Friedrich-Alexander-Universität
Medizinische Fakultät

Pulseq-simulation in python
and its usage in teaching and research

Prof. Dr. Moritz Zaiss
Max-Planck Institute for biological cybernetics, Tübingen
Department for Artificial Intelligence in biomedical engineering
University Clinic Erlangen, Friedrich-Alexander University (FAU) Erlangen-Nürnberg

moritz.zaiss@fau.de

www.mr-physik.med.fau.de/ag-zaiss

Overview

1. **What you can do**
   - Education: MRTwin course example: GRE to FLASH
   - Research: Debugging and applications

2. **How to do it – code demos**

   - Playground MR0 in Colab

MRI-Pulseq course at FAU, Erlangen

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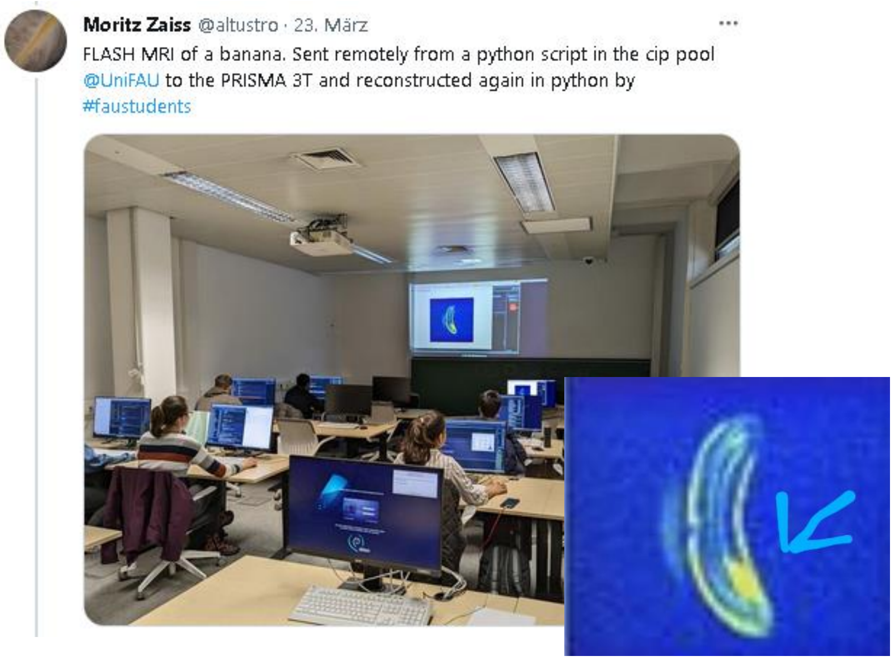


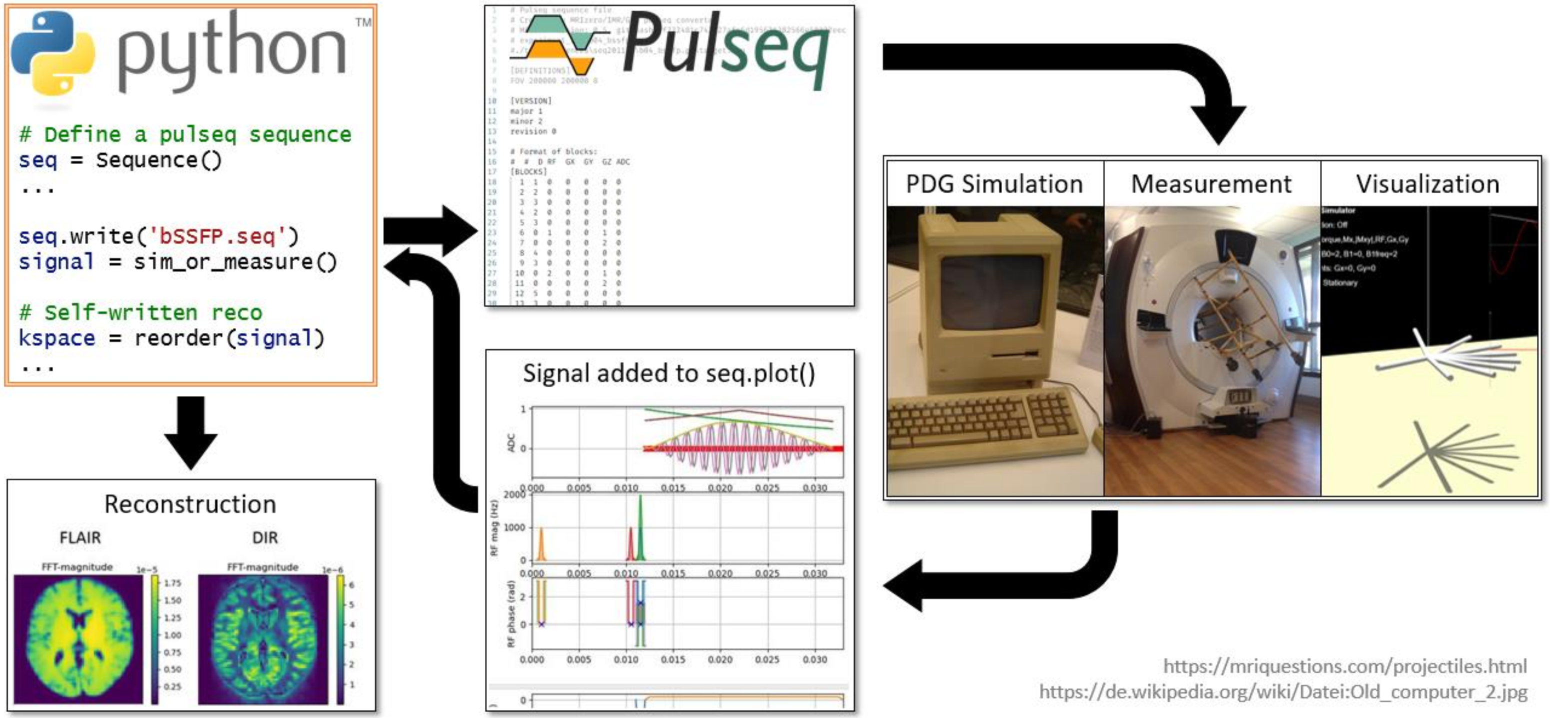
https://github.com/mzaiss/MRTwin_pulseq/

