MR Hardware and Imperfections

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Overview

- MRI Hardware Components
- Main Magnetic (B_0) Field
- Shims
- B1 (+ / -) Fields
- Gradients
- System Timing

MRI Hardware Components

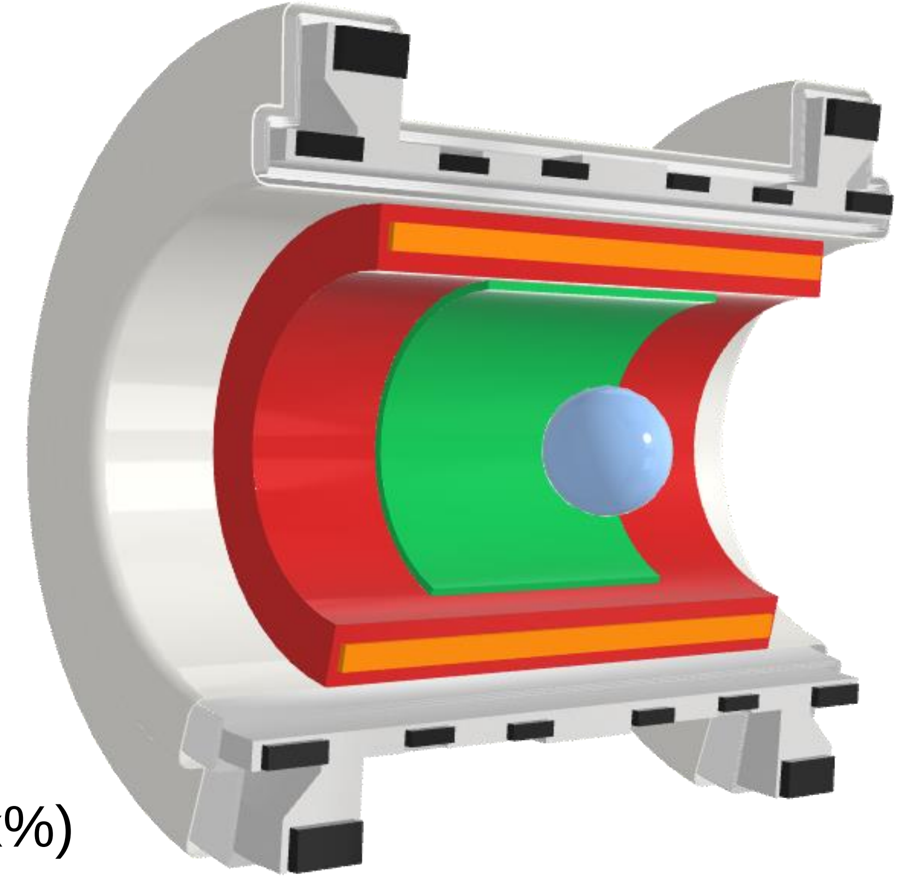
What is required for the (N)MR Signal?

What may cause trouble?

- Sample => Signal source (^{1}H, ^{13}C, ^{17}O, …)
- Magnet => Polarization (T; static (0Hz); ppm)
- RF coil => Excitation/ Acquisition (µT; MHz; xx%)

$\Rightarrow$ Basic NMR Spectrometer

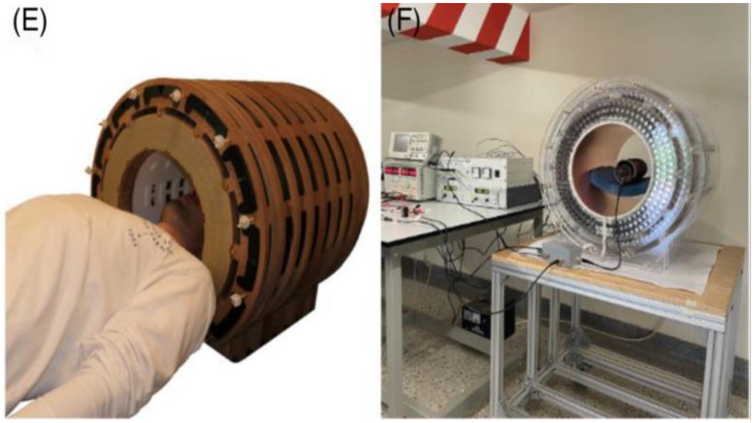
- Shims => Field Homogenization
- Gradient Coils => Signal Localization (mT; mT/m; x%)



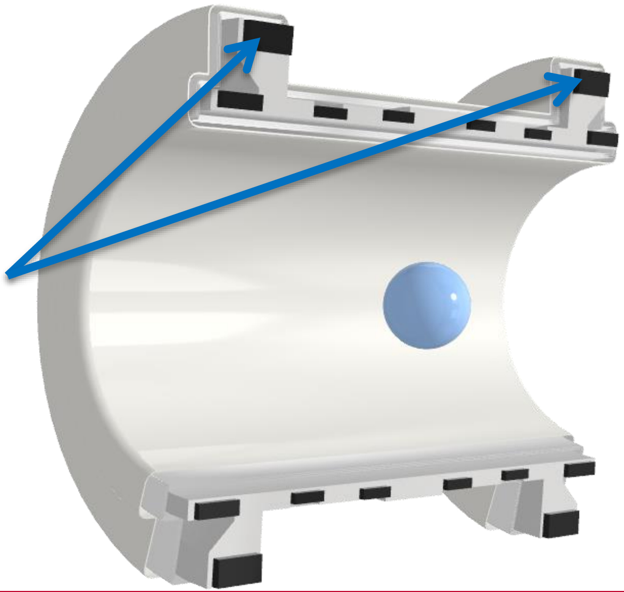
Main Magnetic (B_0) Field

- Permanent magnet(s): Low Field
- Electromagnets: Most simple => Solenoid
- Mainly superconductive electromagnets for diagnostic imaging
  - Cryogenic temperature
- Shielding to suppress B_0 outside
- Optimized for ppm (parts per million) accuracy

$\Rightarrow$ Why don’t we have perfect B_0, if the main magnet has ppm accuracy?

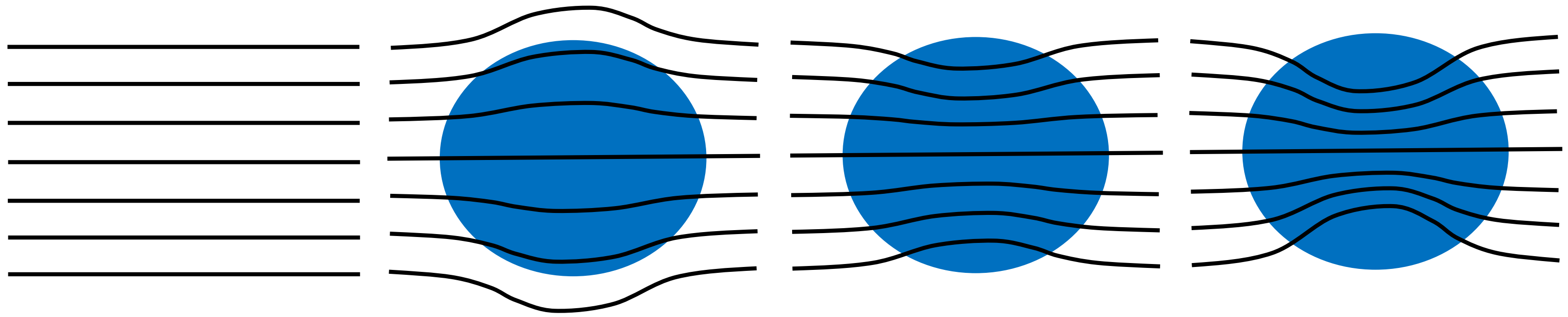


NMR in Biomedicine, 20 November 2023, DOI: (10.1002/nbm.5052)



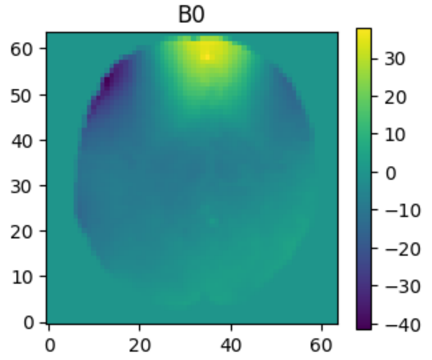
Susceptibility Differences

- Susceptibility (χ): Measure to which extent a substance is magnetized in an external magnetic field



