Fast Scan: Echo Planar Imaging

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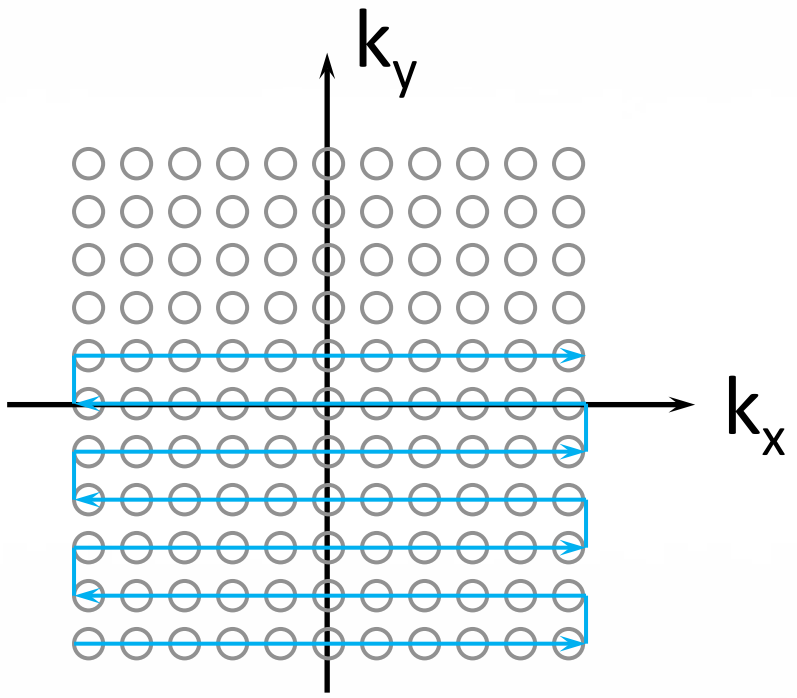
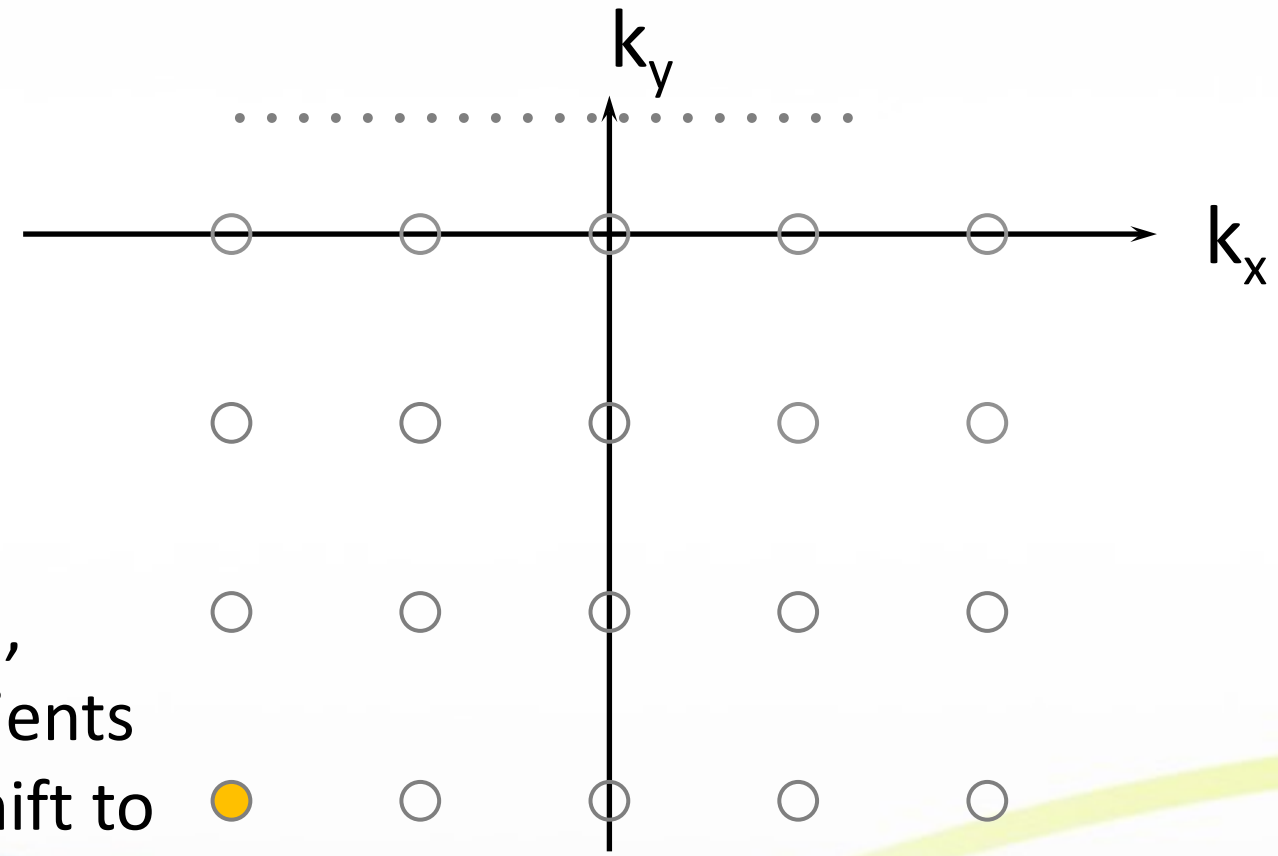
K-space trajectory



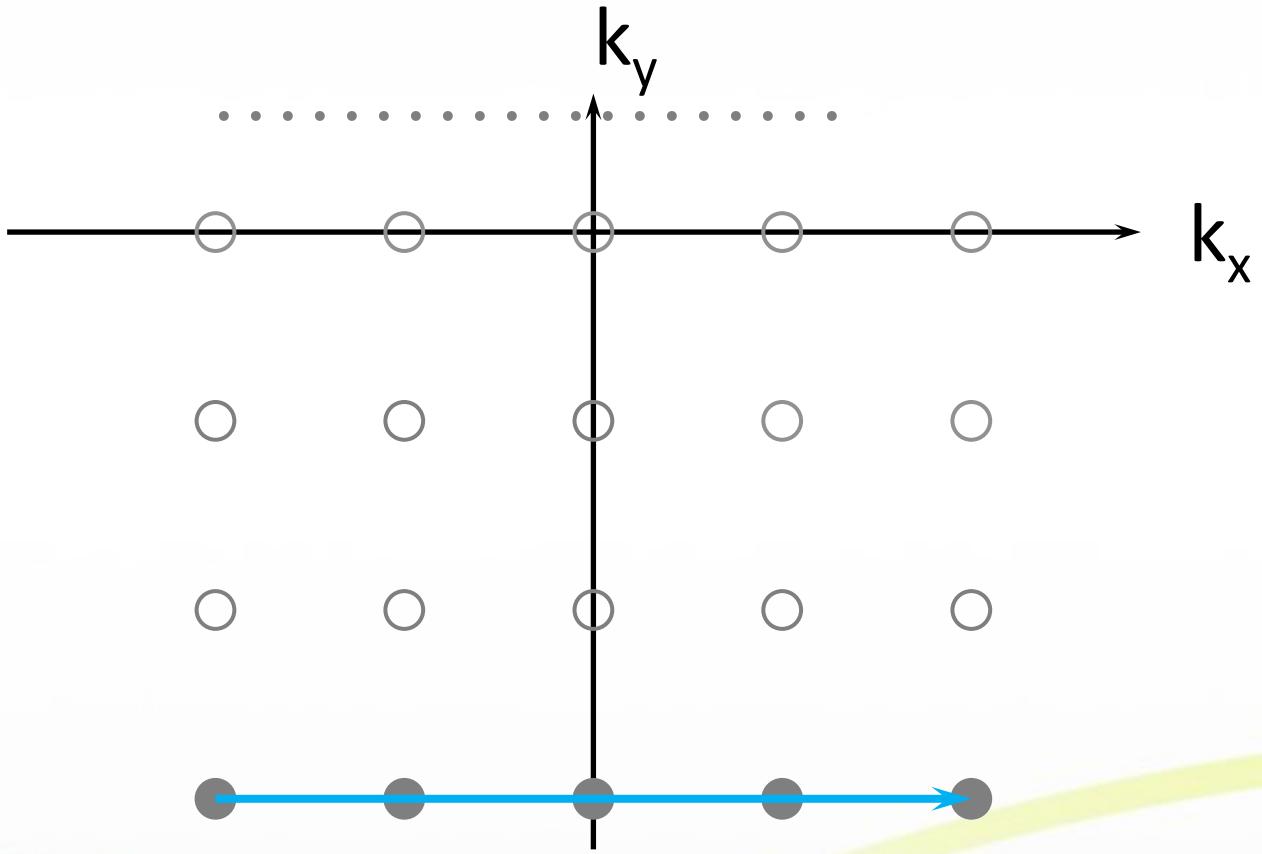
How to finish this trajectory?