Next **February 26, 2023 - 8 of March**

also open for virtual participation

1. Aubau eines MRT, Physik-Wiederholung
2. Freier Induktions-zerfall, Spin-Echo
3. GRE, voxel position and 1D imaging
4. 2D MRI: frequency and phase encoding
5. Fast MRI: GRE MRI to FLASH MRI
6. Reordering
7. Magnetization preparation
8. EPI and EPSI
9. Spin echo imaging
10. RARE
11. SSFP and bSSFP
12. Scan at real system
13. Radial Imaging
14. Compressed sensing

MRI-Pulseq course at FAU, Erlangen

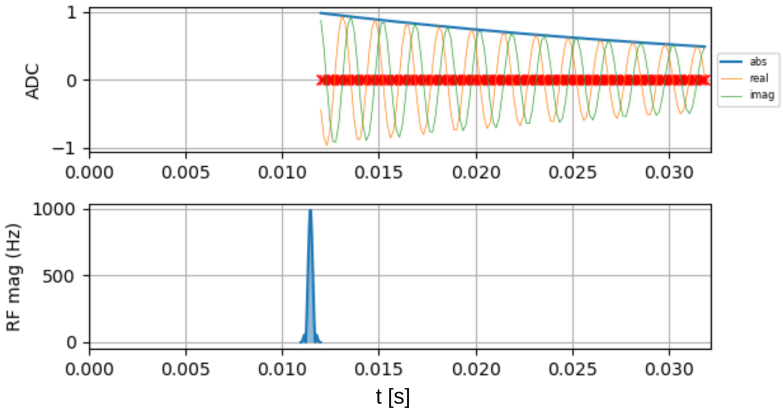


https://mriquestions.com/projectiles.html
https://de.wikipedia.org/wiki/Datei:Old_computer_2.jpg