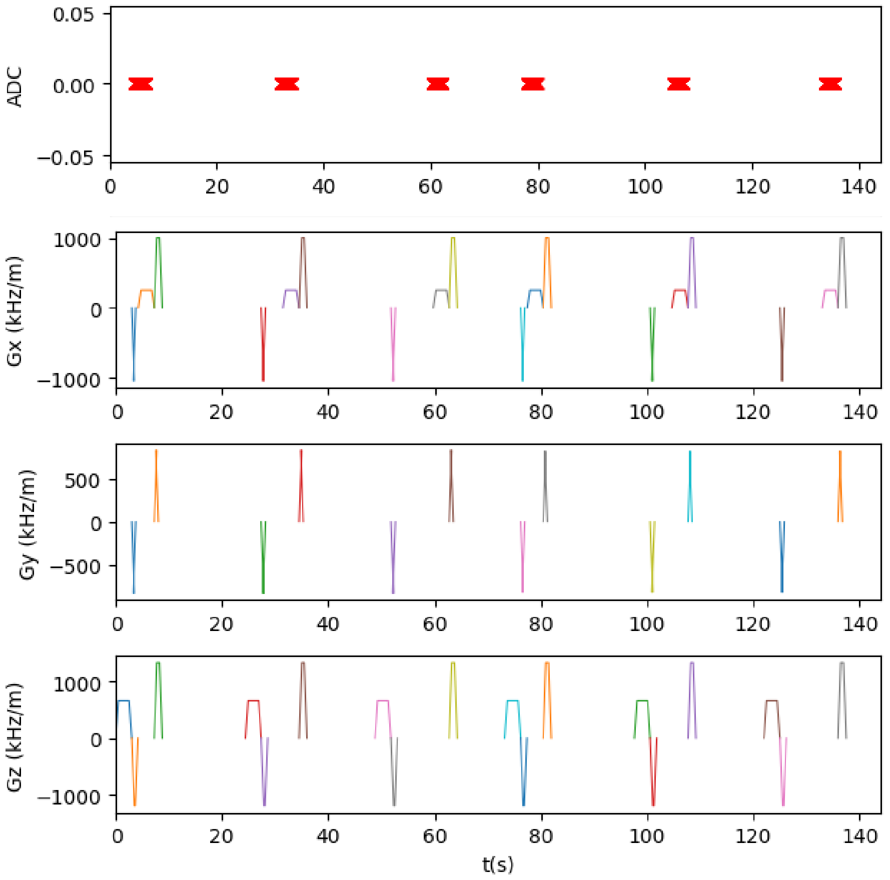
$\chi = 0$ Homogeneous Field | $\chi < 0$ Diamagn. substance | $\chi > 0$ Paramagn. substance | $\chi \gg 0$ Ferromagn. substance

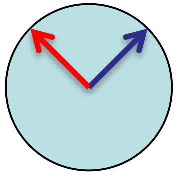
- Substances with different χ: Local B_0 gradients
- Cause of B_0 inhomogeneities

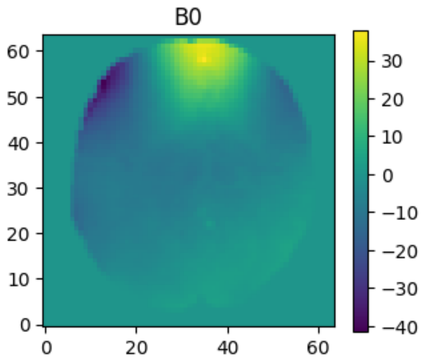


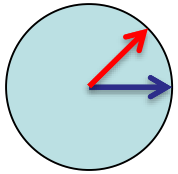
B_0 mapping

- Precession frequency depends on B_0 : $\omega(\vec{x}) = -\gamma B(\vec{x})$
- Phase evolution $\propto B_0$
- Measure multiple TEs
- Example: Flash sequence



- B large 

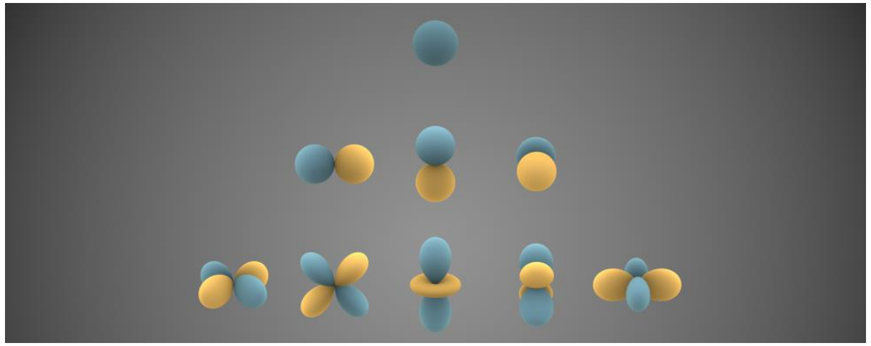


- B small 

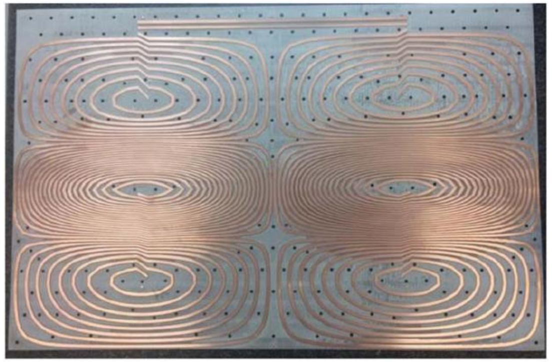
B_0 Shimming

- Shimming: B_0 correction/ field homogenization
- Spherical (volume) harmonics
- Resistive coils
- Source of distortion: Inside
- Correction fields: Outside
- Perfect correction not possible

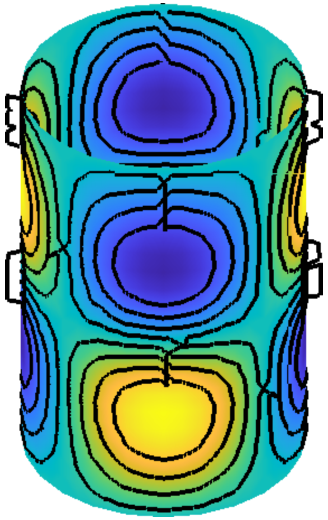
- Temporal stability? Drift?



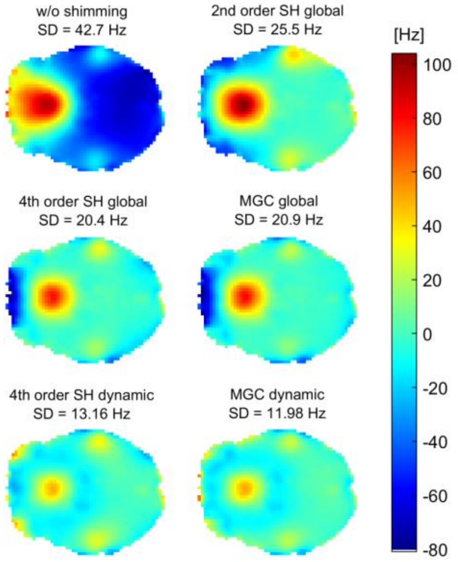
https://en.wikipedia.org/wiki/Spherical_harmonics