Navigate k-space by switching gradients



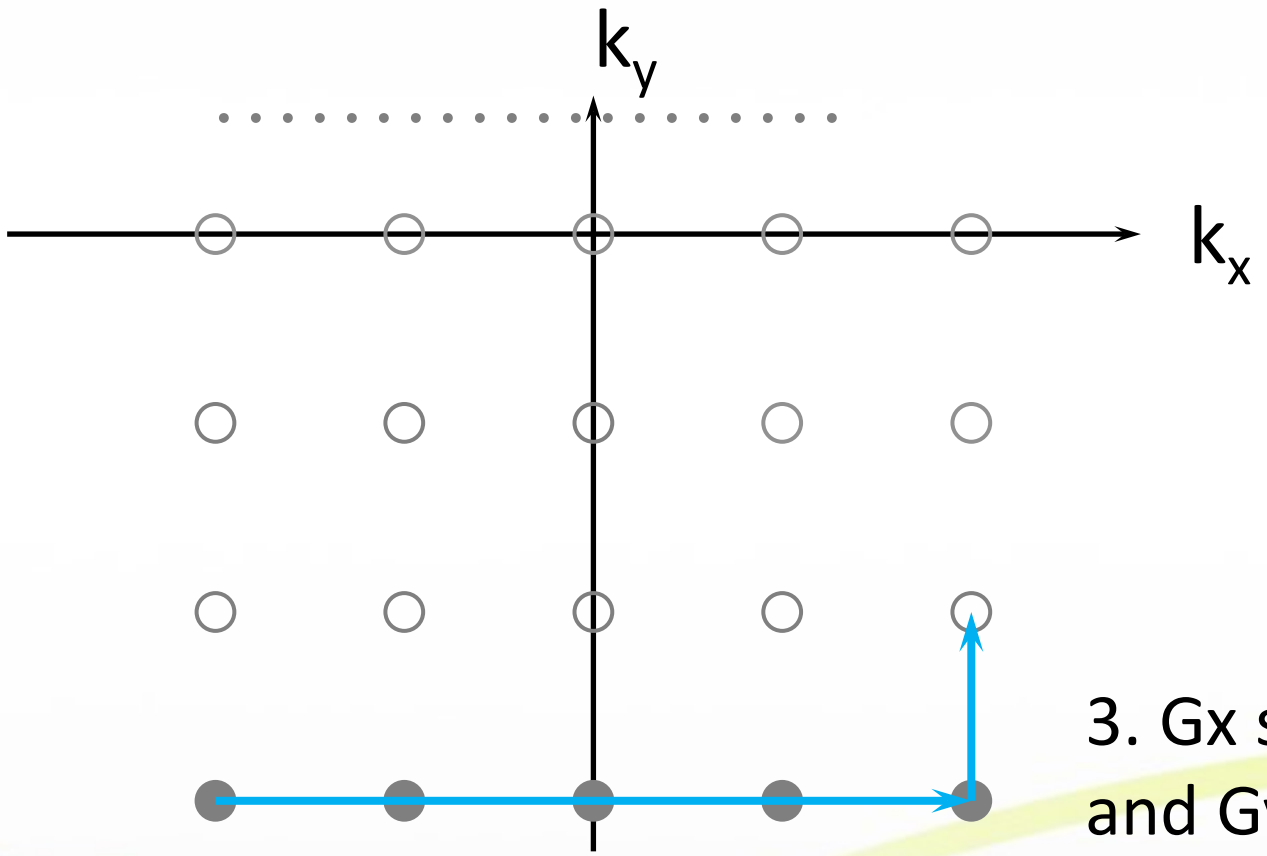
1. RF excitation, preparing gradients applied for a shift to this point