It is fast:
64 x 64 images within seconds

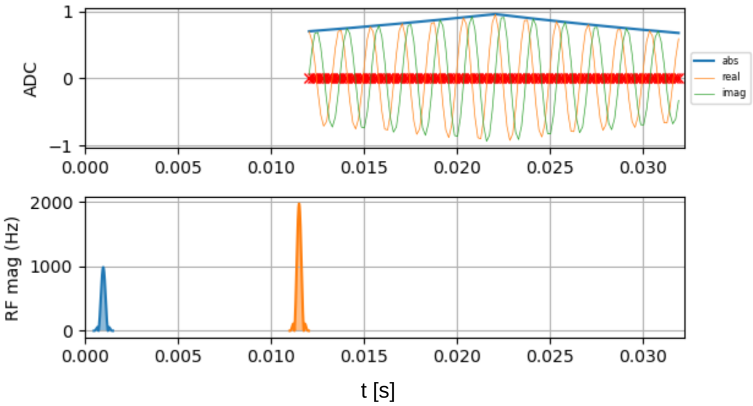
Exercises – basic echoes

FID



exp(-t/T2*)
T2* ≈ 30 ms

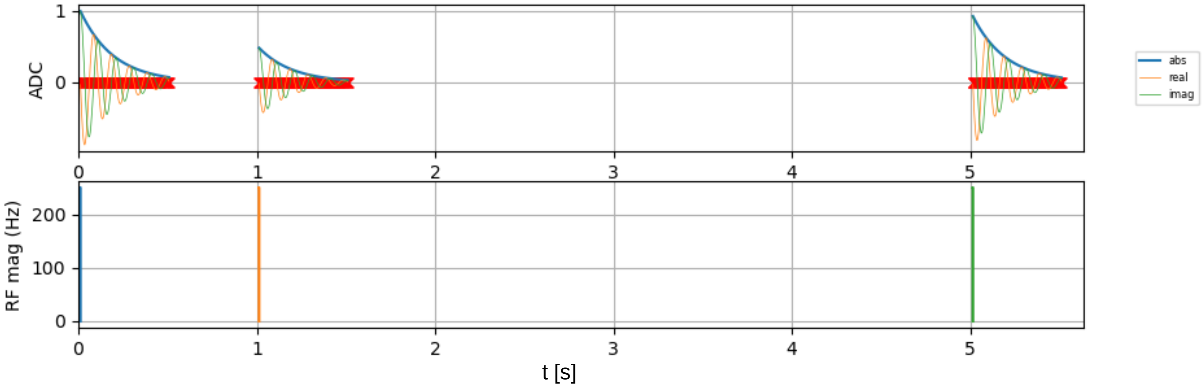
SE



exp(-t/T2)
T2 ≈ 50-100 ms

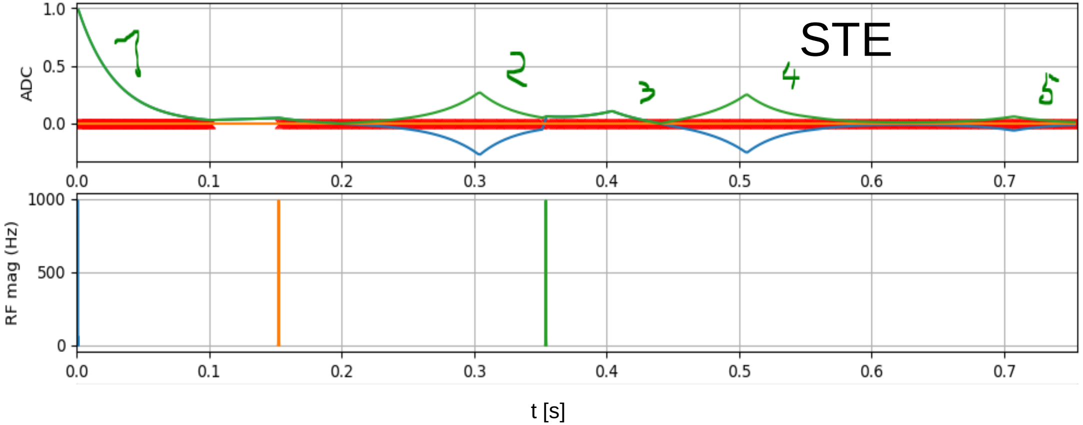
Exercises – basic echoes

rep.
FID



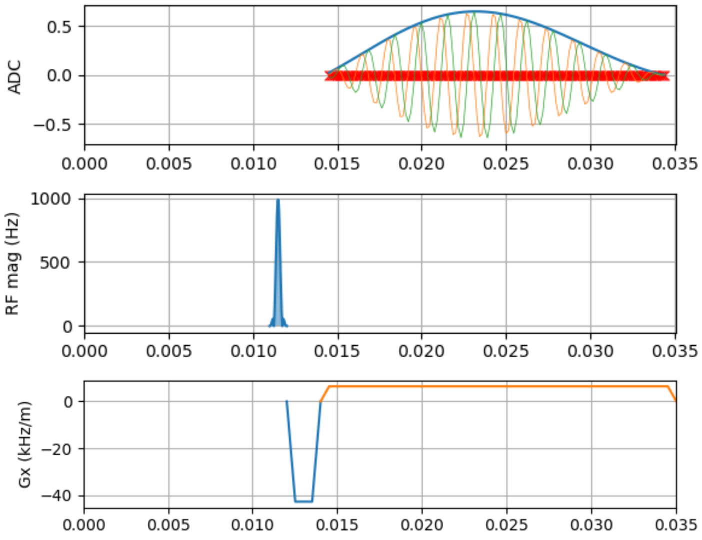
1- exp(-t/T1)
T1 ≈ 1-3 s

3 pulses
5 echoes



Exercises – basic echoes

GRE

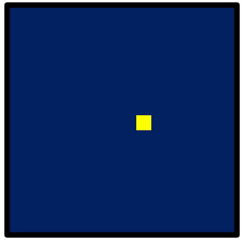


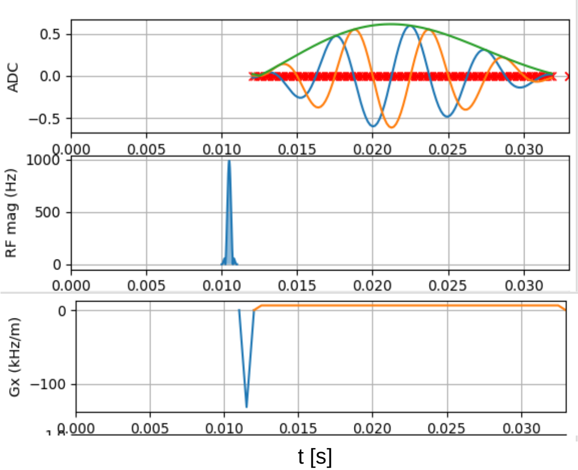
t [s]

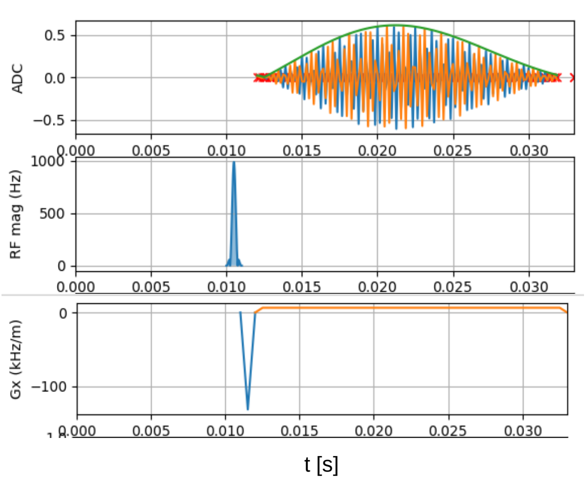
From GRE to 1D-MRI

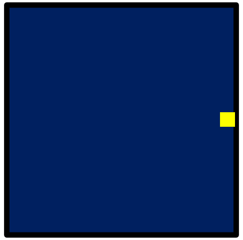
The gradient echo yields spatial encoding!