Handler (2020), Biomed. Phys. Eng. Express 6 045022



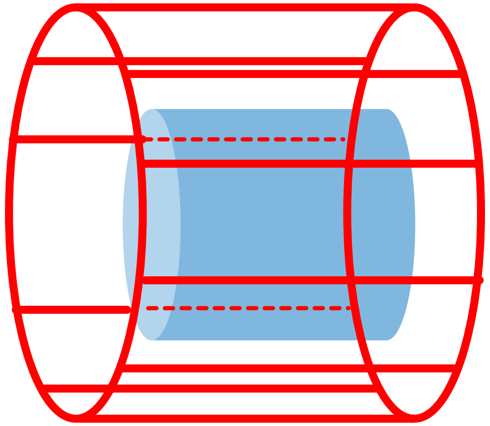
S2 (shim) coil

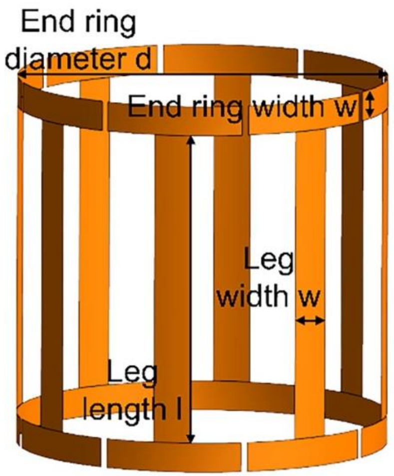


Radio Frequency Coils

B_1^+: Transmit or Excitation

- Body Coil/ Local transmit coils
- Aim: Homogeneous excitation



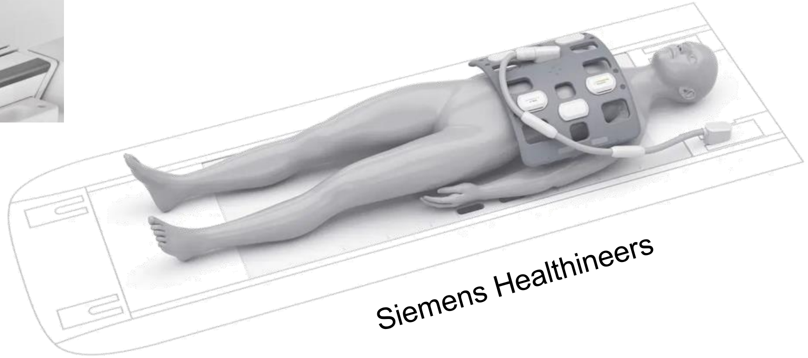


Tesfai; JMR (2020) 319,106825

B_1^-: Signal Reception

- Local receiver coil (arrays)
- Localized reception for PI

Siemens Healthineers



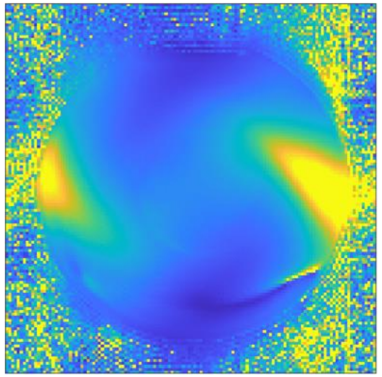
Siemens Healthineers

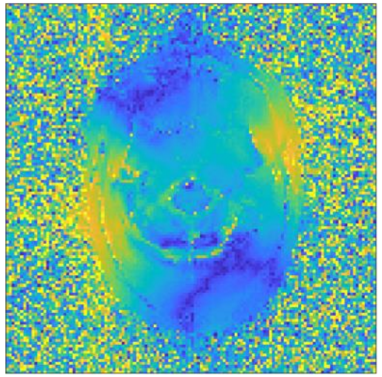
$\Rightarrow$High power vs low signal amplitude

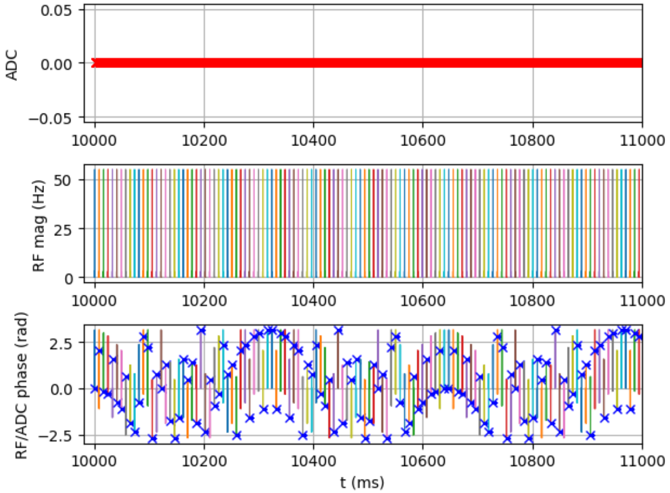
RF coils: B1 Excitation Field Mapping

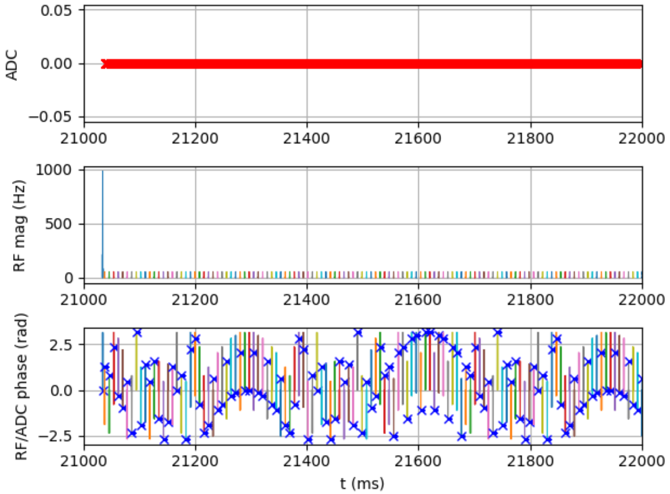
- B_1^+: Transmit radiofrequency field
- w/wo Preconditioning RF pulse
- Centric *k*-space reordering

  $\Rightarrow$ Residual longitudinal magnetization
- $B_1^+ \propto (S_2/S_1)/\alpha_{prep}$
- Further methods
- $SAR \propto B_0^2 \alpha^2$







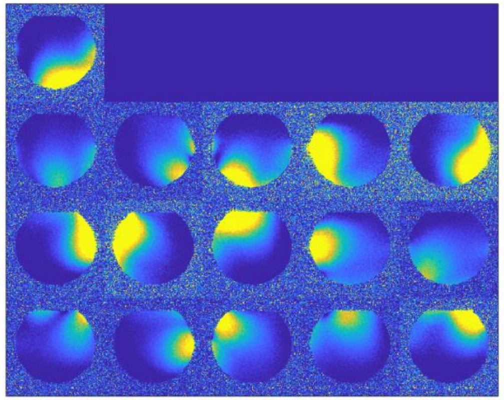


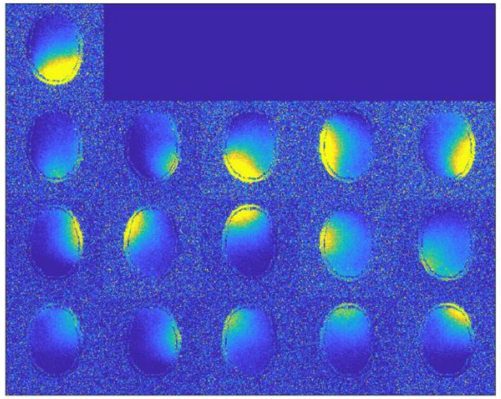
RF coils: Coil Sensitivity Mapping

- B_1^-: Localized signal reception
- Important for parallel imaging
- Excitation using Body Coil (BC)
- Multiple receiver Local Coils (LC)