Navigate k-space by switching gradients



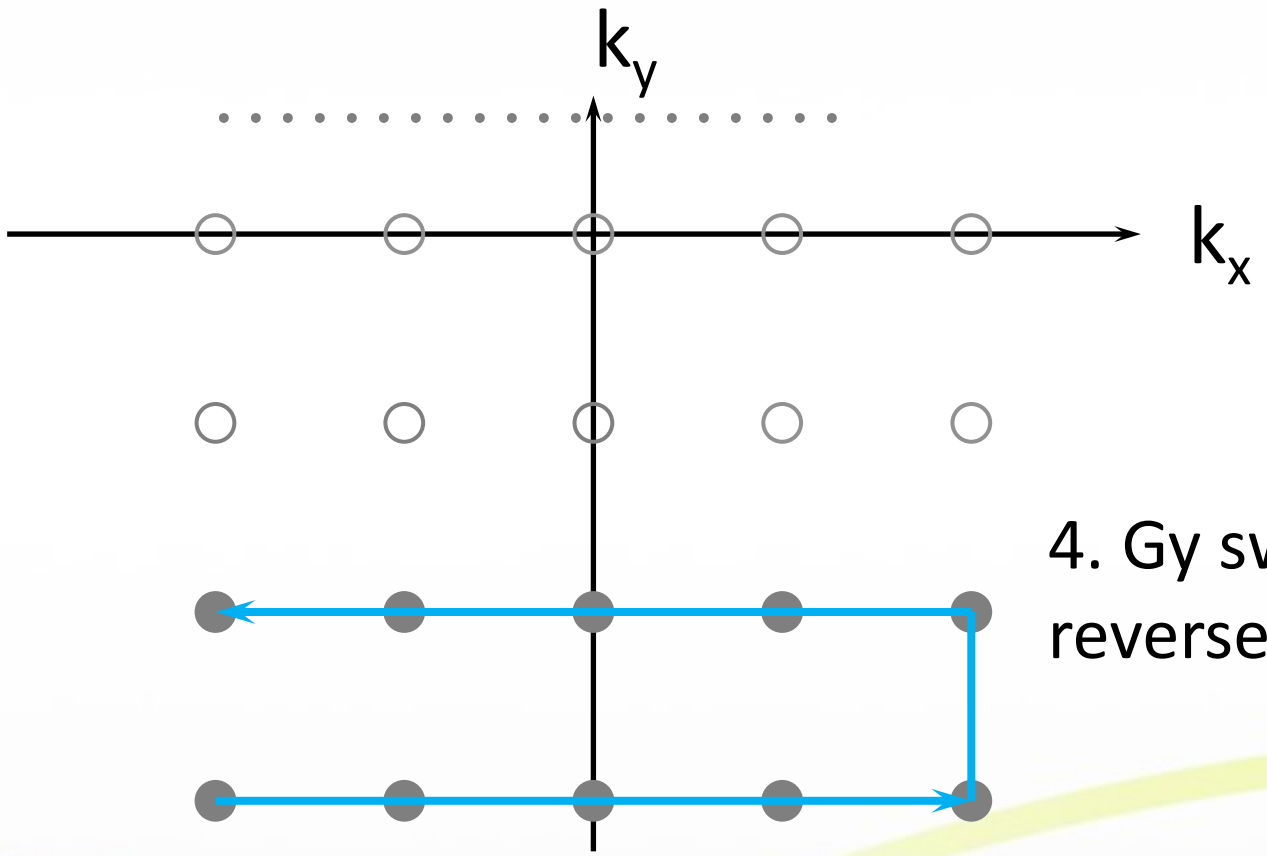
2. Gx switched on
and data sampling

Navigate k-space by switching gradients



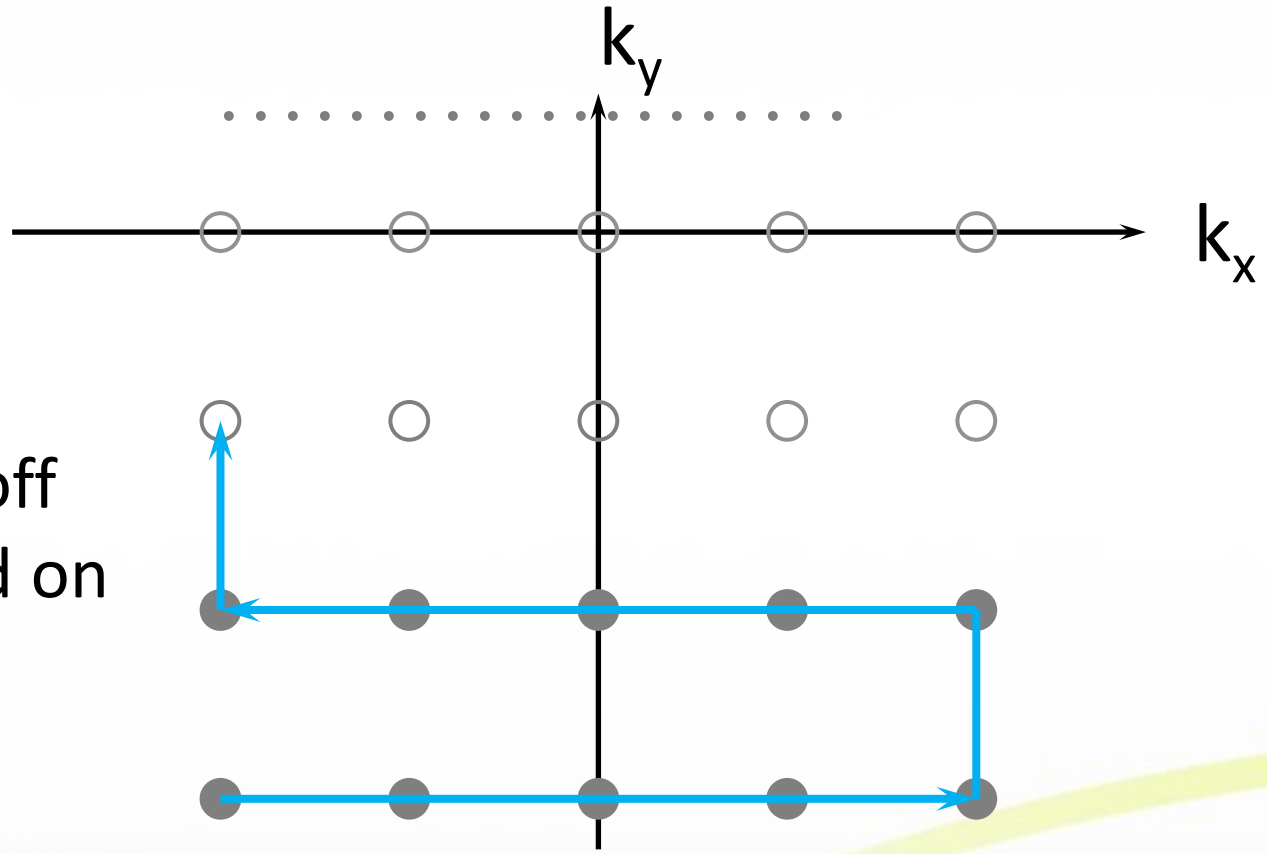
3. Gx switched off
and Gy switched on

Navigate k-space by switching gradients



4. Gy switched off and reversed Gx switched on

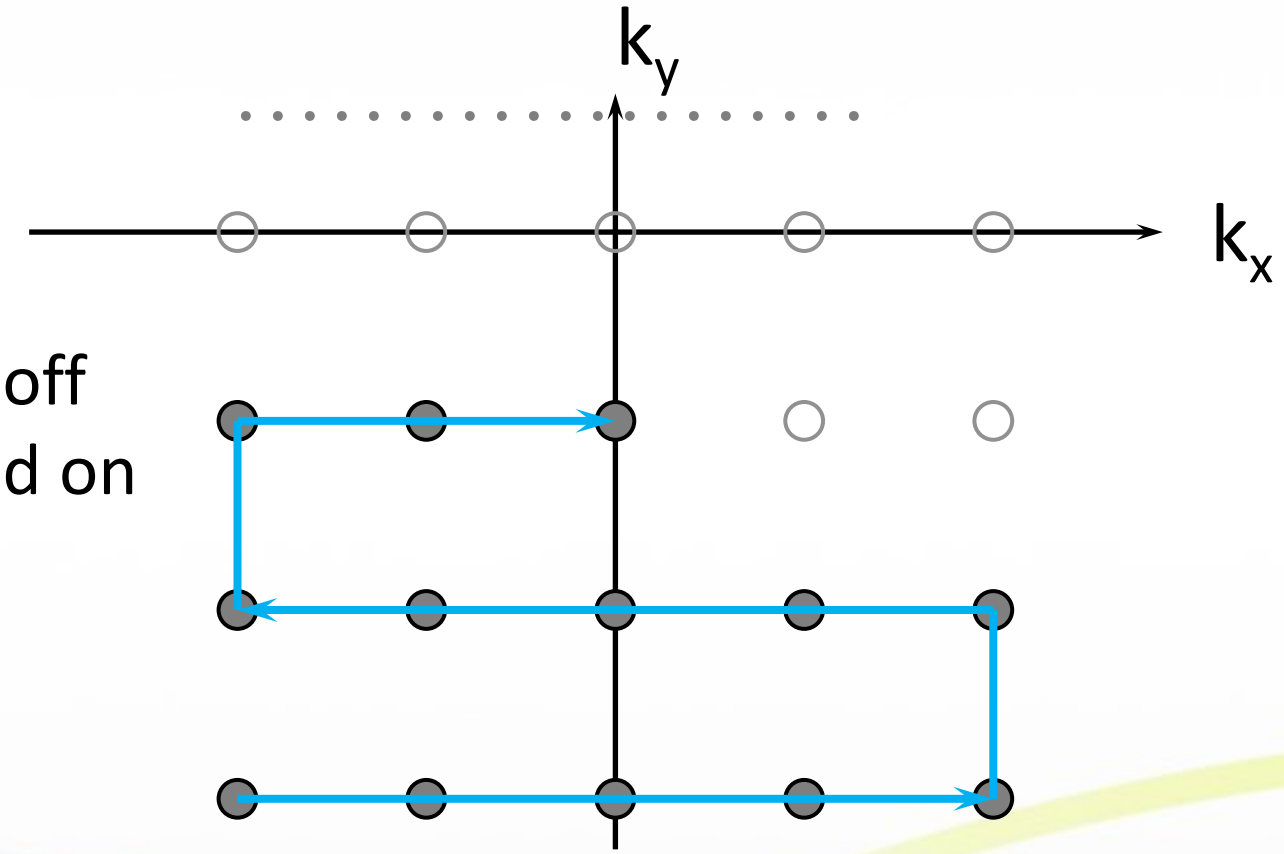
Navigate k-space by switching gradients



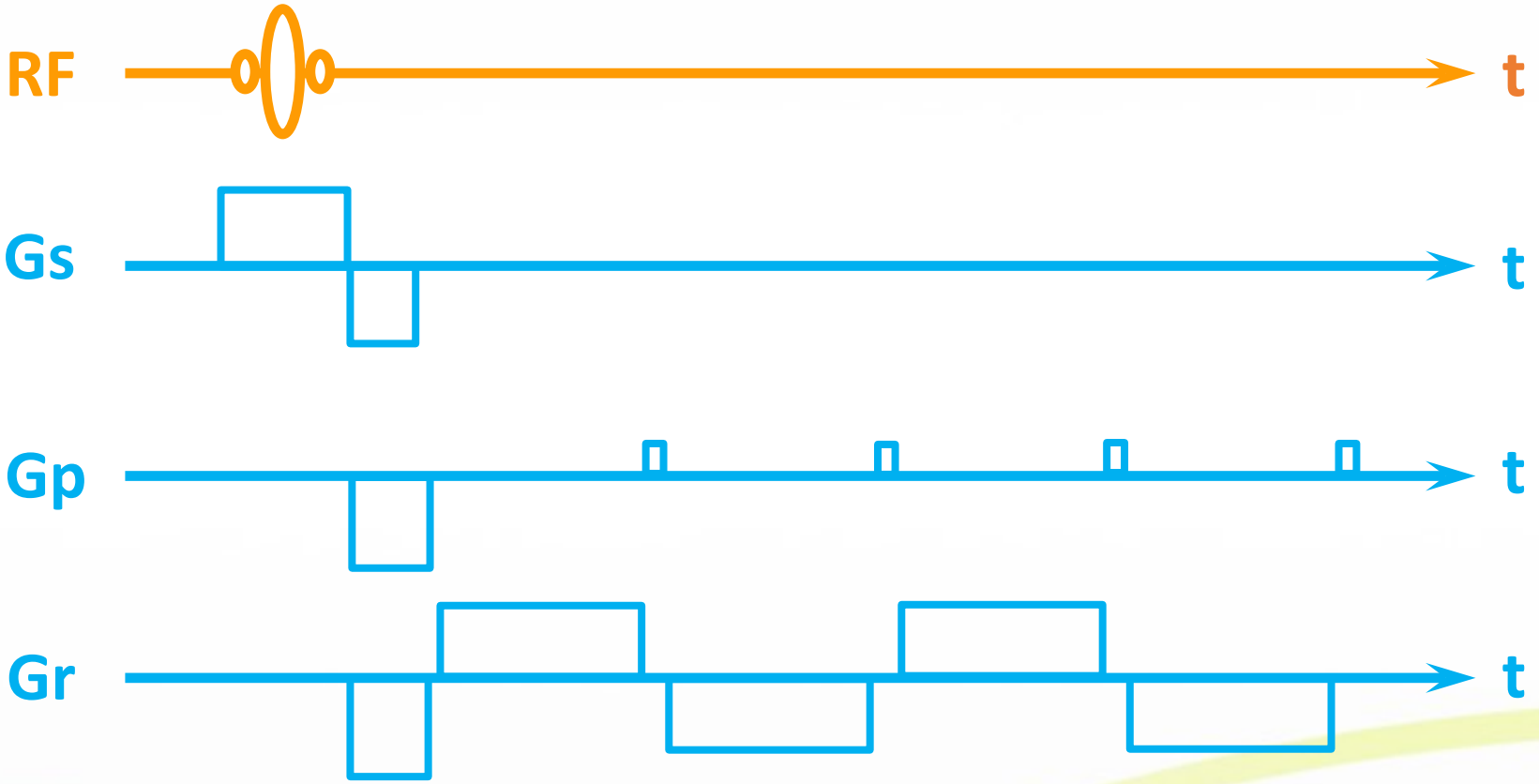
5. Gx switched off and Gy switched on

Navigate k-space by switching gradients

6. Gy switched off and Gx switched on



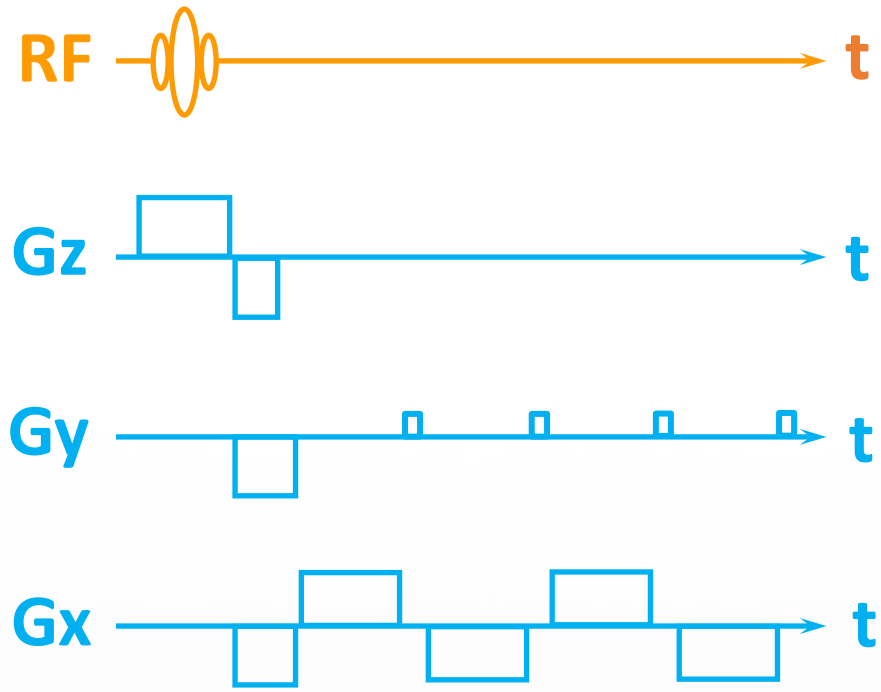
Pulse sequence

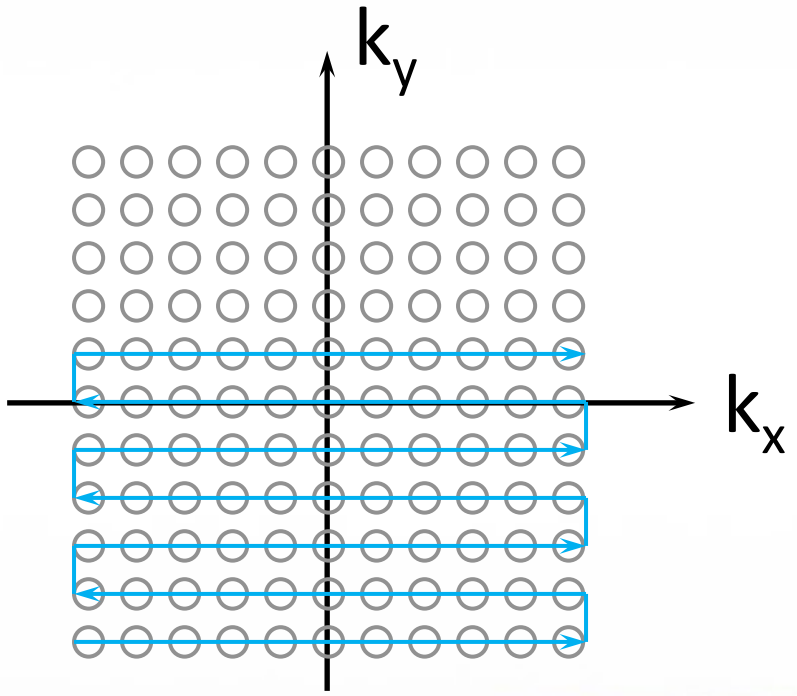


The “snap shot” MRI

- Echo planar imaging (EPI)
- Proposed by Sir Peter Mansfield (1977)
  - 2003 Nobel Prize laureate in Medicine
- Need only one single excitation for all data acquisition
  - Single shot

Echo planar imaging (EPI)