„Pixels at the edge generate fast oscillations“



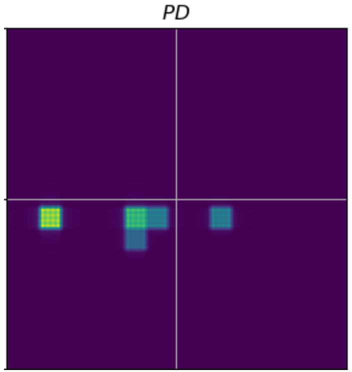


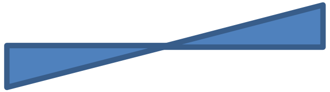


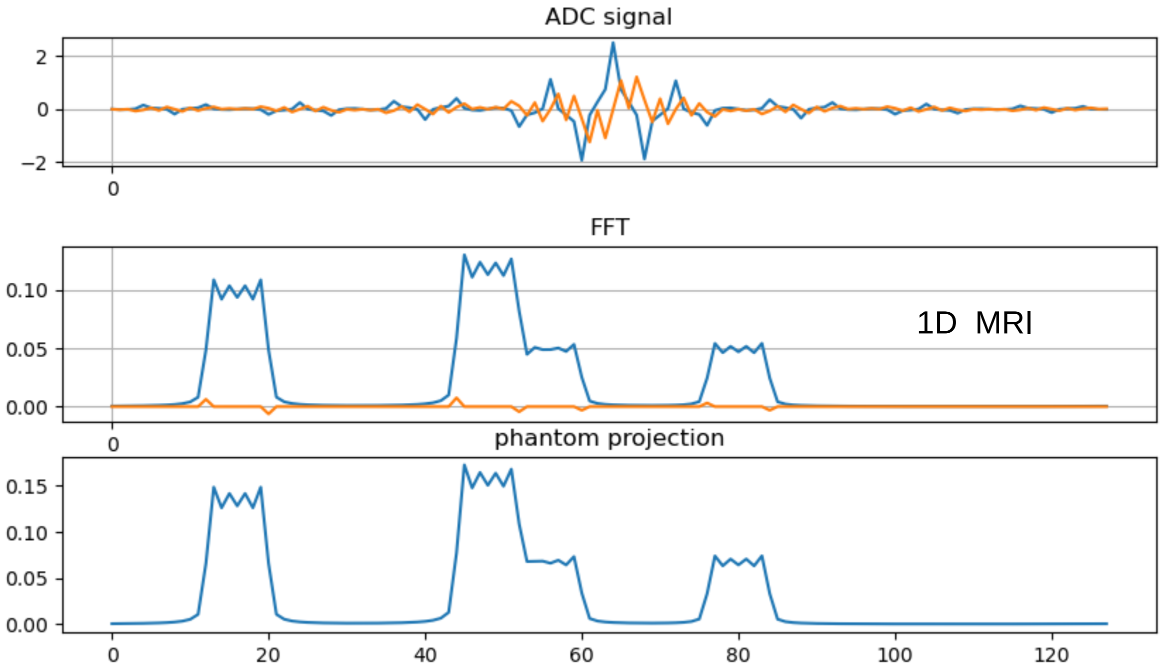


From GRE to 1D-MRI

Frequency encoding of GRE yields 1D MRI

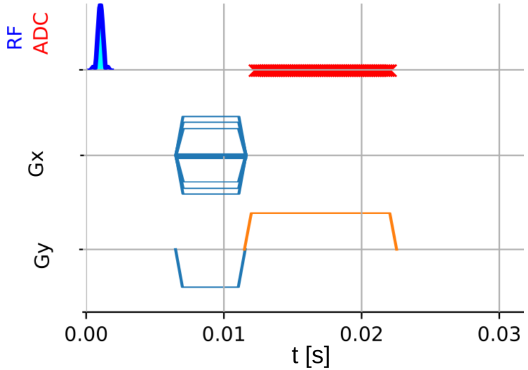


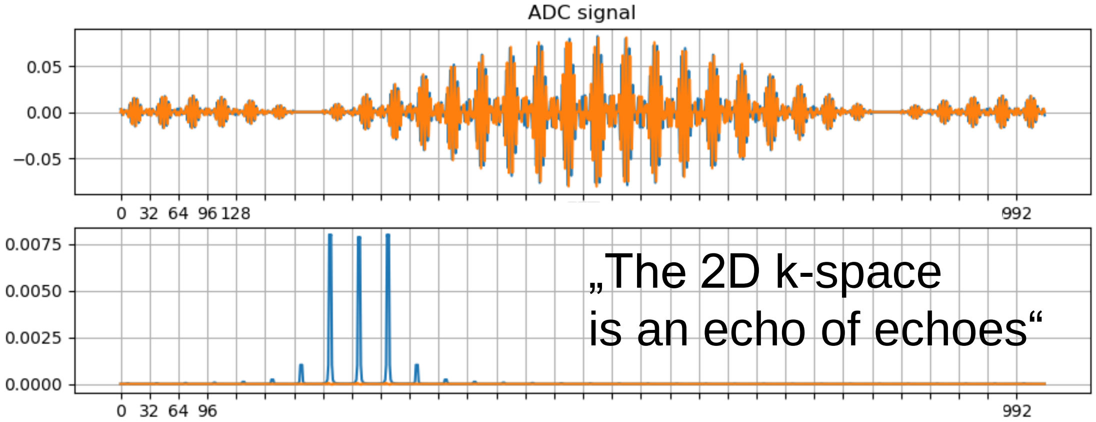

Magnetfeldgradient



From GRE to 2D-MRI

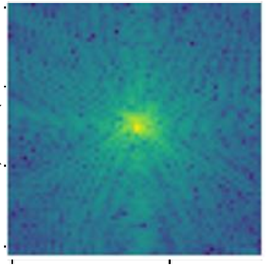
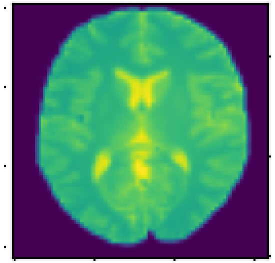
Phase encoding for full 2D MRI