$$\Rightarrow B_1^- \propto \frac{LC}{BC}$$

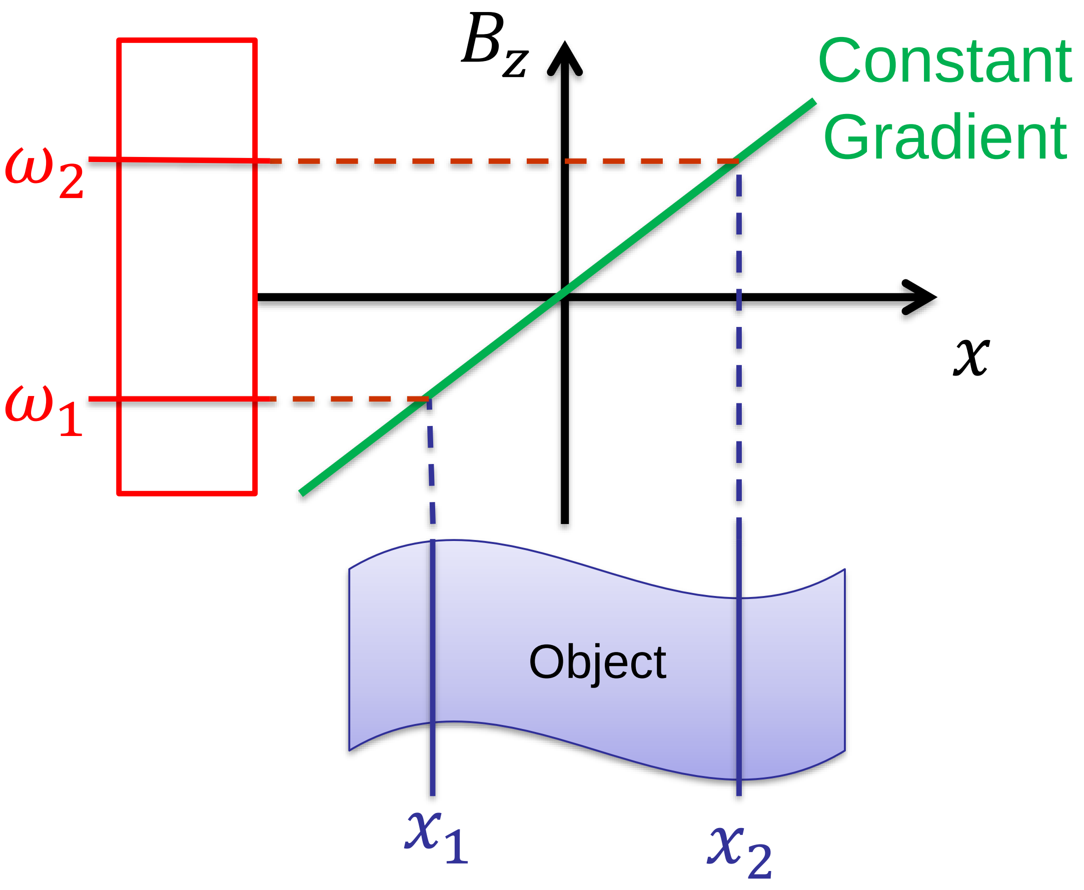
- Numerous software packages available



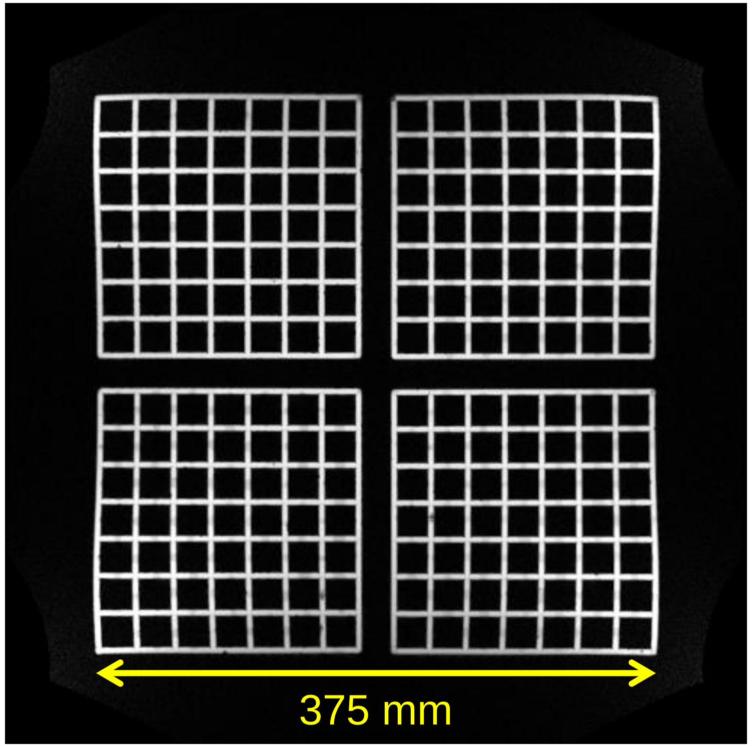


Gradient Coils for Spatial Localization

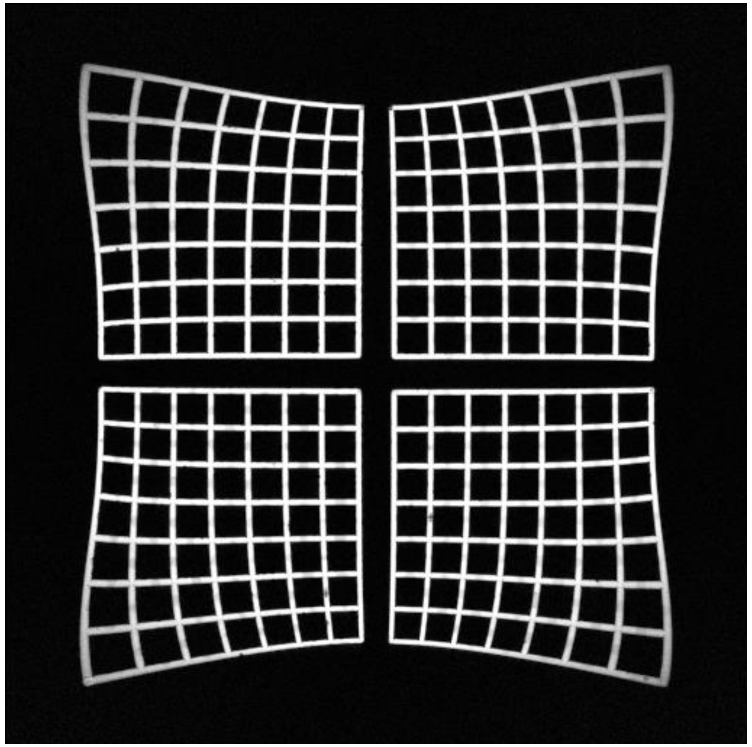
- Linearly varying magnetic field (B_z) = constant gradient
- Local variation of the Larmor frequency
- Linear relation between object and frequency space
- Straight-forward Fourier Transform (FFT)
- Usually three orthogonal magnetic field gradients along spatial directions x,y and z



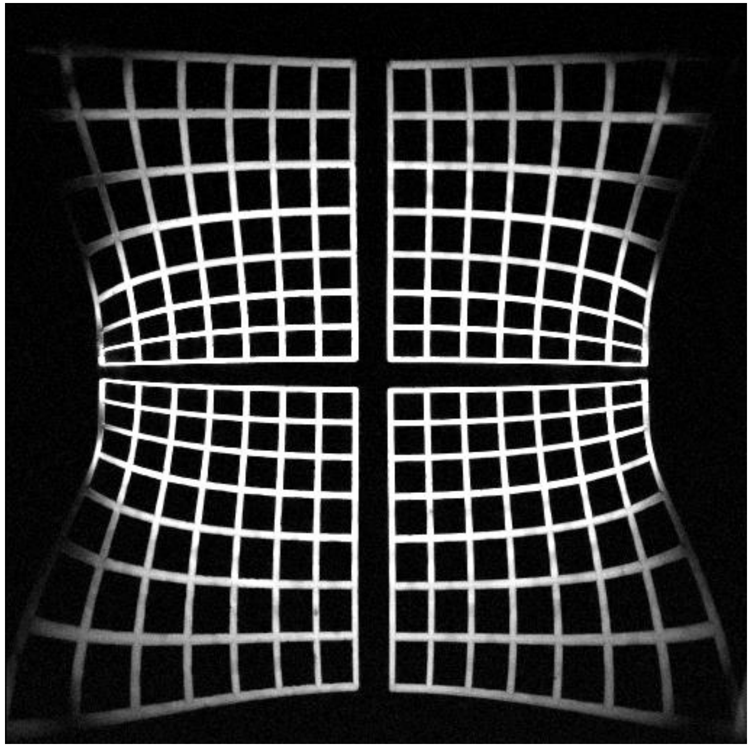
How linear are our encoding fields?