Scan time

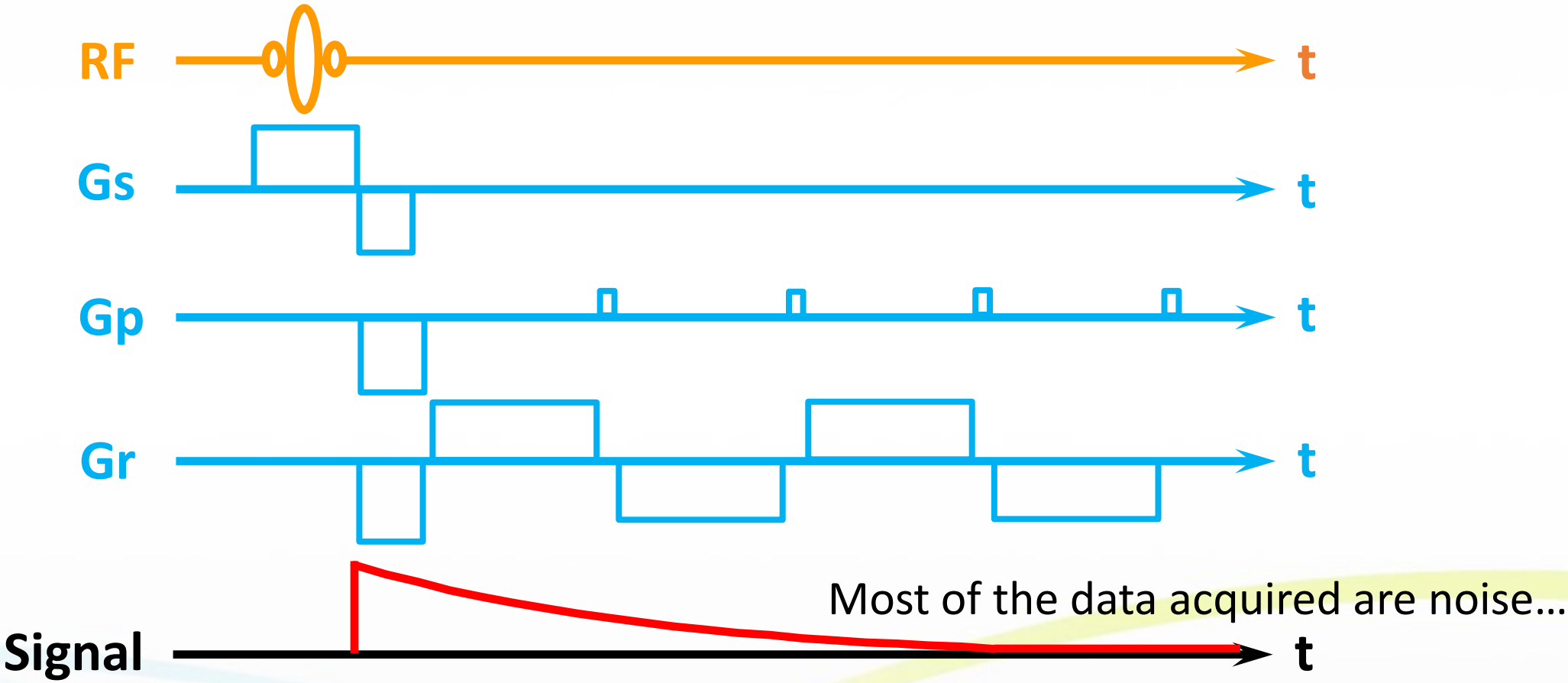
- If sampling frequency = 32 kHz (generally high)
  - 32 data points for every msec
  - 8 msec for 256 points
  - 256x256 matrix: 8x256 ≈ 2 sec
- Looks good !?

MR signals decay rapidly…

- Time duration for data acquisition = 2 sec
- T2* of soft tissues is around 40 ms at 1.5 T

- Signals are gone very early due to T2* decay

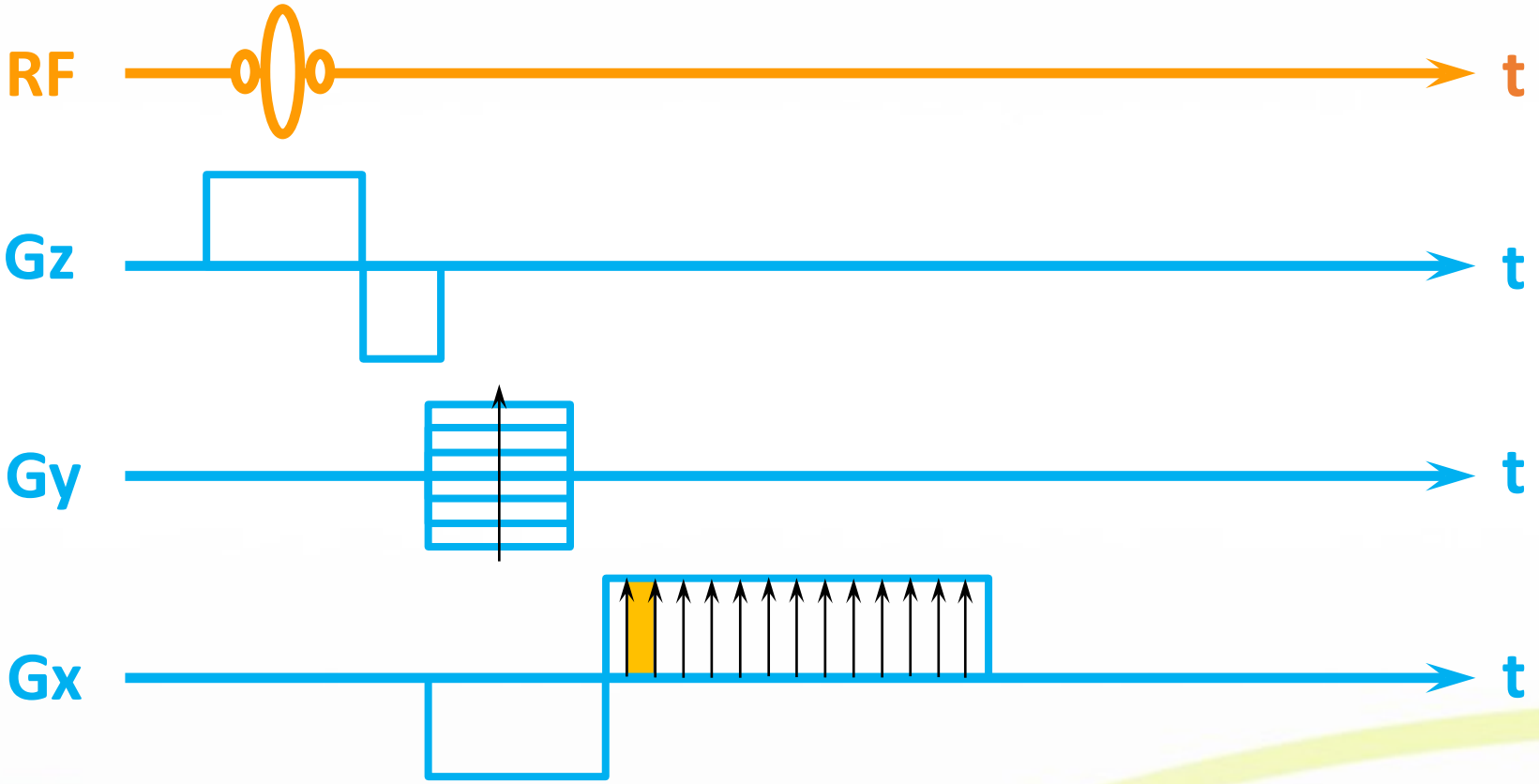
EPI and T2* decay



How to reduce the total readout

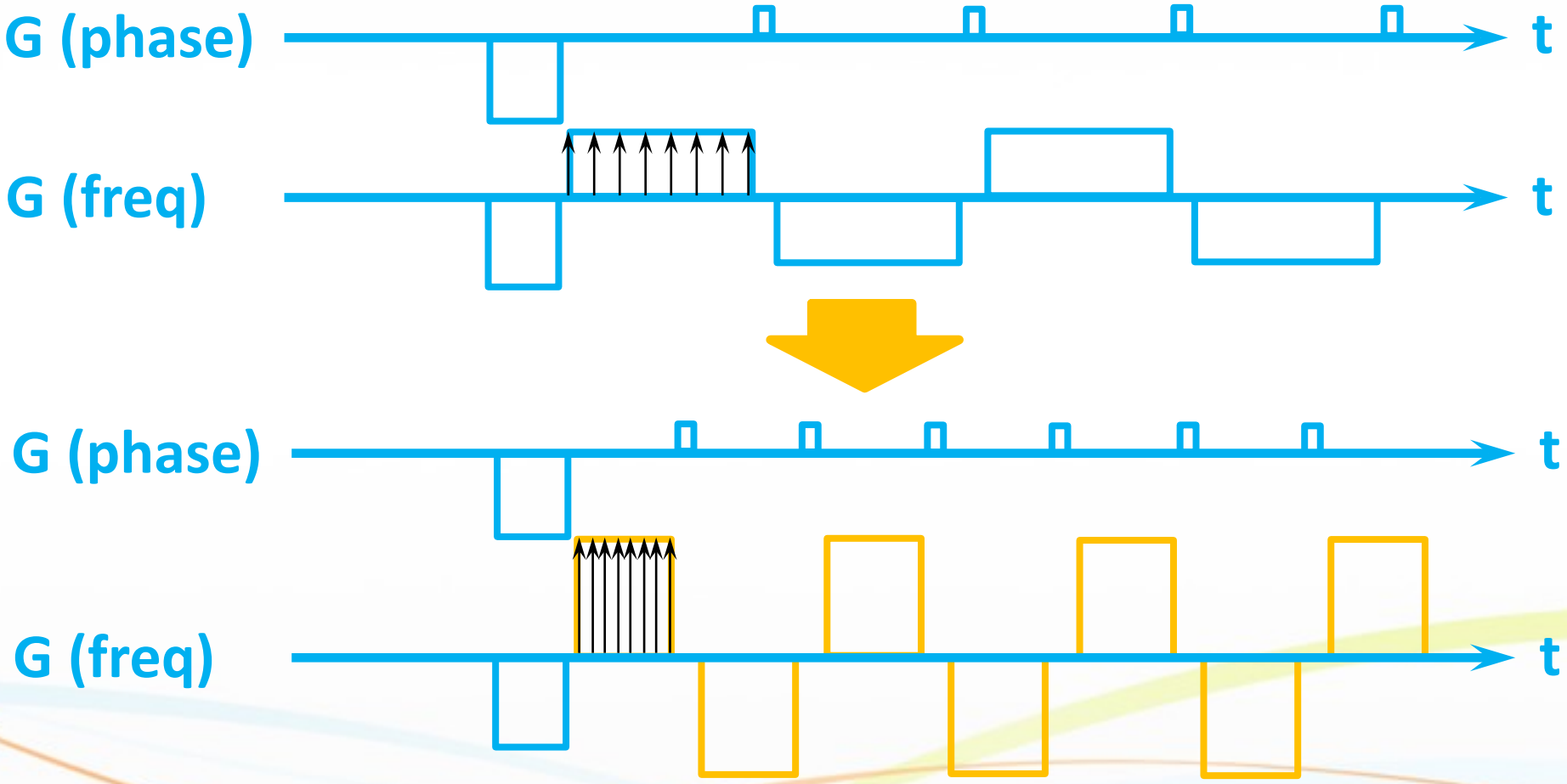
- Reduce the imaging matrix (64x64?)
  - Tradeoff: lower resolution
- Increase the sampling frequency (128 kHz?)
  - Stronger gradients required

