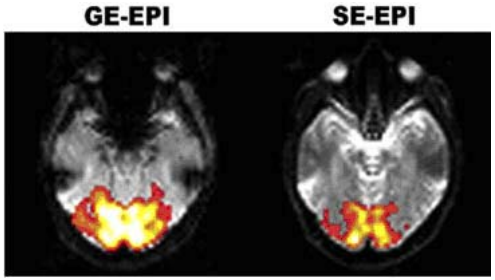
EPI: characteristics

- T2* or T2 weighted
- Usually 2D interleaved slice excitation with long TR
  - Avoid T1W
  - Multiple slice imaging w/o slice profile crosstalk
  - Efficient sequence design (for Seg-EPI)
- Can be single shot or segmented
- Acceleration/filter effect reduction
  - Parallel imaging
  - RO segmentation
- 3D available
  - Higher resolution and SNR
  - Longer scanning time and has mixed T1 weighting

EPI: considerations

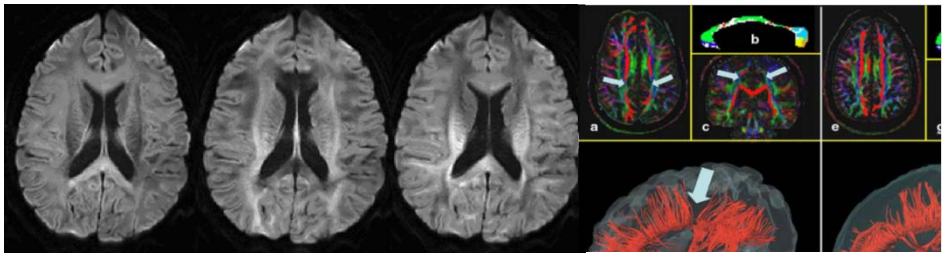
- RO resolution (sampling rate)
  - High bandwidth to shorten each readout
- PE resolution
  - Collect all lines roughly within T2* value
- PE blips
  - Constant blip gradients
- RO bandwidth (typically 2k-3kHz/px)
  - Sampling rate, SNR, RO duration
- PE bandwidth (BW_{PE}=1/echo spacing ≈ BW_{RO}/N_{RO})
  - Image distortion, T2* effects, chemical shift
- Scanning speed
- Safety (noise, vibratio, neuro-stimulation)

ssEPI images and artifacts

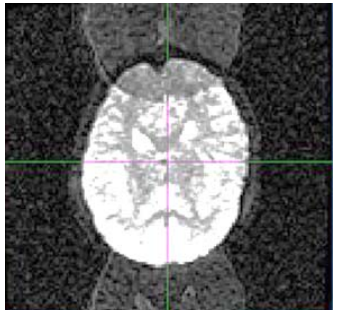


(Ye, et al. Neuroimage, 2010)

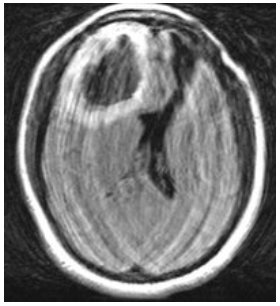
DWI / DTI



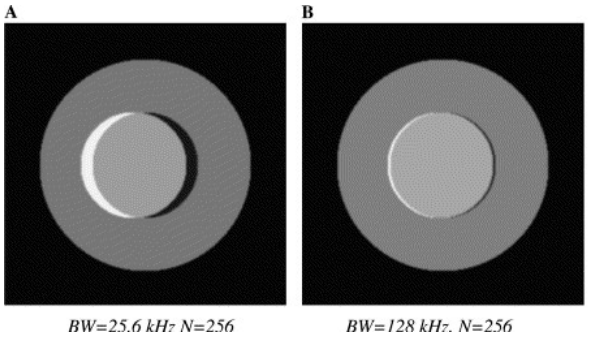
(e-mri.blogspot.com)



N/2 ghosting



Motion artifact



Chemical shift artifact

(Benoit-Cattin, JMR, 2005)

- GE- vs. SE-EPI
- Limited resolution
- Image distortion
- Signal dropouts (susceptibility artifact) or mis-registration
- N/2 ghosting
- Chemical shift artifact
- Motion artifact (rare)