clinical scanner, XZ (coronal) slice
FOV=50cm, iso-center



FOV=50cm, iso-center
no gradient distortion correction



FOV=50cm, 20cm above iso-center
no gradient distortion correction

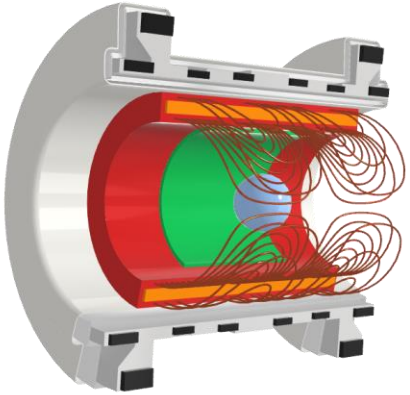
⇒ No gradient system is perfect

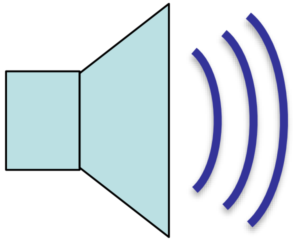
Gradient Coils in practice

- High gradient amplitude (mT/m, scales with current)
- Fast switching/ slew rate (T/s, scales with voltage)
- Modern PWM amplifiers >1000A; >2kV
- Currents inside a magnetic field: $\boldsymbol{F} = I \int d\boldsymbol{l} \times \boldsymbol{B}$
  - Similar to a loudspeaker: Source of most noise in MRI
  - Multiple kW of heat: active cooling required
- Fast switching:
  - „Eddy currents“: Opposing fields from currents induced in cryostat with decay times > 1s

$\Rightarrow$ Magnetically screened, „shielded“ coils

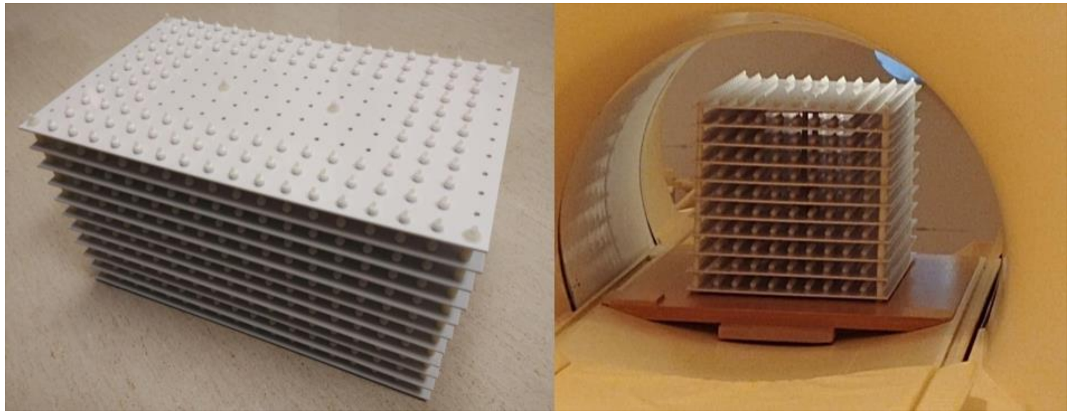
- In practice: Limitations given by physiology (PNS)



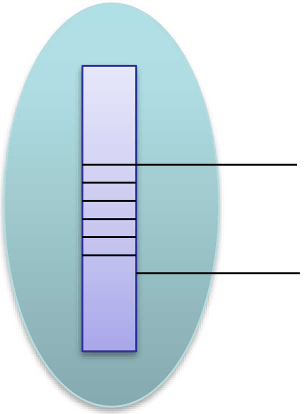


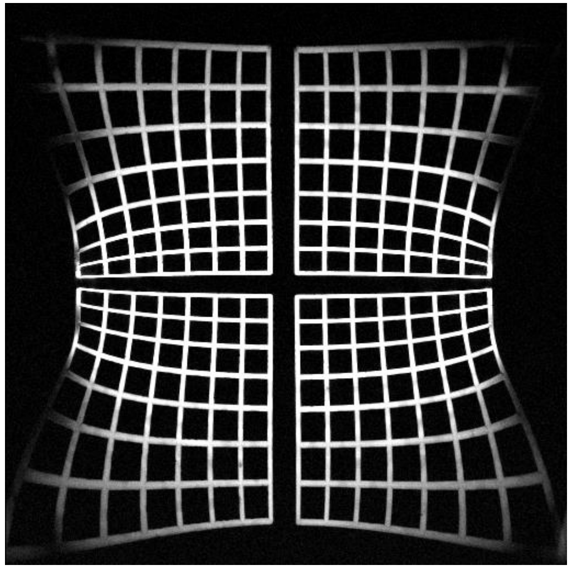
Gradient Mapping

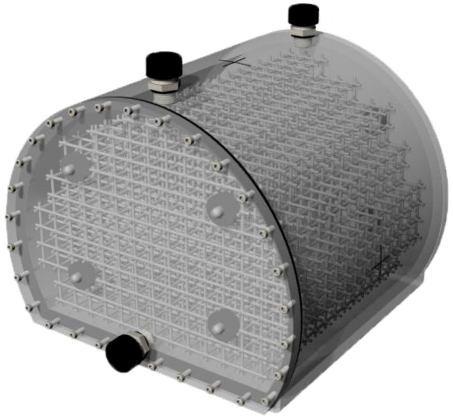
- Distortion phantoms
- Dedicated devices (Hall probes)
- Field probes



ISMRM 2022 #5032: Distortion Measurements Using a Large-volume, Lightweight, Modular MRI Phantom With Solid Signal Sources



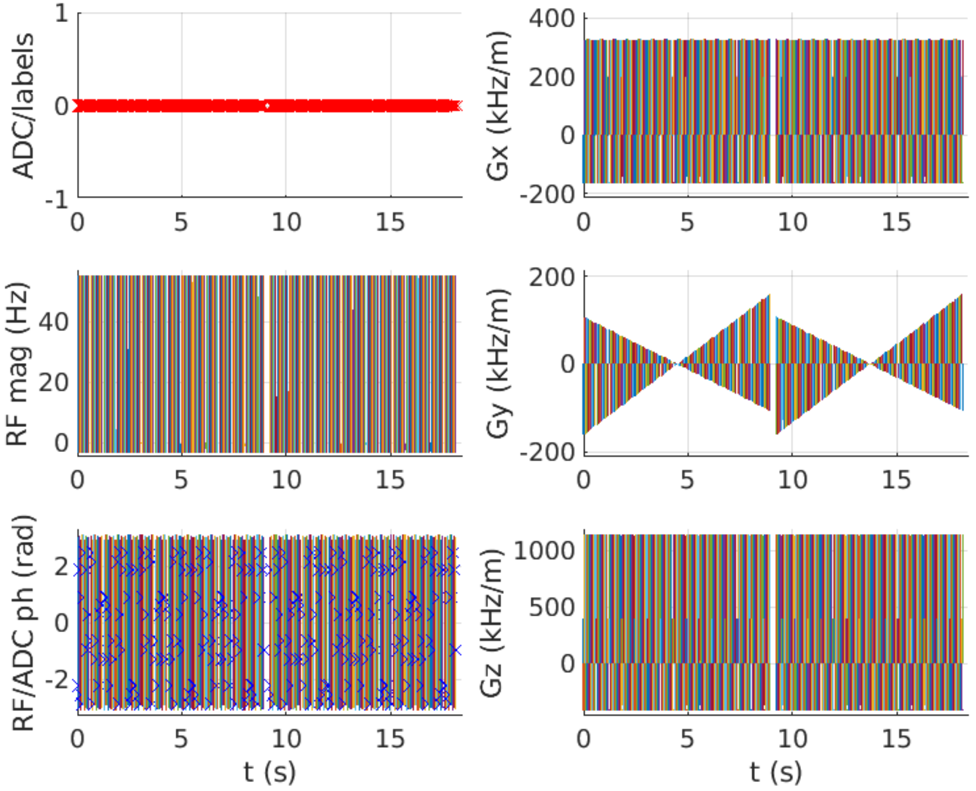


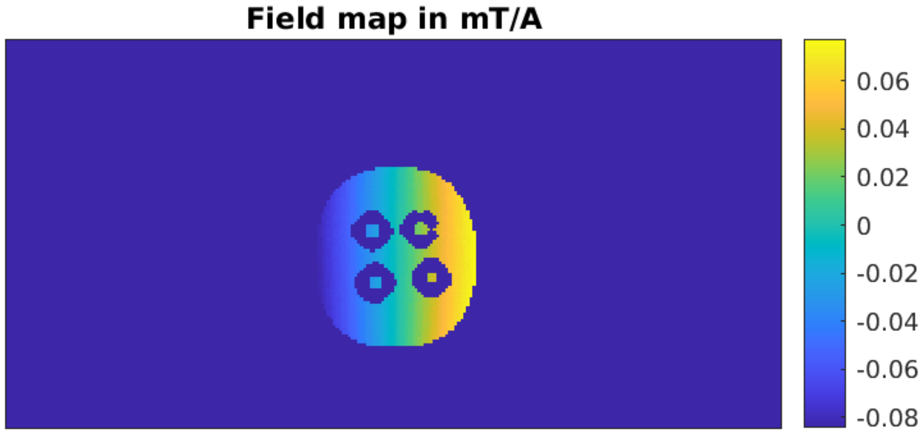


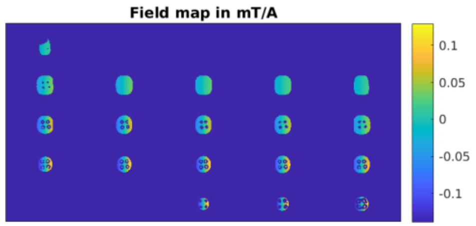
https://www.sunnuclear.com/products/large-field-mr-distortion