Gradient and sampling frequency



FOV is inversely proportional to the area of colored region

Acceleration of data sampling



Re-calculation for higher fs

- If sampling frequency = 128 kHz
  - 128 data points for every msec
  - 64 msec for 128x64 matrix

- Gradient = 1.25 G/cm when FOV = 24 cm

An example for brain EPI

- Given a 128x128 matrix with FOV = 20 cm
  - Fs = 256 kHz → Total readout = 64 ms
  - G(readout) ~ 3.0 G/cm

- Approaching limitation of gradient strength

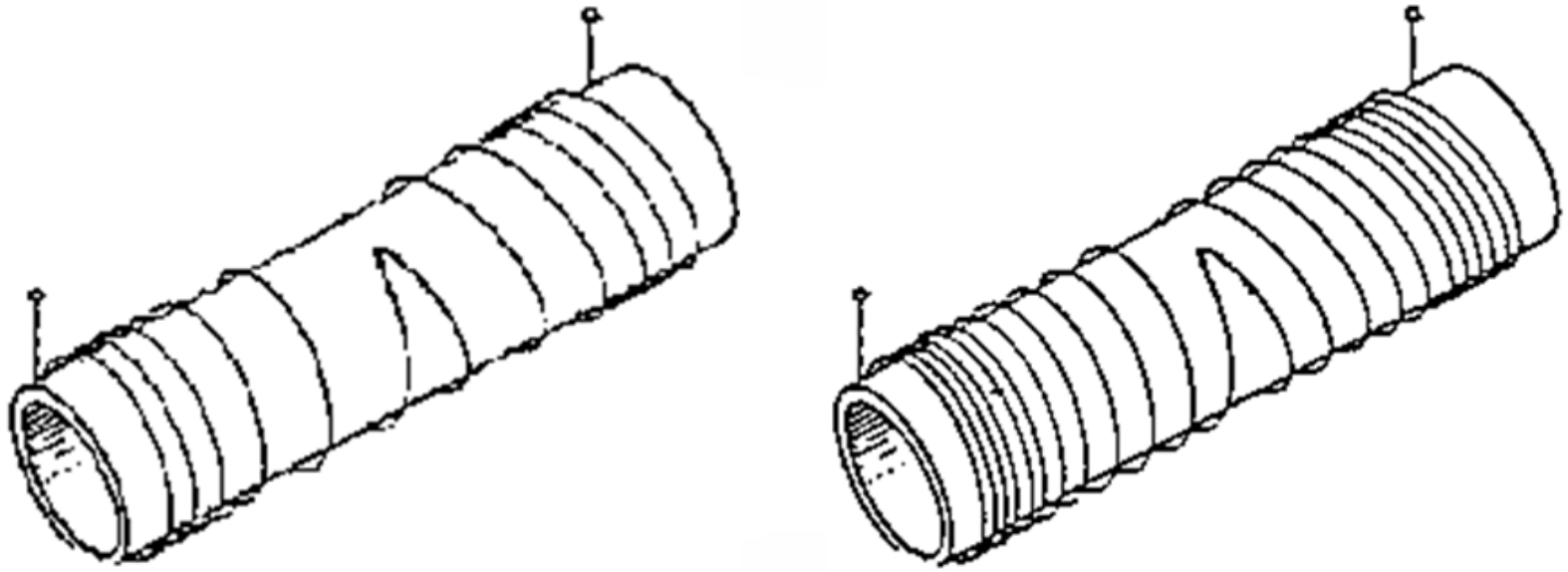
Basic requirement for EPI

- Strong gradient system
- High-speed data acquisition and processing
  - High data rate
  - Large memory unit
  - Fast processing

And EPI might need more…

- Gradient coil: electromagnet with specific wiring
- Strong gradient → more wiring
- More wiring → higher inductance
- Higher inductance → longer rise time

More wiring for stronger gradient

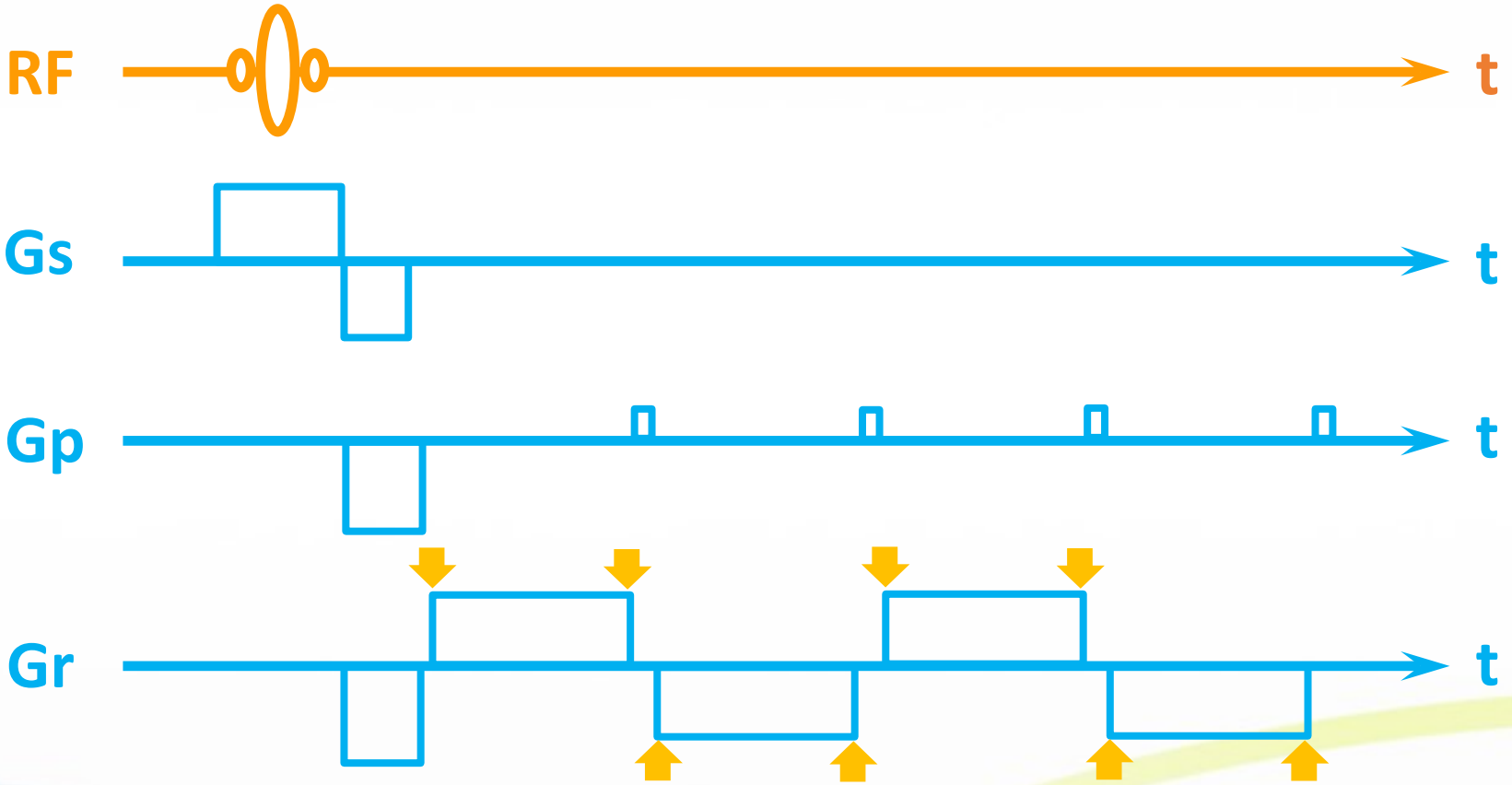


Higher inductance and longer rise time

Rise time of gradients

- Lenz’s law: the direction of induced current opposes the changing of applied current
- Gradient fields won’t change as fast as you want.
- The stronger the gradients, the longer the rise time.

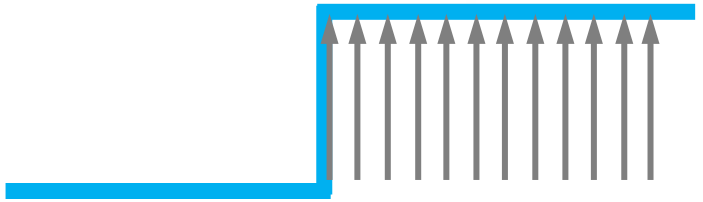
Pulse sequence



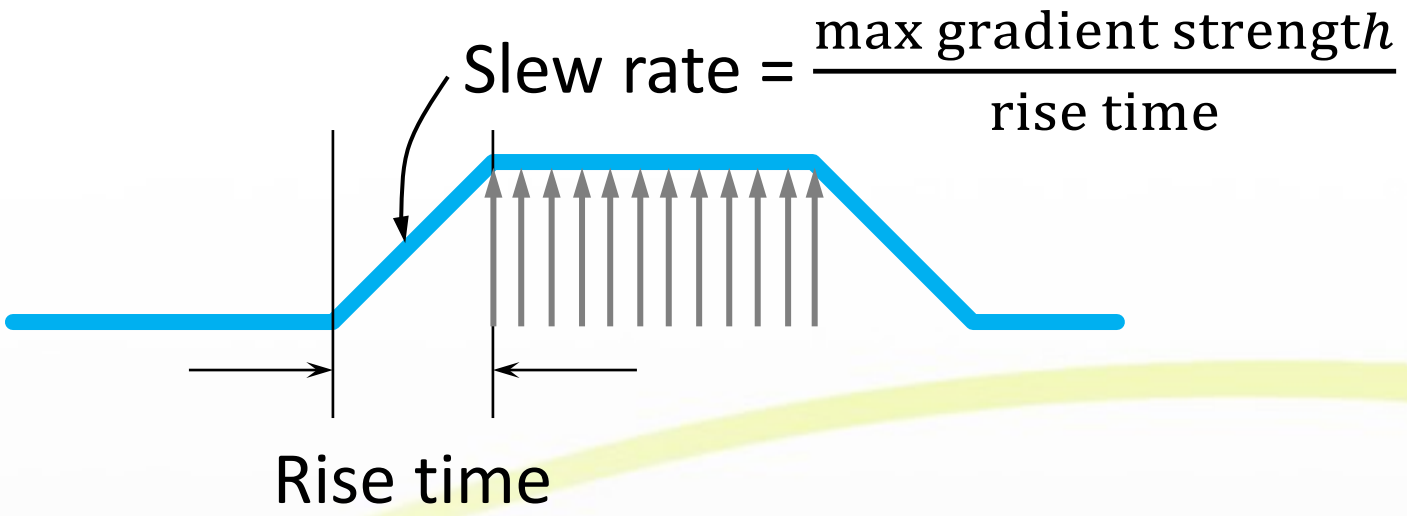
Not an ideal rectangular shape in practical

Welcome to the real world

What we hope for



What it actually happens



Rise time for EPI gradient

- 0.5-1.0 msec in 1990s
  - 0.5 x 2 x 128 = 128 msec
  - No time for data sampling…
- 0.1-0.3 msec in 2020s
  - Slew rate 200 T/m/s

Constraint on EPI readout

- Time for DAQ + Time for gradient preparation < 1-2 T2* of tissues (40-80 msec)
- Rise time = 0.1-0.3 msec
- Sampling freq. has to be raised. (1 MHz!)