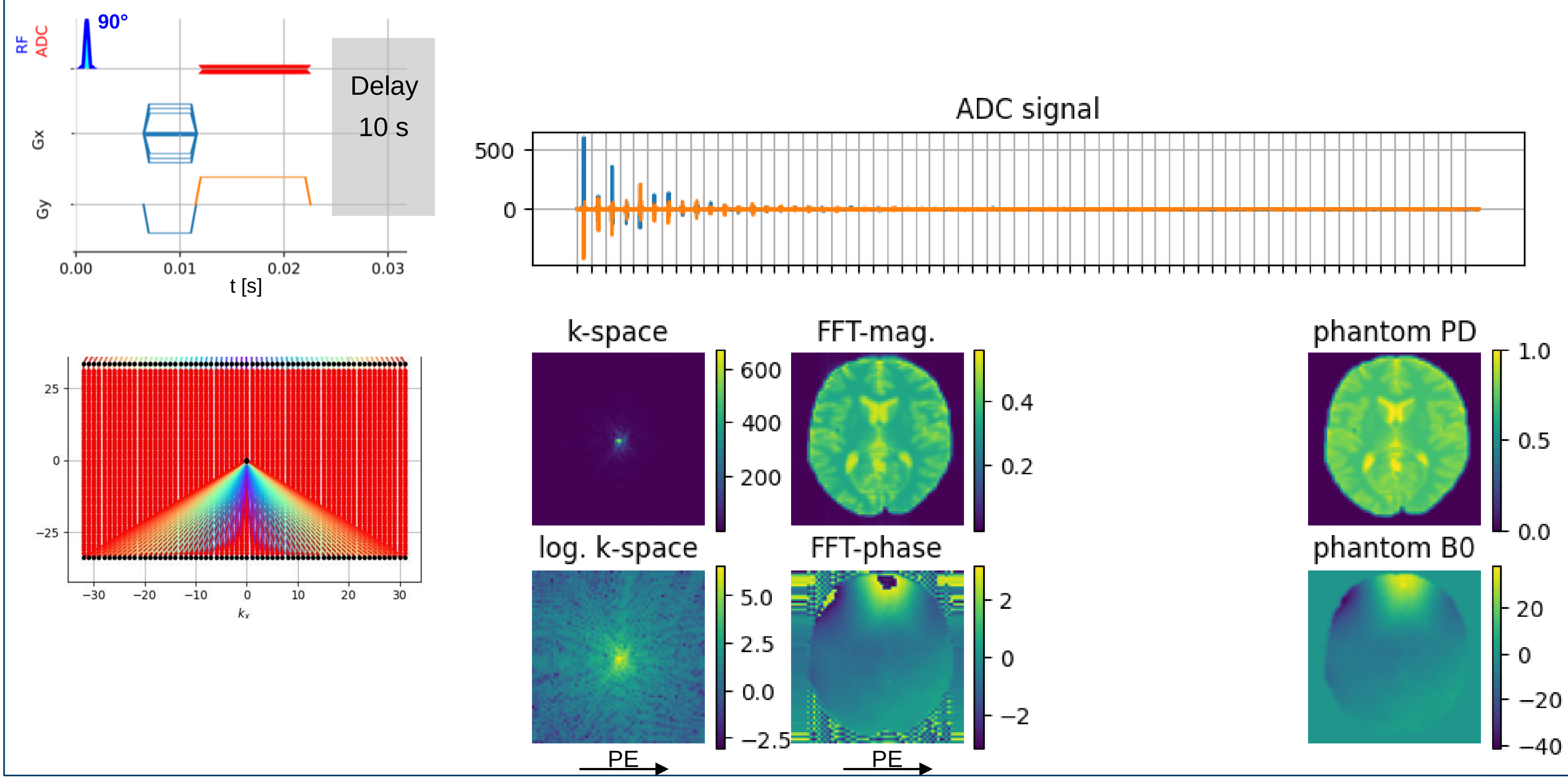
„The 2D k-space
is an echo of echoes“

2D k-space

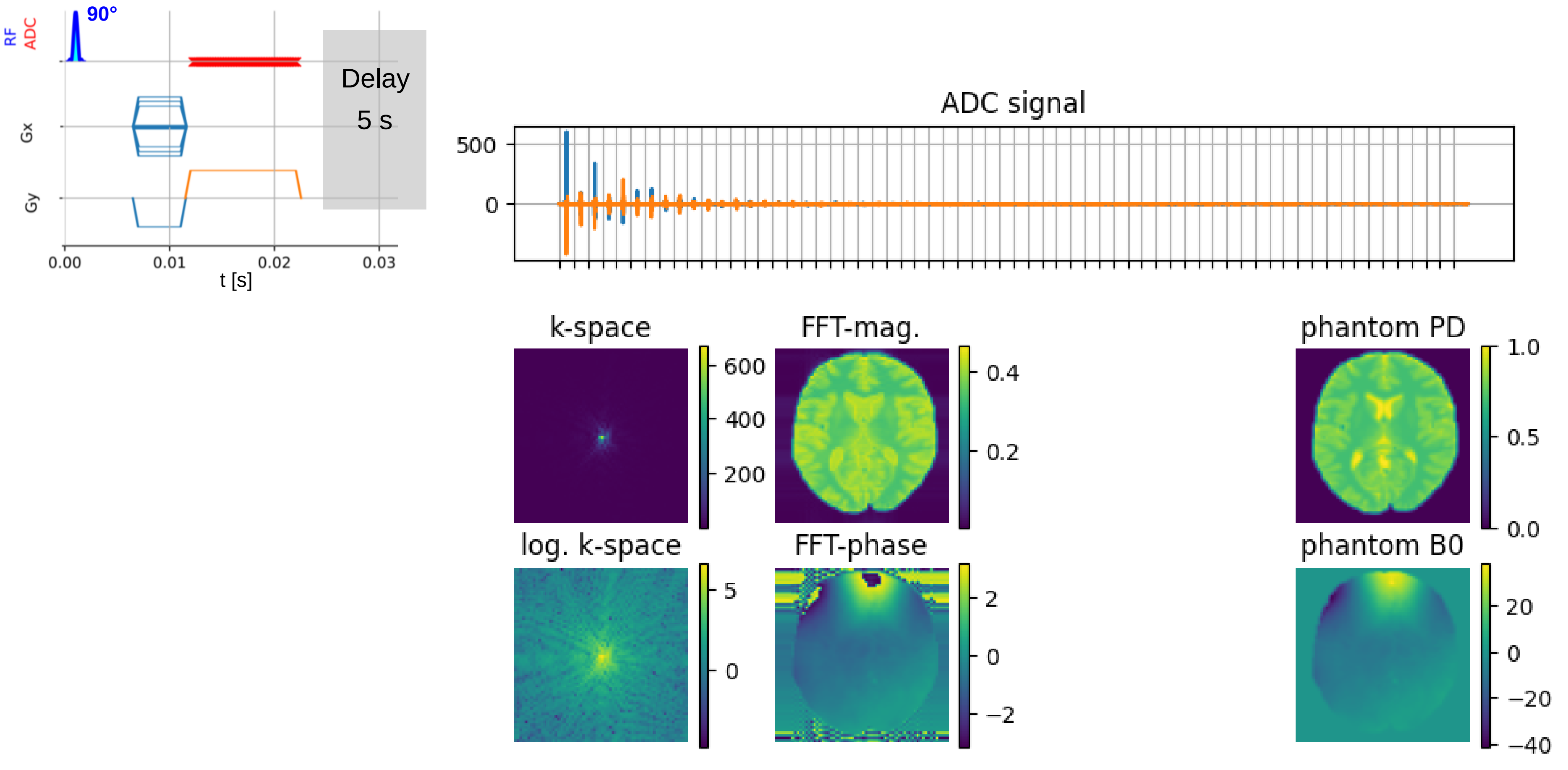
FFT2() = 

2D MRI

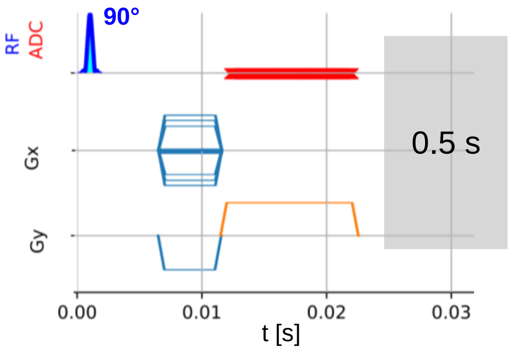