Alternative forms of EPI

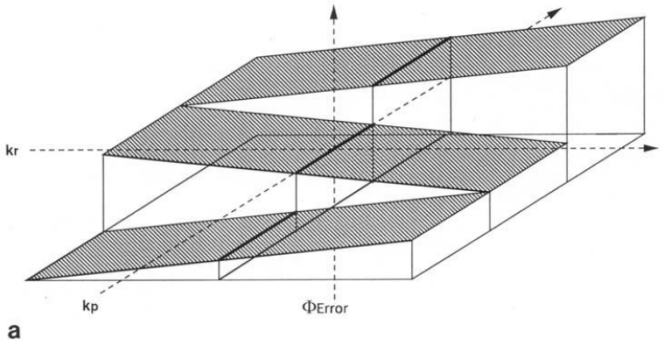
- Nonuniform sampling (during ramp-ups and -downs)
- Segmented EPI
  - Simple offset segments
  - Interleaved segments
- Angled k-space EPI
- Segmented EPI with Oscillating Gradients
- Spiral readout EPI
  - Another popular form for short TE EPI

EPI summary

- Pros and Cons
  - Temporal vs. spatial resolution
  - T2*W vs. susceptibility artifacts
  - SNR vs. distortion
- EPI-dominated applications
  - Functional MRI
  - Perfusion (ASL, contrast enhanced PWI)
  - Diffusion

Segmented k-space: Artifacts and phase correction

Phase error source	Artifact	Solution
Global BG gradient G'	K-space shift	Navigator, phase correction
Chemical shift	Water/fat shift	Fat saturation
Eddy current	Geometric distortion	Reduce ETL
Motion	Ghosting artifact (segmented)	Head fixation, navigator



(Feinberg, MRM, 1994)

Q: What is the difference between this phase error and EPI's N/2 artifact?

Spin echo based segmented acquisition

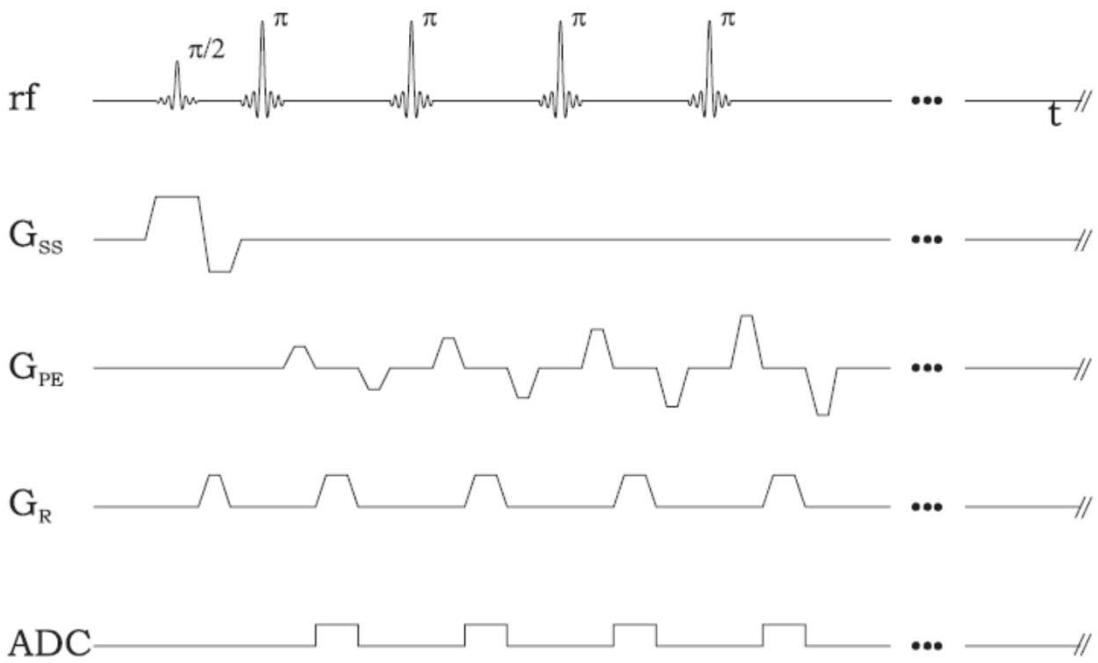
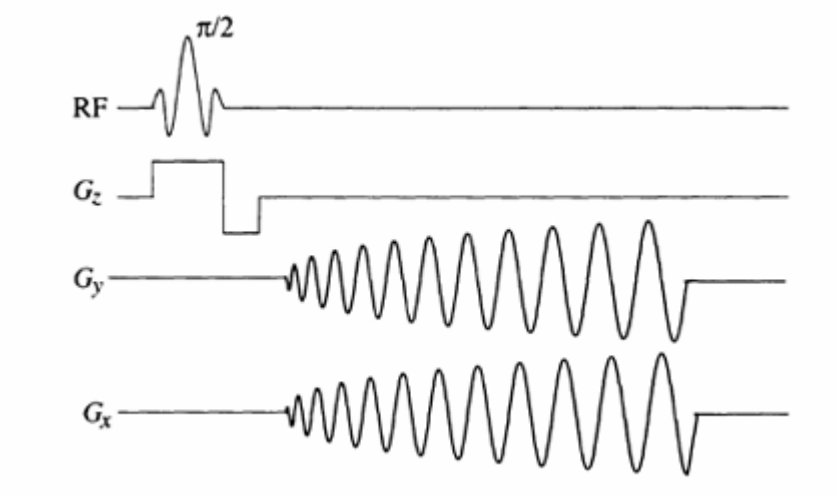
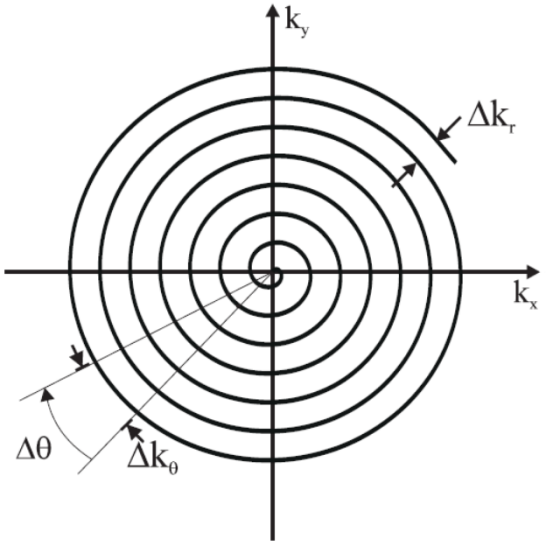