Hardware requirement for EPI

- High-speed data acquisition and processing
- Strong gradient system
- Ultra-short rise time

- $$$

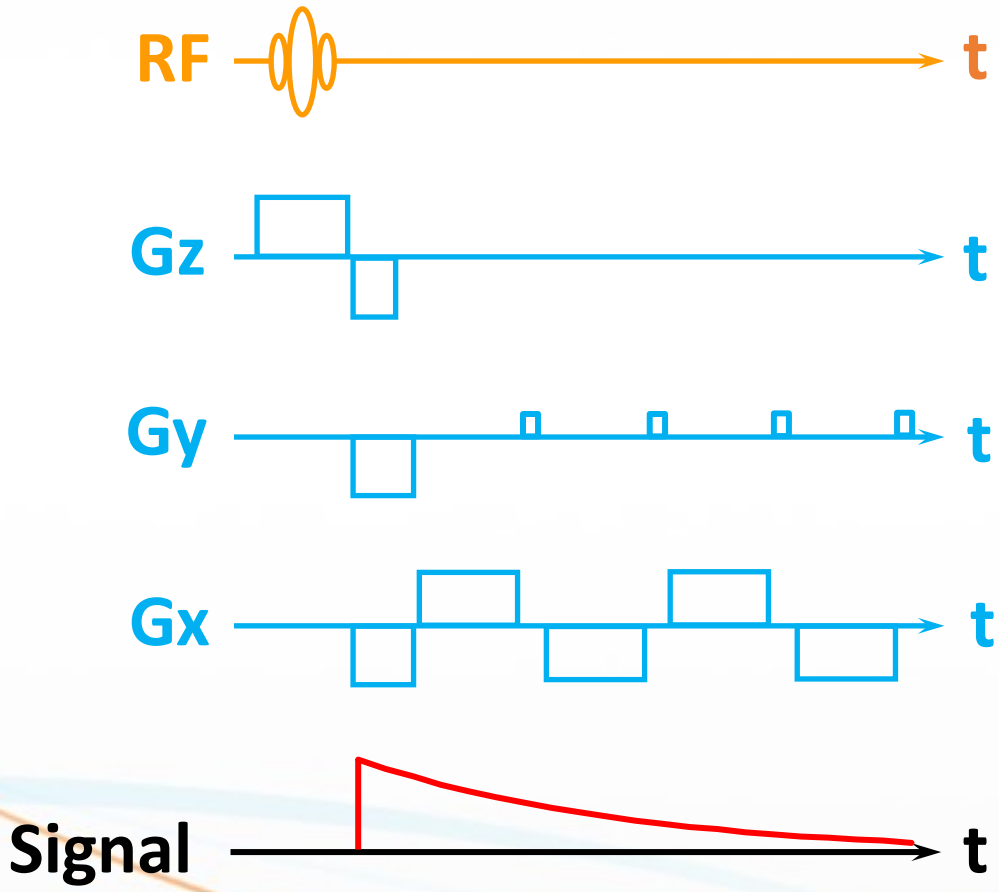
Even so…

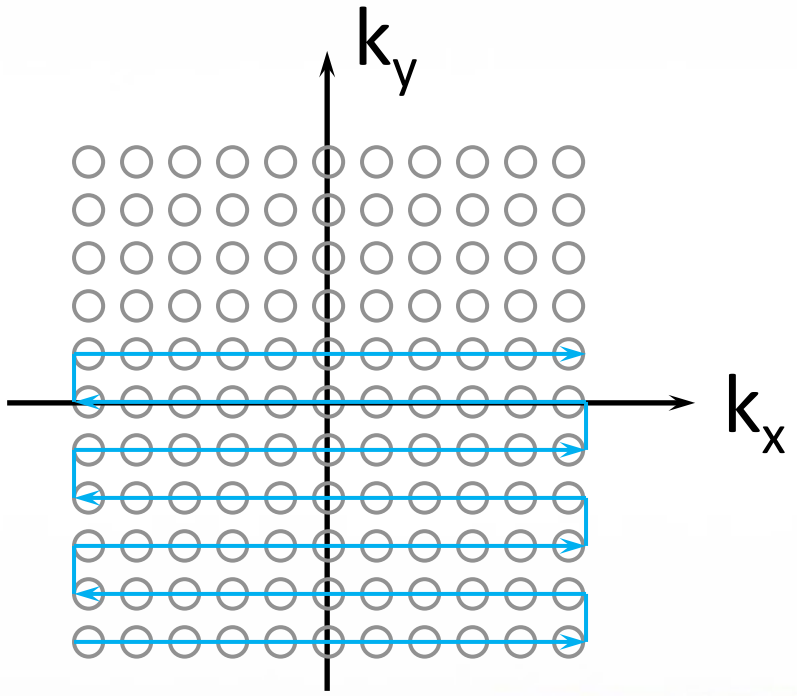
- **Low spatial resolution**
  - 128x128 matrix is almost the limit for SS-EPI
- **Low SNR** due to high bandwidth
  - SNR $\propto 1/\sqrt{BW}$
  - As fs is increased from 16 kHz to 1 MHz, SNR becomes to its one-eighth

More than that…

- In comparison with T2*, EPI readout (> 60 msec) is relatively long.
- K-space data is influenced by different T2* weighting.
  - Undesirable effects on image appearance

T2* effect on EPI

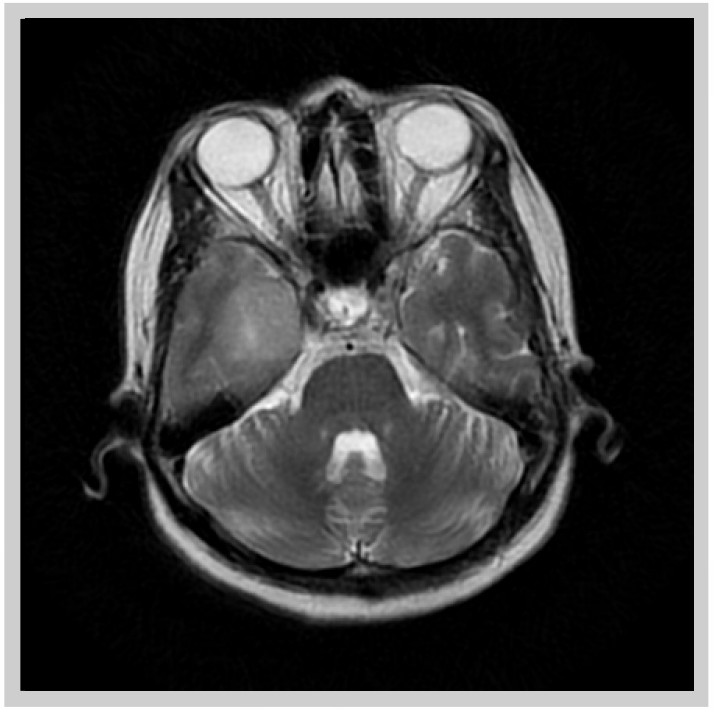




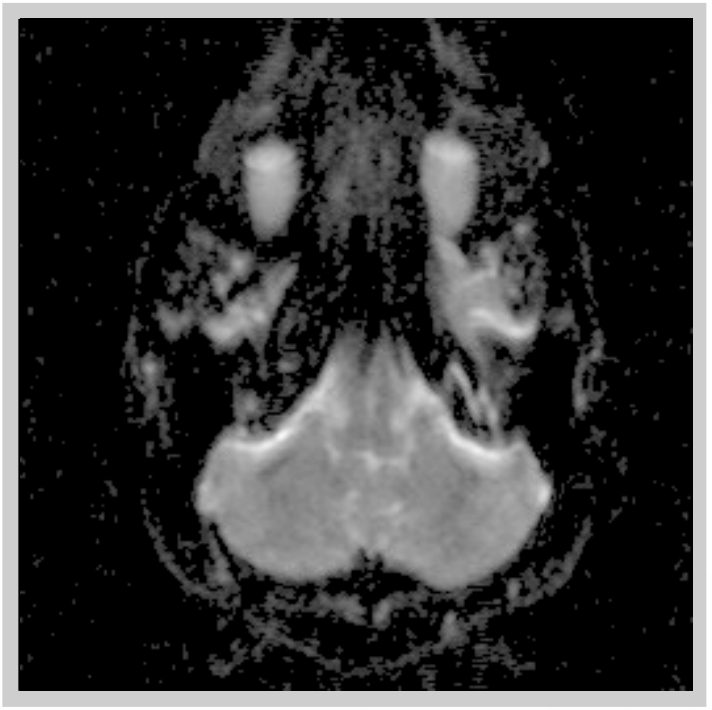
Artifacts in EPI

- Amplification of off resonance
  - Chemical shift
  - Susceptibility
  - Bias of center frequency
- Image distortion due to eddy currents and residual gradients
- Nyquist ghost