From GRE to FLASH



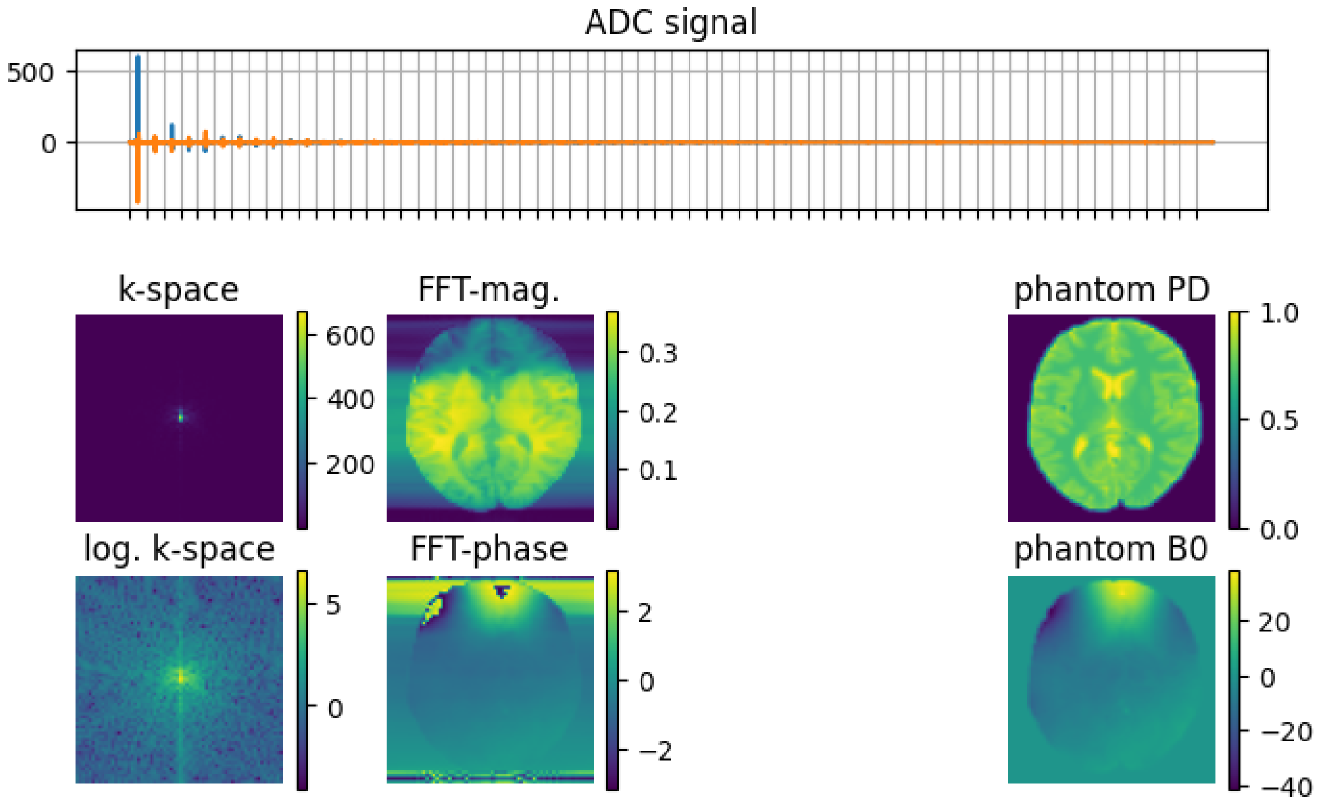
Reduce Delay to 5s



Delay 0.5 s

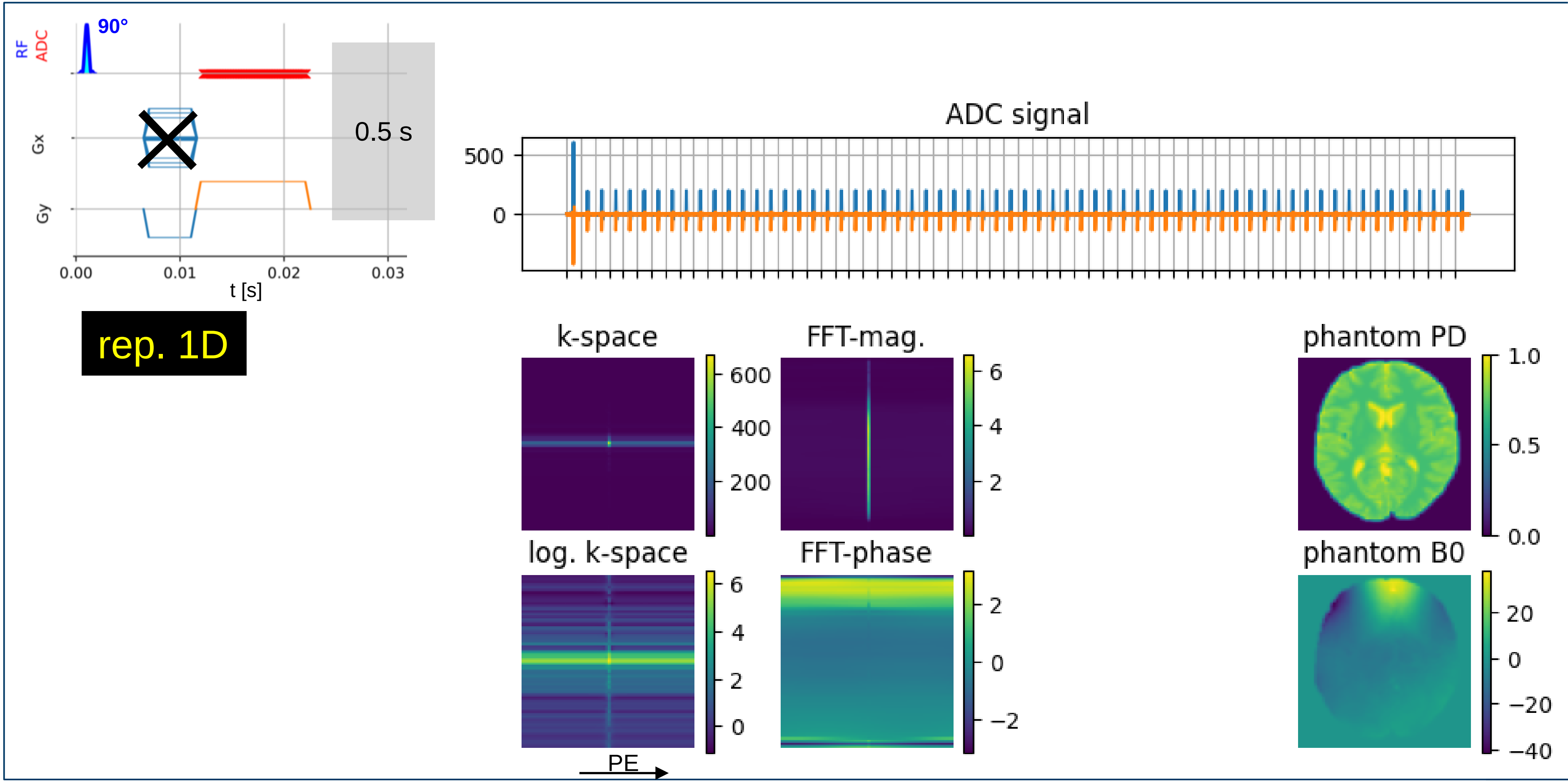


RF
ADC
90°
Gx
Gy
0.5 s
0.00
0.01
0.02
0.03
t [s]

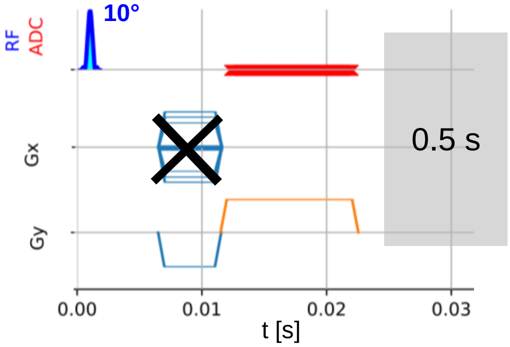


ADC signal
500
0
k-space
600
400
200
FFT-mag.
0.3
0.2
0.1
phantom PD
1.0
0.5
0.0
log. k-space
5
0
FFT-phase
2
0
−2
phantom B0
20
0
−20
−40