Gradient Mapping of Insert Coils

- Play out blips on additional gradient channel(s)
- GRE sequence to measure phase w/wo blips
- Calculate phase difference

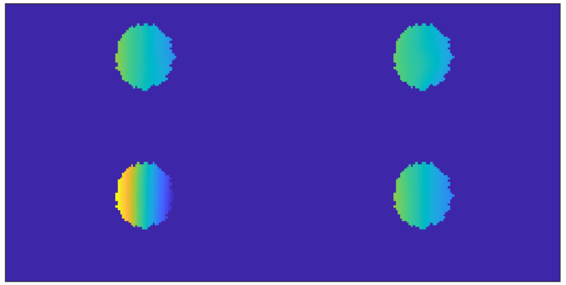


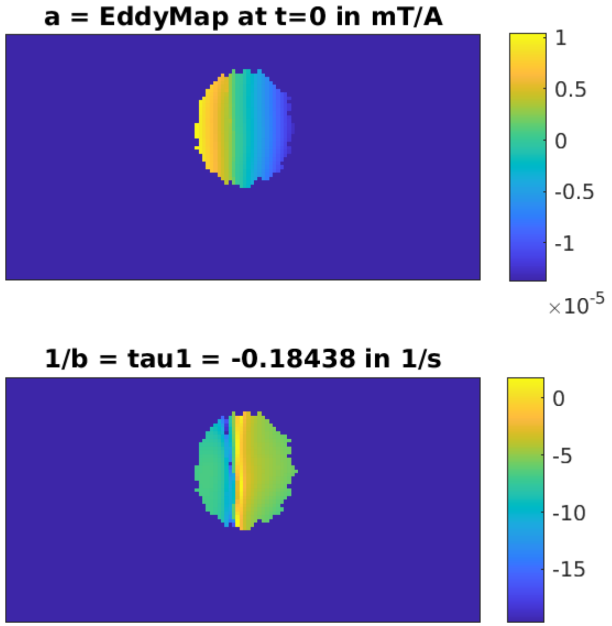


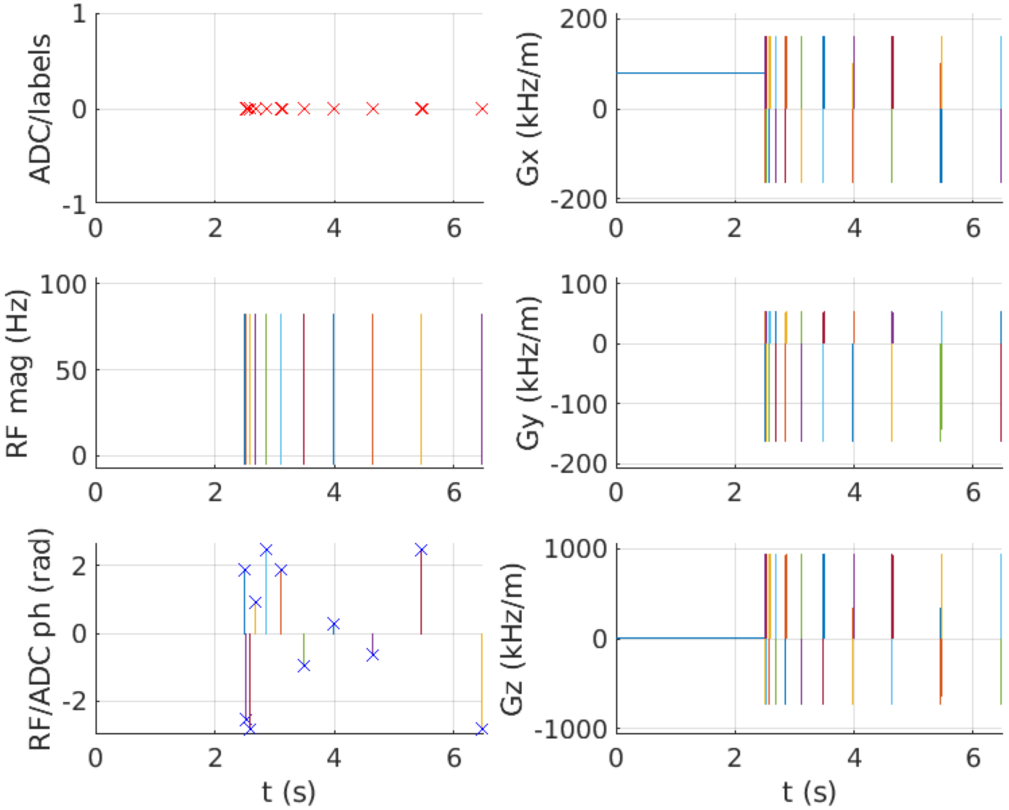


Eddy-current mapping

- Switch on gradient, hold and wait (minimize effects from switching on)
- Switch-off fast and measure
- Map phase evolution from eddy-currents (phase differences similar to field mapping)







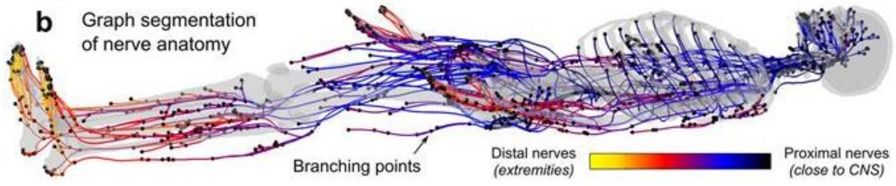
Before you start on the scanner

- Peripheral nerve analysis

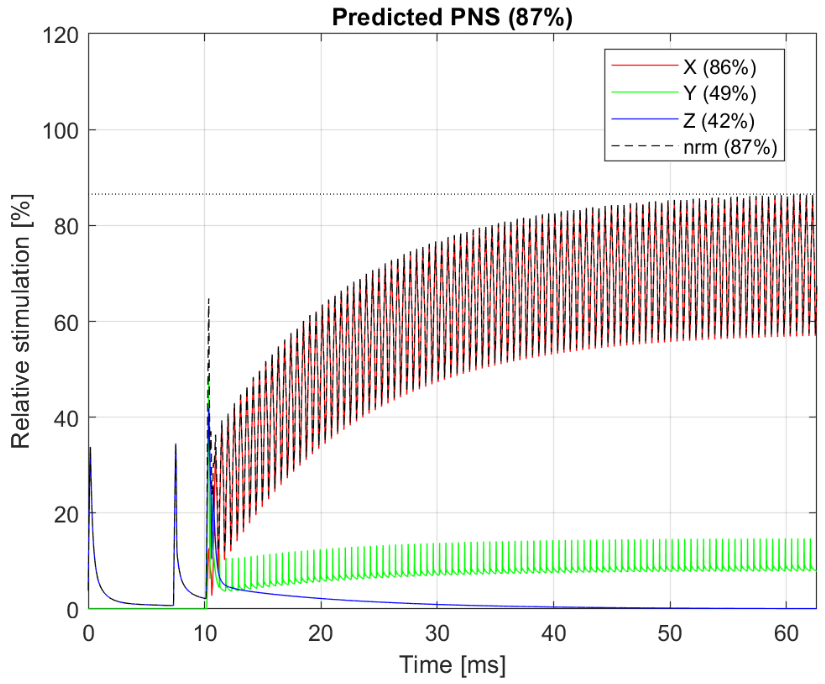
- Avoiding acoustic resonances (for fast sequences)

Gradient Interactions: Safety I (PNS)

- Unwanted Peripheral Nerve Stimulation (PNS)
- Maxwell-Faraday equation: $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$
- Voltage along nerve fibers, strong enough to trigger discharge through ion channels
- Usually below cardiac stimulation thresholds
- Magnetic fields generated by gradient coils go beyond FOV
- All field components (B_x, B_y, B_z) interact with the human body
- Prediction in Pulseq possible



Human nervous system model [1,2]



[1] M Davids et. Al. Scientific Reports 2017;7:5316.
[2] M Davids et Al. *MRM* 2019;81:686-701.