Strong image distortion in EPI



TSE T2



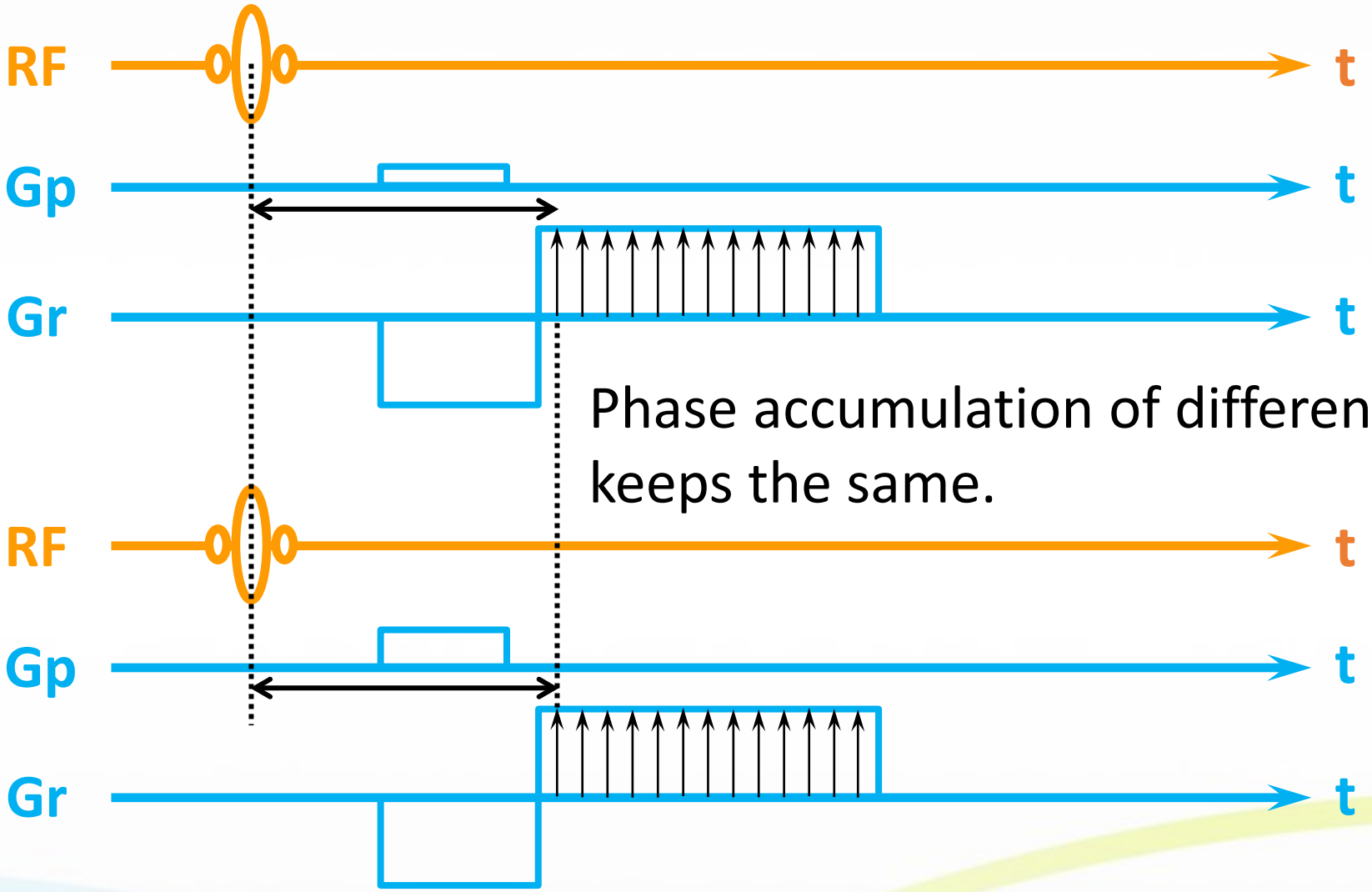
EPI T2

Let’s start with chemical shift artifact

- Magnetic field – resonant frequency – location
- The resonant frequencies of water and fat are intrinsically different.
- Shift in resonant **frequency** leads to shift in positioning along **frequency** encoding direction.

Chemical shift in FE and PE directions

- Chemical shift is only shown in frequency encoding direction.
- No chemical shift in phase encoding direction!
  - Phase accumulation due to chemical shift is not changed by phase encoding gradients

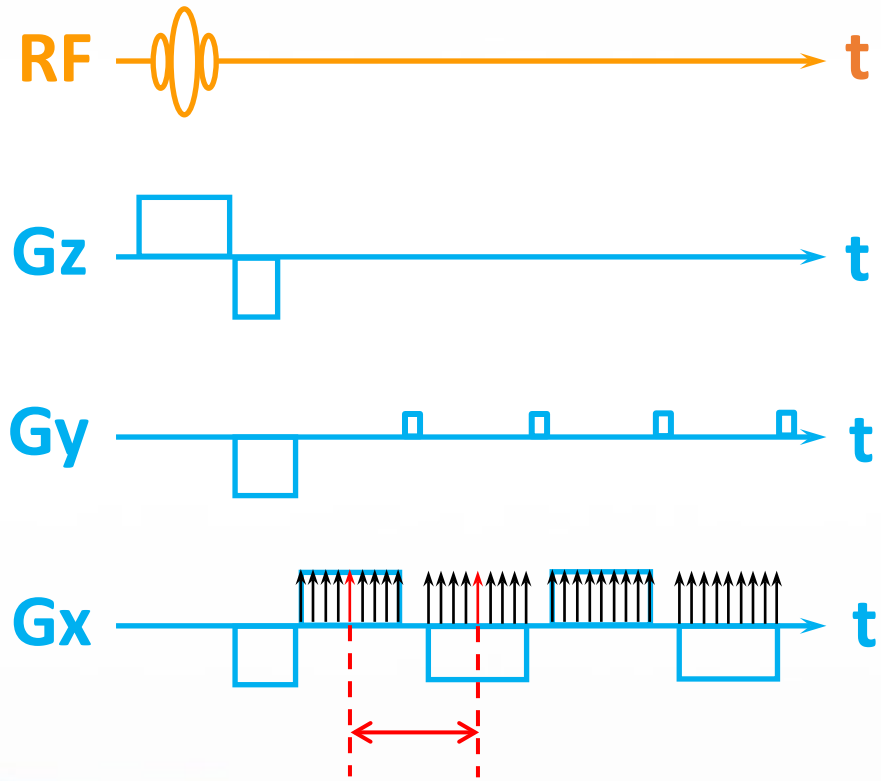


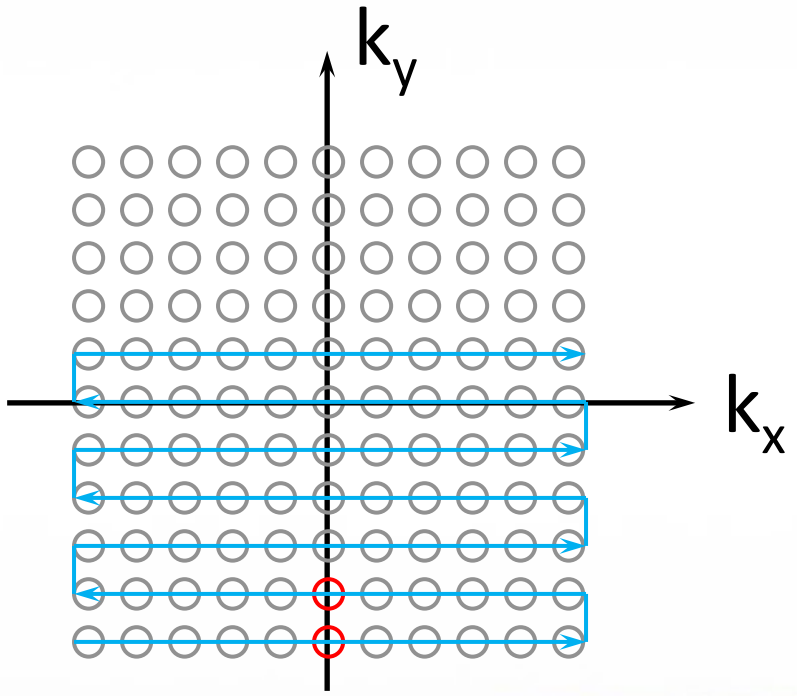
Phase accumulation of different PE keeps the same.

EPI is an exception here

- All data are acquired after one single excitation.
  - Even data of different phase encoding
- Sampling along FE direction is much faster that that in PE direction.
- Very low pixel bandwidth along PE direction