Fig 19.29

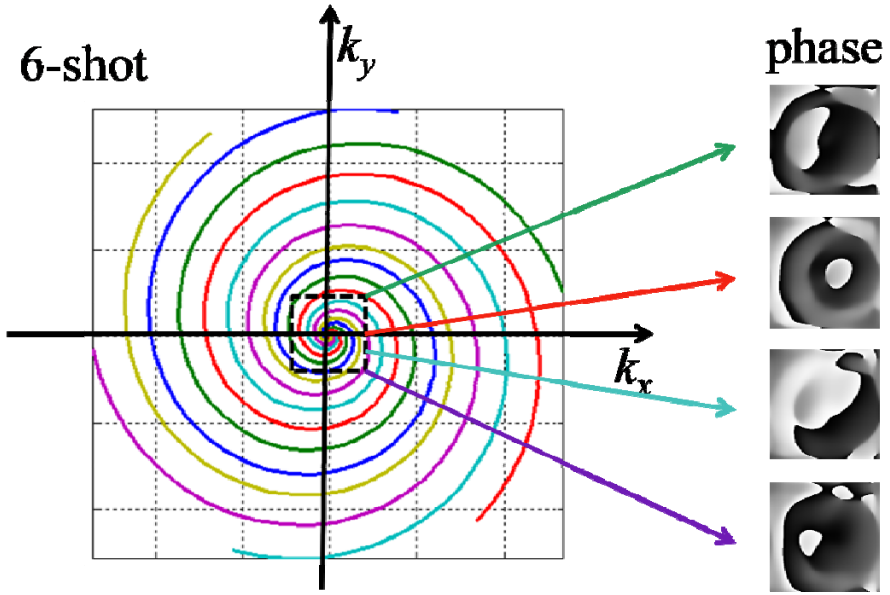
- FSE or TSE
- Scan time, SAR & T2 decay demands segmented acquisition
- More flexible reordering schemes due to flexible PE gradient table
- CPMG design, variable flip angle