Pulseq PNS prediction

- Peripheral neural stimulation (PNS) prediction on Siemens is based on the so-called SAFE model

  F.X. Herbank and M. Gebhardt. SAFE-Model - A New Method for Predicting Peripheral Nerve Stimulations in MRI. ISMRM 2000, #2007. https://cds.ismrm.org/ismrm-2000/PDF7/2007.PDF

- Open-source implementation by Filip Szczepankiewicz and Thomas Witzel: https://github.com/filip-szczepankiewicz/safe_pns_prediction

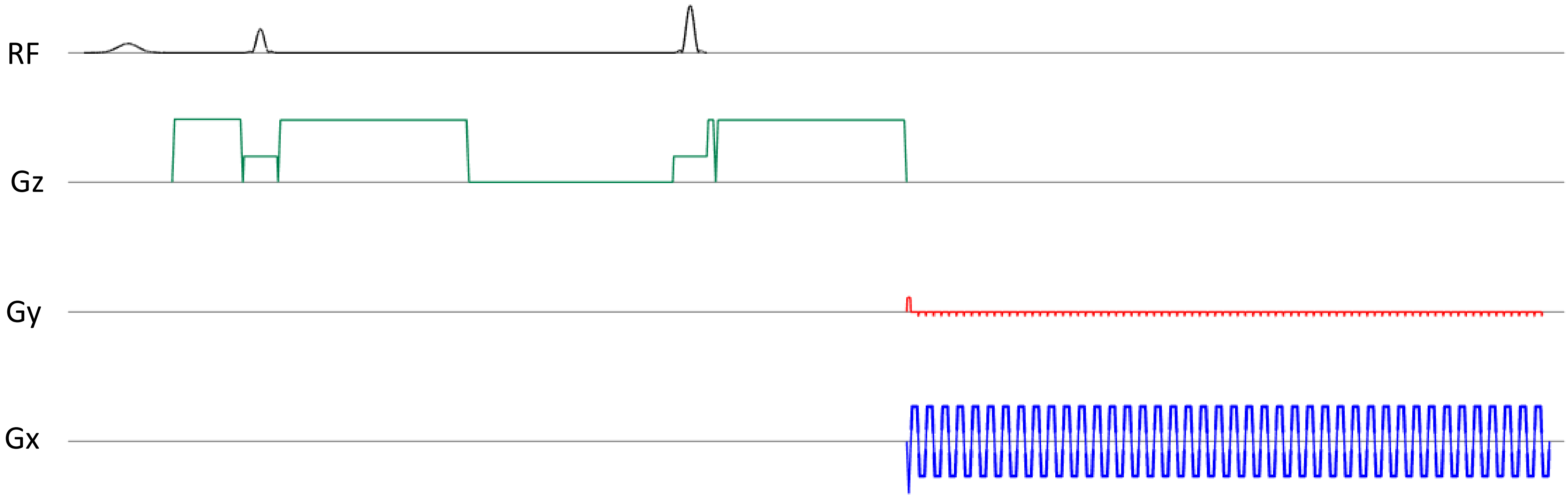
- Direct interface in Matlab-Pulseq

Caveat & Solution

- Need scanner-specific model parameters
- Extract your gradient system description file from IDEA
  - Type “sys” in the IDEA shell selecting your system
    (you may need to select something else first to see the verbose output)
  - Note the strings after “GPA Type” and “GC Type”
  - Go to C:\MIDEA\N4_VE####\n4\pkg\MrServers\MrMeasSrv\Config\InitMeas and pick the file named MP_GPA_<your_GPA>_<your_coil>.asc and copy it somewhere where your Matlab or Python can read it
  - *Path under NumarsX is left as an exercise for the interested reader*
- You can now predict PNS in the same way IDEA and scanner do it

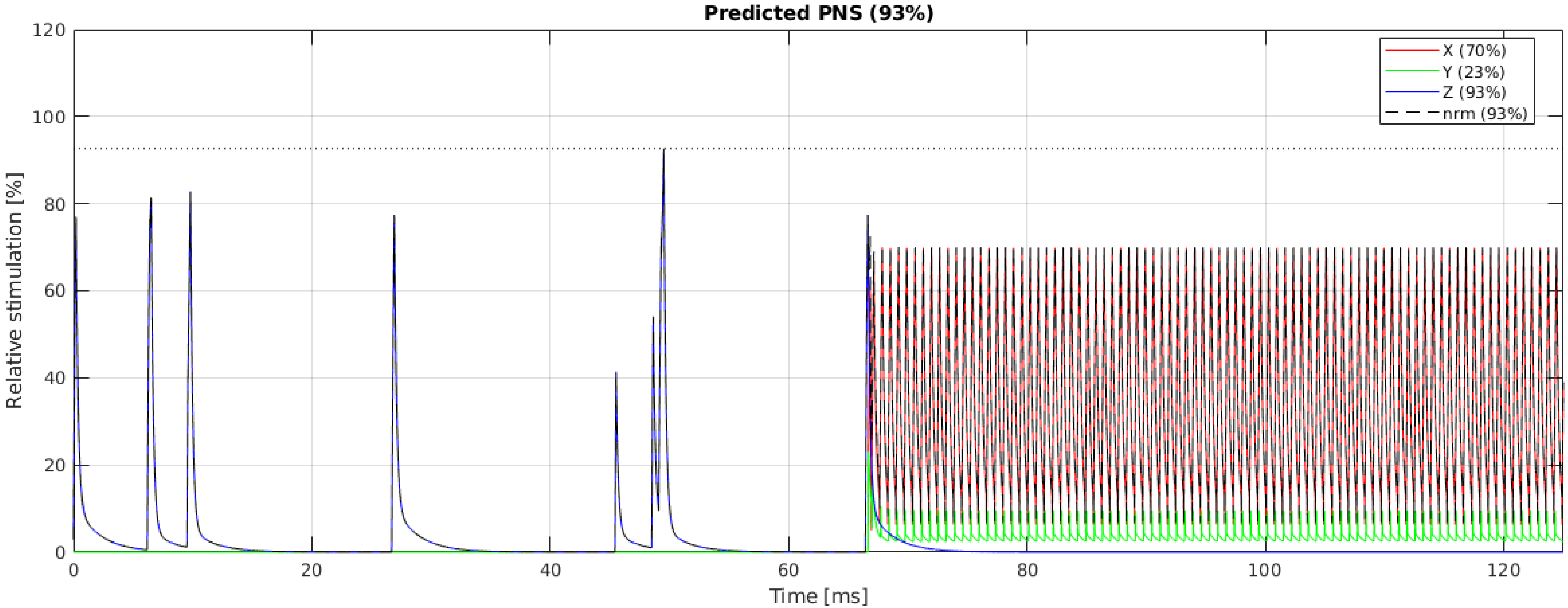
Example: DW-EPI

- bFactor=1000, TE=78ms, Gmax=38mT/m SR=180T/m/s



PNS Stimulation: DW-EPI

seq.calcPNS('idea/asc/MP_GPA_K2309_2250V_951A_AS82.asc');