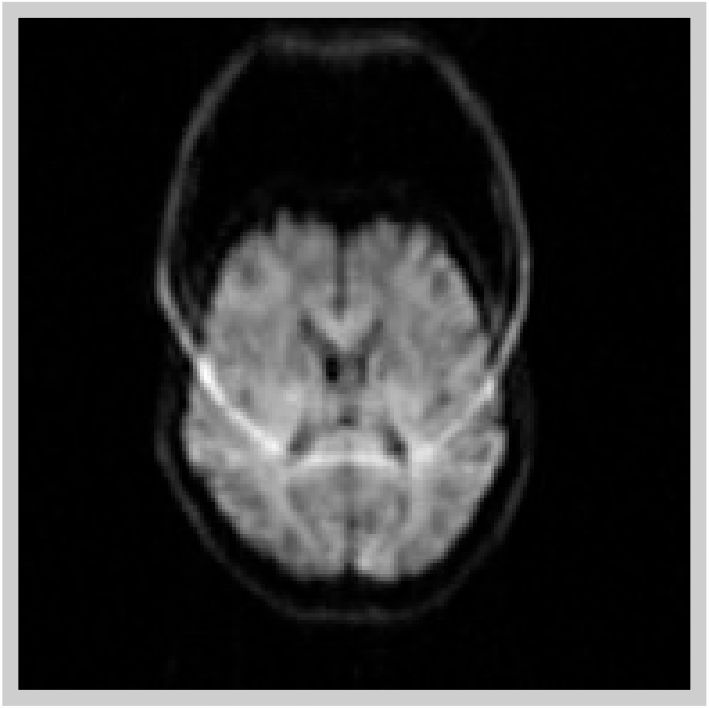
Low sampling frequency in PE direction





Sampling period along PE direction

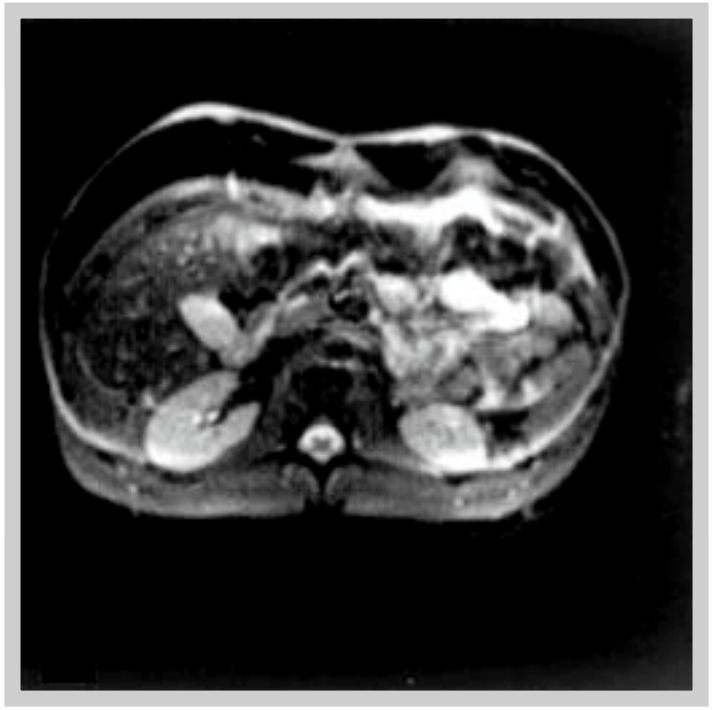
Chemical shift artifact in EPI



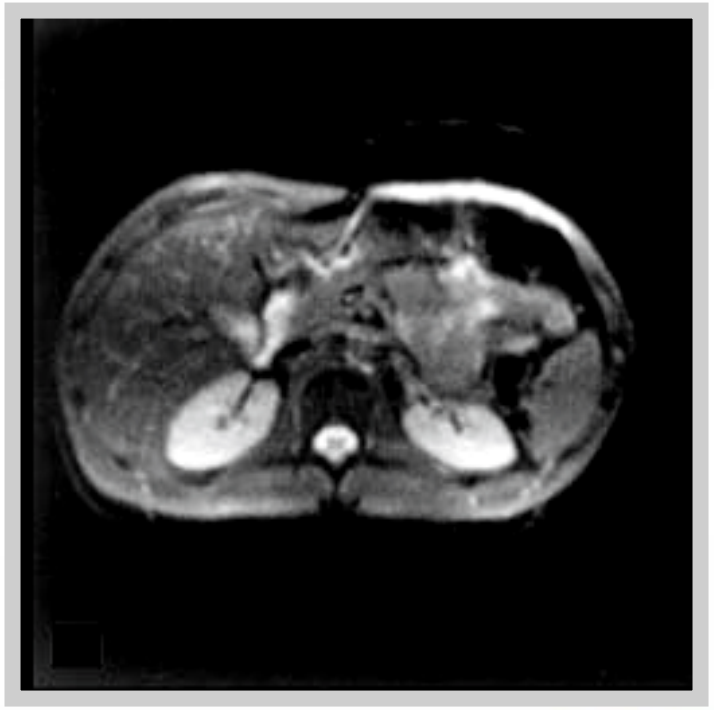
Phase encoding direction:
Anterior-Posterior (A/P)

EPI sequence **must** has
Fat SAT!

Chemical shift artifact in EPI



No Fat SAT



With Fat SAT

Low sampling frequency in PE direction

- Spatial displacement, which is induced by off resonance, in phase encoding direction is amplified in EPI.
  - Not only chemical shift
  - But also inhomogeneous field due to susceptibility

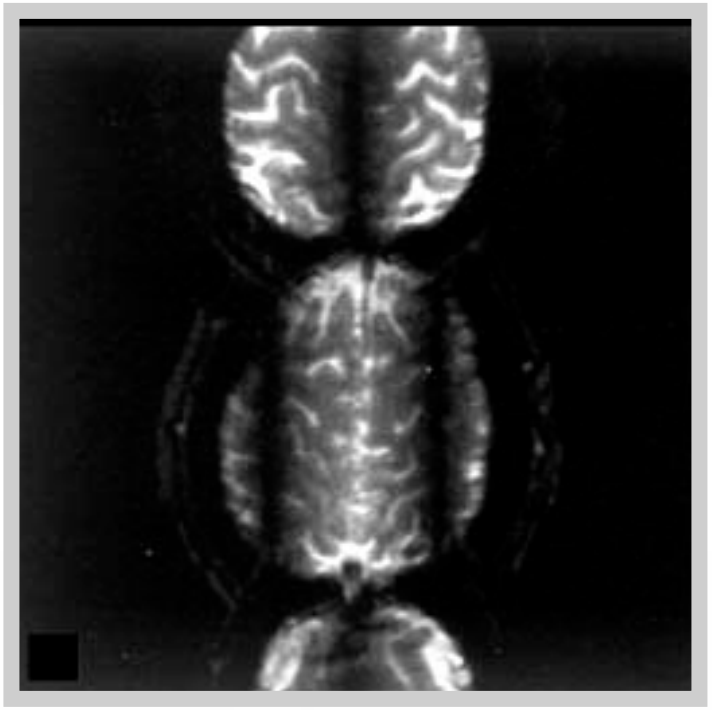
Geometric distortion in EPI

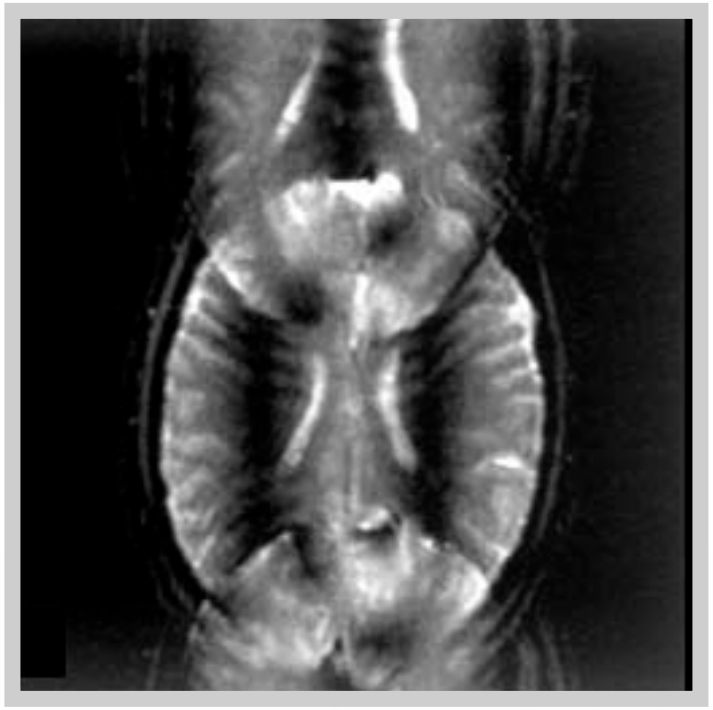
- An inhomogeneous field results in prominent geometric distortion in EPI
  - Regions near air-tissue interfaces, such as skull base
  - More severe in chest and abdomen
  - Shimming may help

Artifacts in EPI

- Amplification of off resonance
  - Chemical shift
  - Susceptibility
  - Bias of center frequency
- Image distortion due to eddy currents
  - Residual gradients
- Nyquist ghost

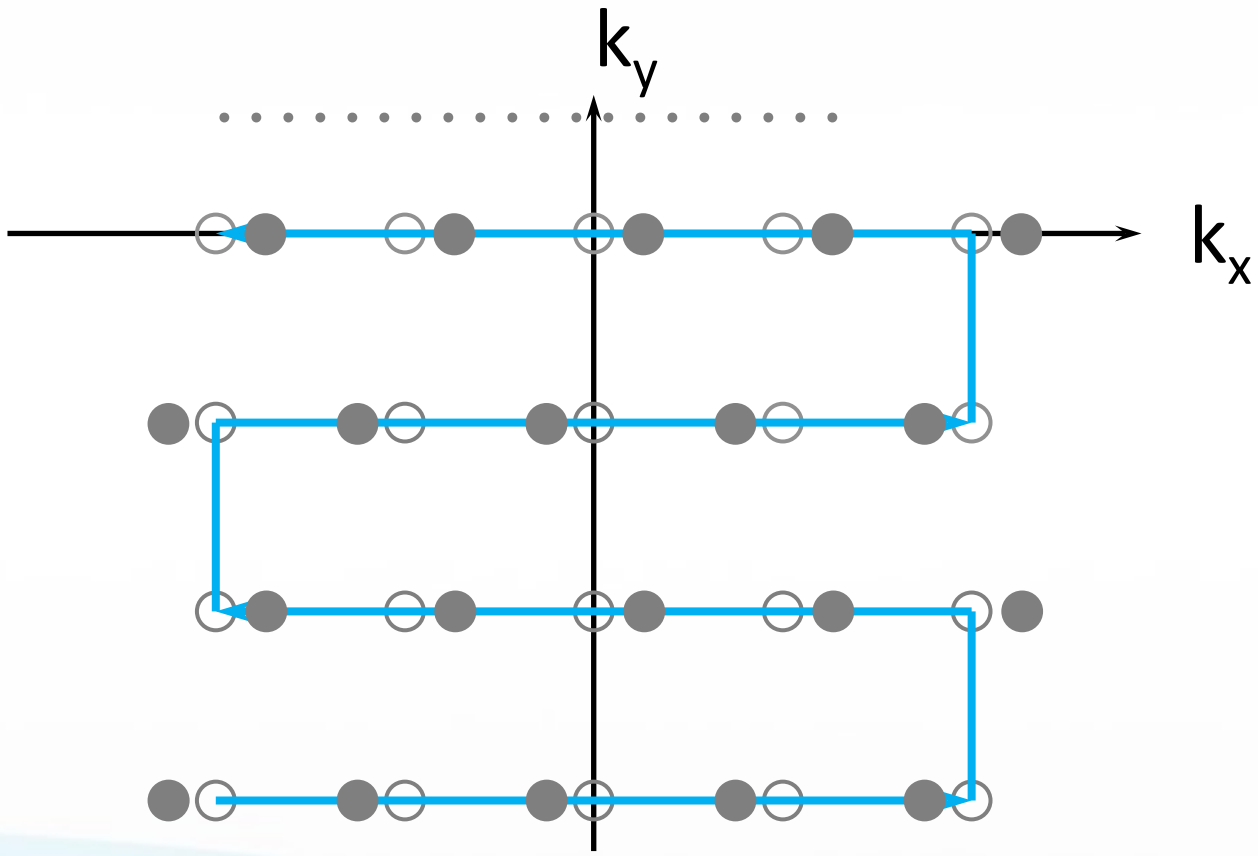
Nyquist ghost (N/2 ghost)





Nyquist ghost occurs in PE direction

Nyquist ghost



- ○ Data points to be collected
- ● Data points actually being collected

An example of constant shift of echoes

Summary of EPI

- Very fast (40-80 msec per scan)
- Image quality is not impressive
- Demanding in both hardware and software
- Clinical applications?

Applications of EPI

- Definitely not going to replace all the other pulse sequences
- Usually, EPI is applied only when there's no better choice…
  - Diffusion MRI, perfusion MRI, functional MRI…
- EPI is still very important. But developing other rapid imaging techniques is also desired.

Fast Scan: EPI