Spiral acquisition





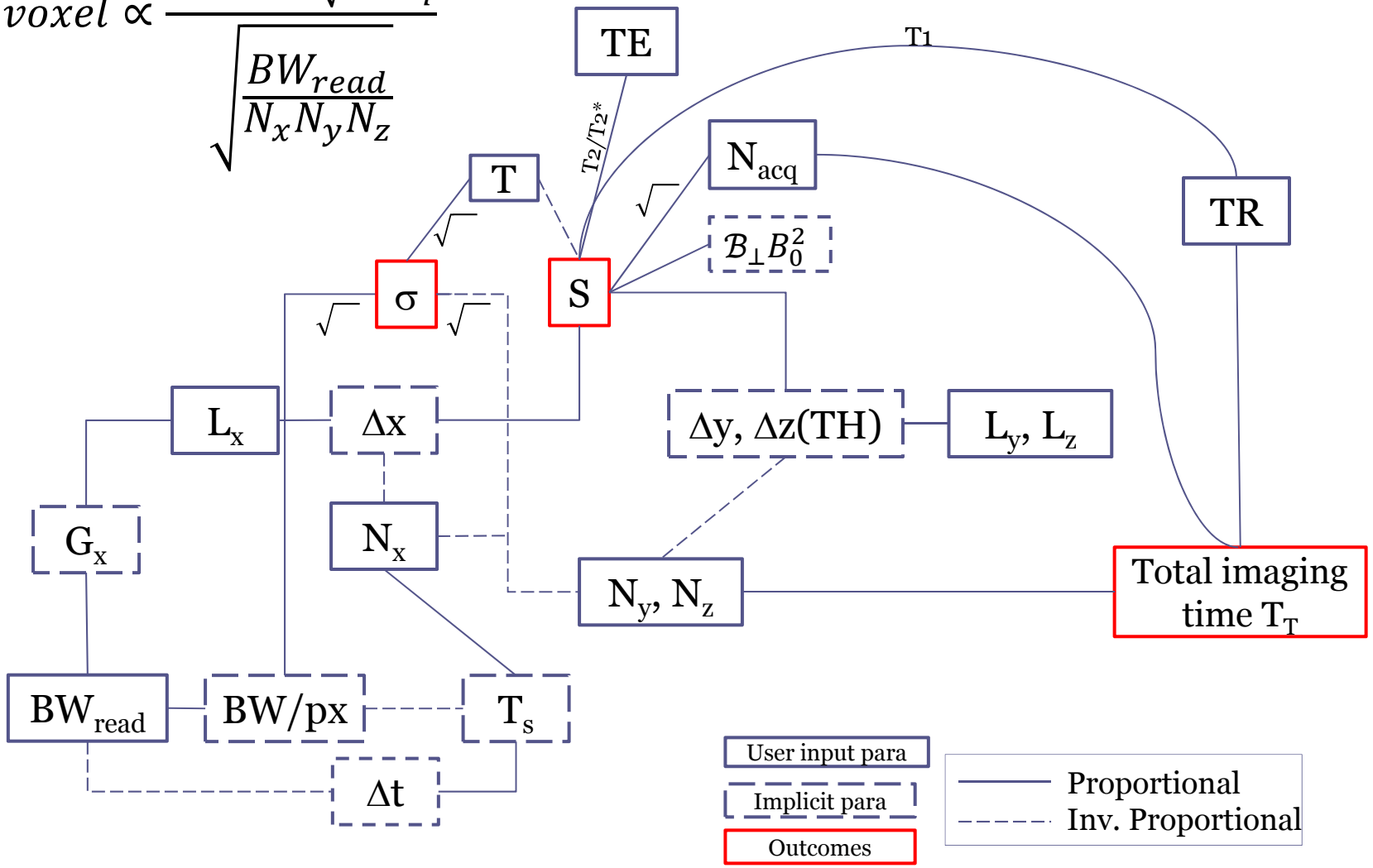
- Smooth gradient changes
- Very short TE
- Very fast scan even for higher resolution
- Segmented acquisition compatible



http://cbir.med.tsinghua.edu.cn/

SNR dependence on imaging parameters

$$SNR/voxel \propto \frac{\Delta x \Delta y \Delta z \sqrt{N_{acq}}}{\sqrt{\frac{BW_{read}}{N_x N_y N_z}}}$$



Homework

19.1 – 19.5

Next Session

Chapter 20.1-4/6