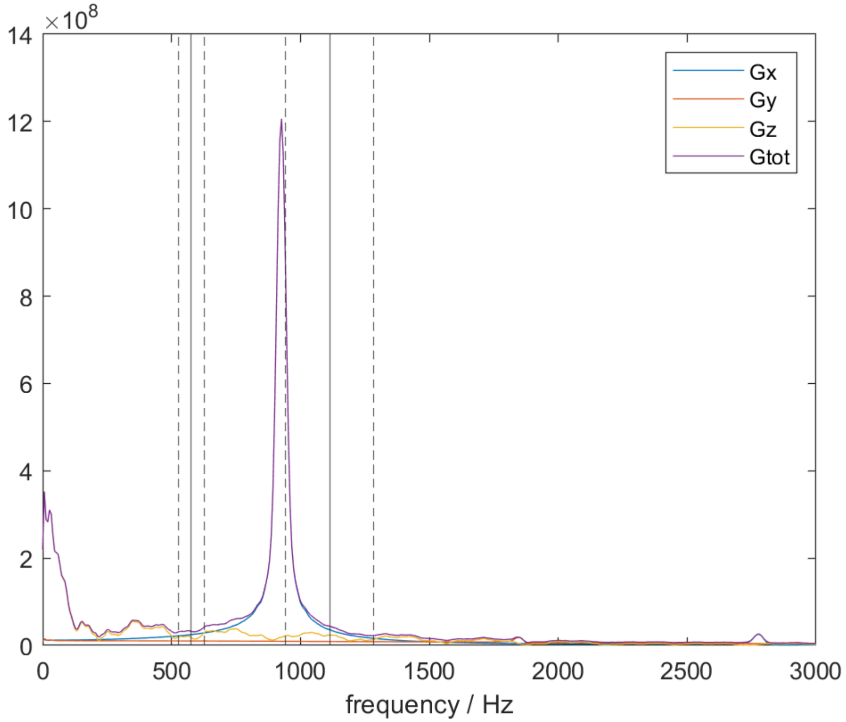


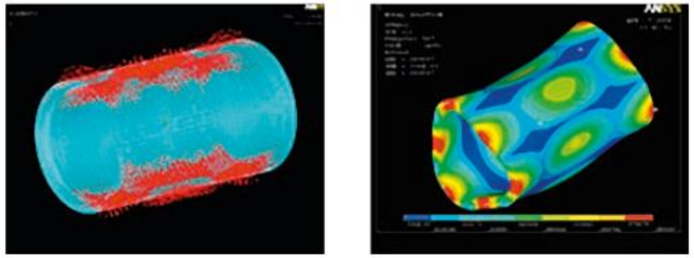
Gradient Interactions: Safety II (Mechanical)

- Mechanical: $\boldsymbol{F} = I \int d\boldsymbol{l} \times \boldsymbol{B}$
  - Vibrations
  - Mechanical resonance

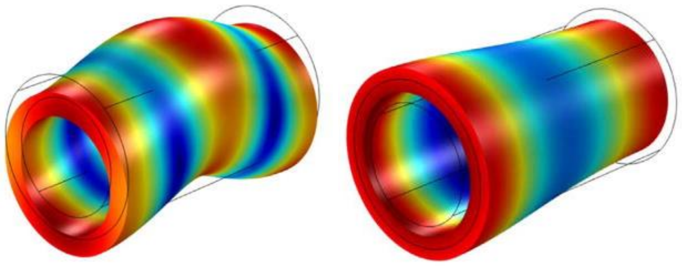
  $\Rightarrow$ Acoustic noise
  - Electromechanical coupling

  $\Rightarrow$ Helium boil-off
- Predication of “Forbidden Frequencies” possible (additional knowledge about hardware required)

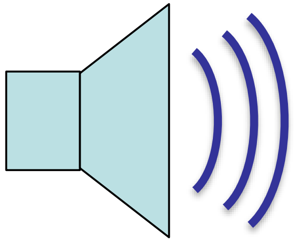




R Kimmlingen. MAGNETOM Flash (68) 2/2017



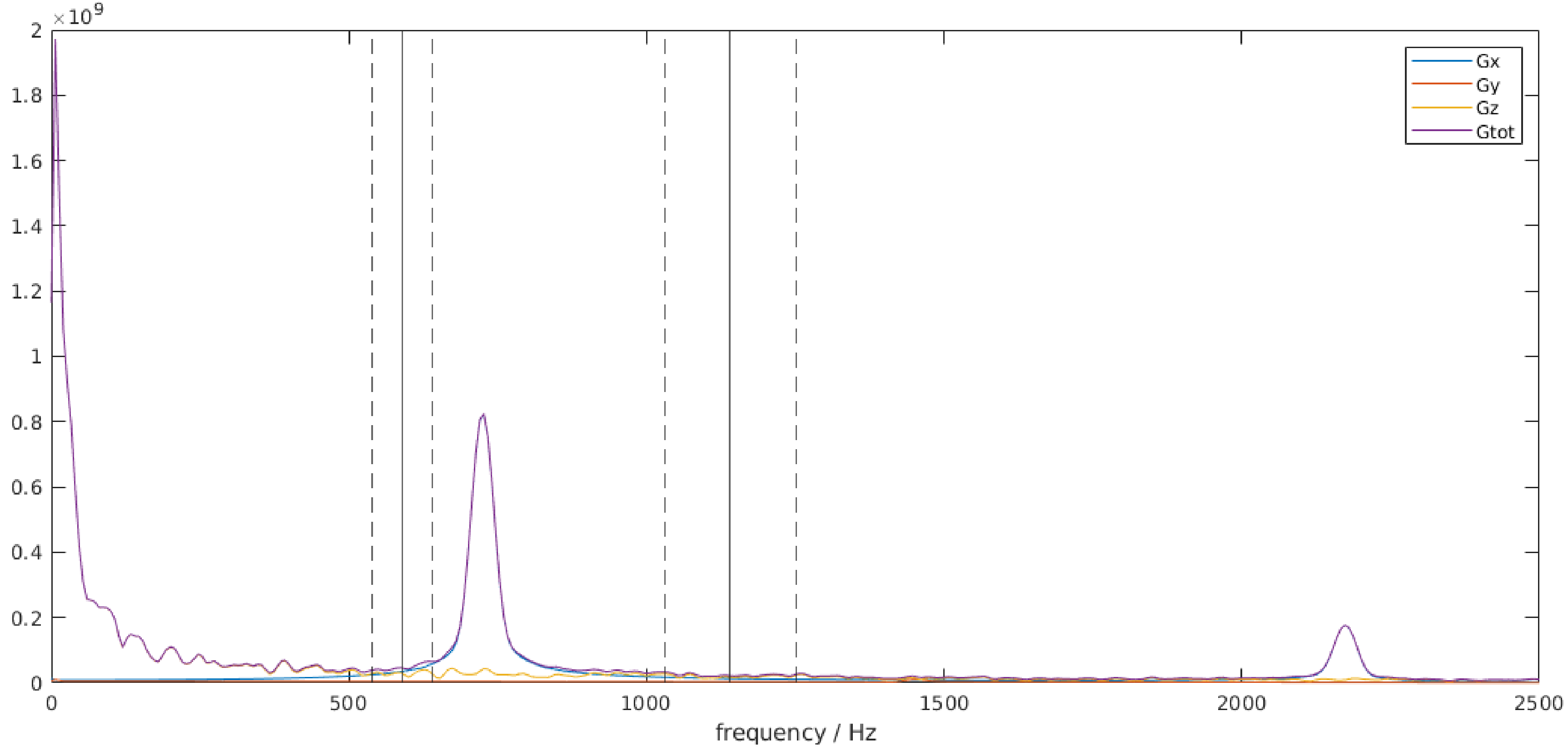
SA Winkler et. Al. NeuroImage 2018;168:59 –70.



Acoustic resonance analysis

- Extract your gradient system description file from IDEA as above
- Create your sequence in memory
  (populate the “seq” object with events)
- Run “gradSpectrum.m” script in “matlab/demoUnsorted”
  - Set ascName=‘….’ to your gradient system .asc file to see resonances marked

Acoustic analysis: DW-EPI



seq.sound(); % another option for acoustic assessment in Matlab ;-)

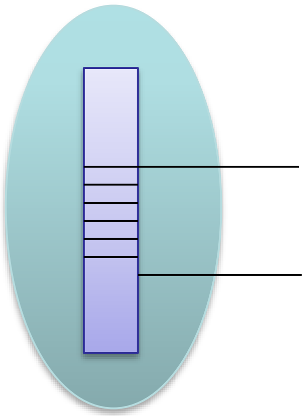
System Timing

- Different sub-systems have to operate synchronously
  - RF / ADC (MHz) / Gradients (kHz)
  - Different orders of magnitude

  ⇒ RF pulse synced with gradient?

  ⇒ ADC center at TE?
- Nominal vs real trajectory
- Measurements, eg field probes

  ⇒Skope uses Pulseq…



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Whole Pulseq Team

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HORIZON-WIDERA-2021-ACCESS-03
MRITwins