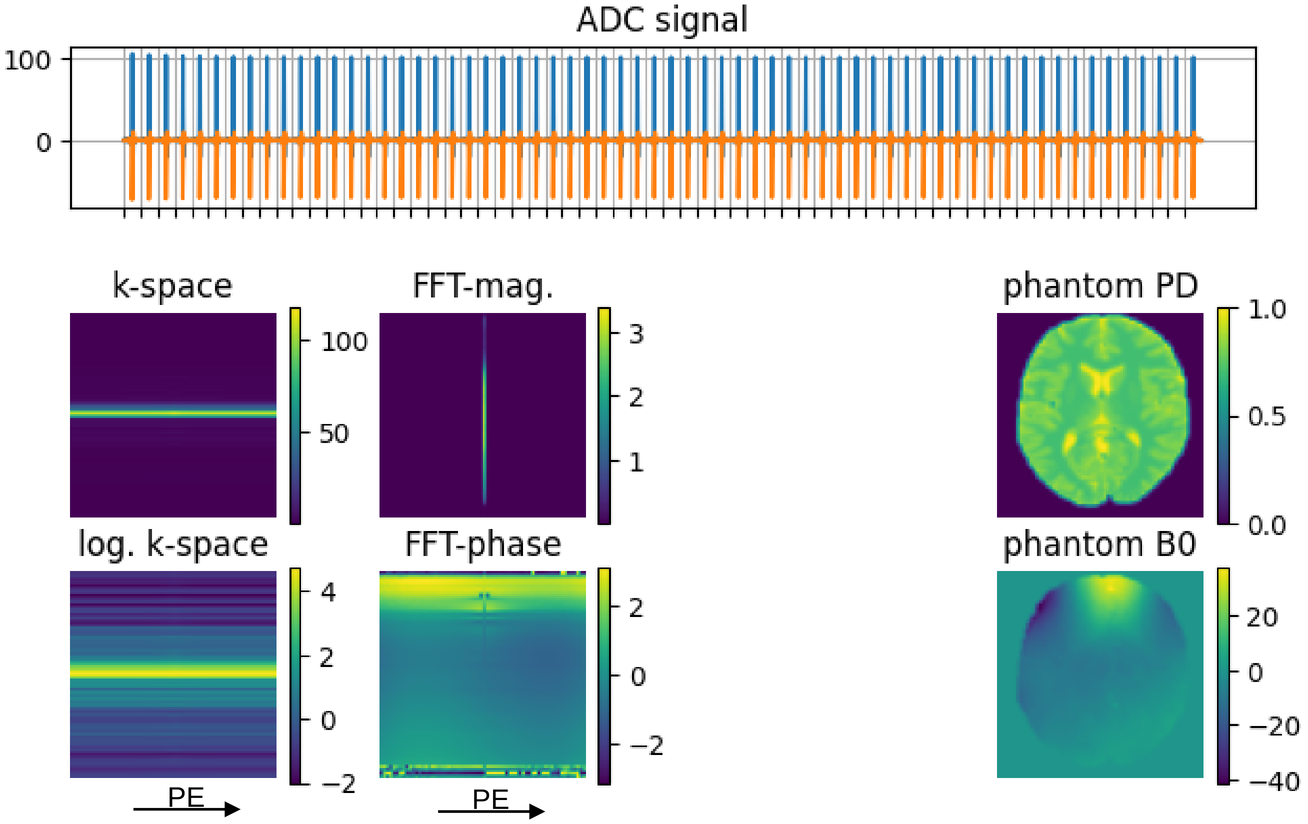
Delay 0.5 s, FA 90°



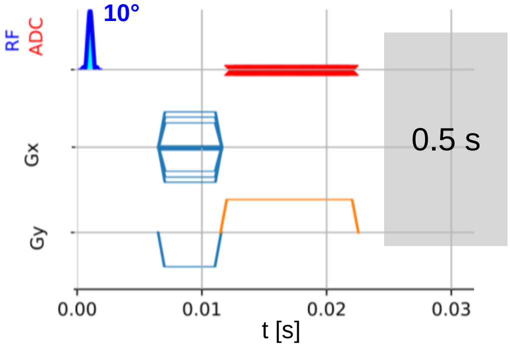
Delay 0.5 s, FA 10°

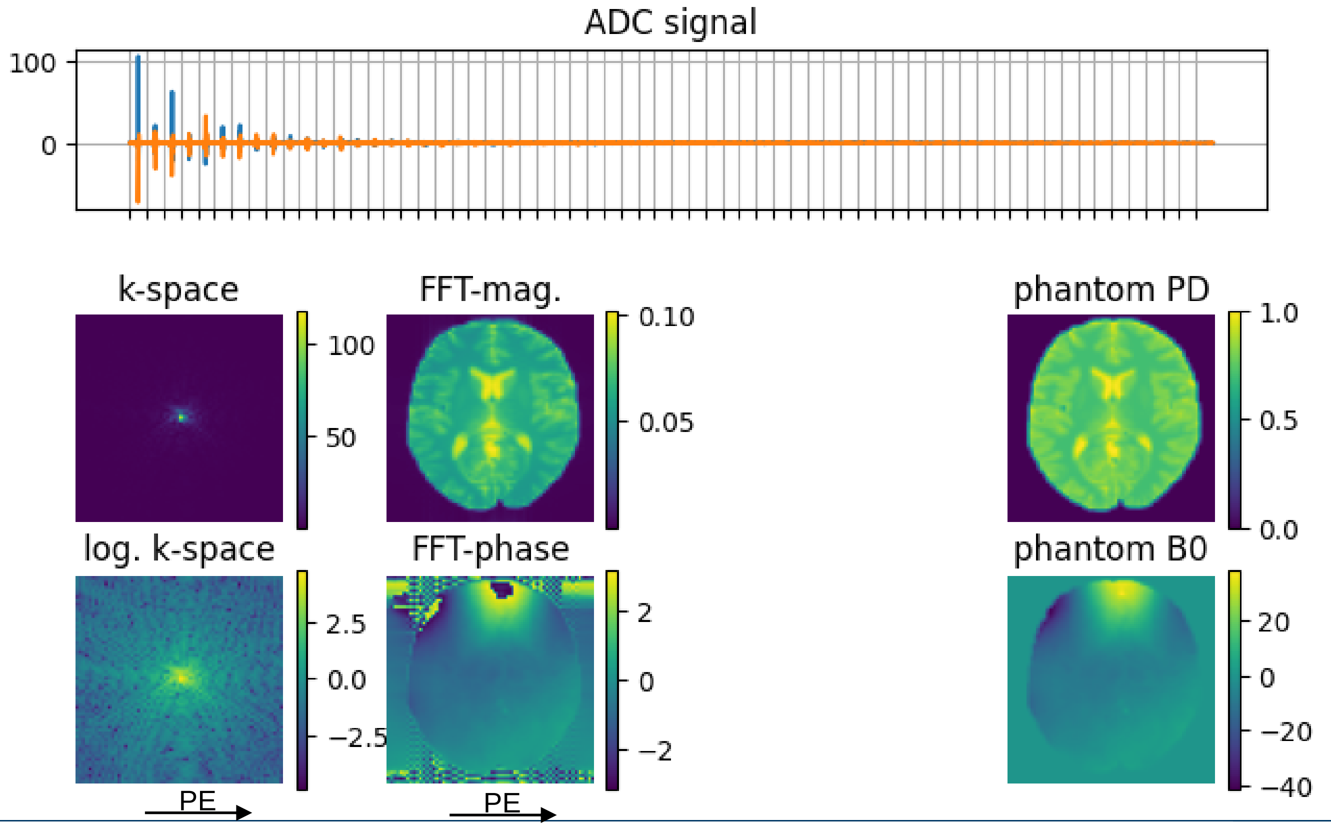


rep. 1D

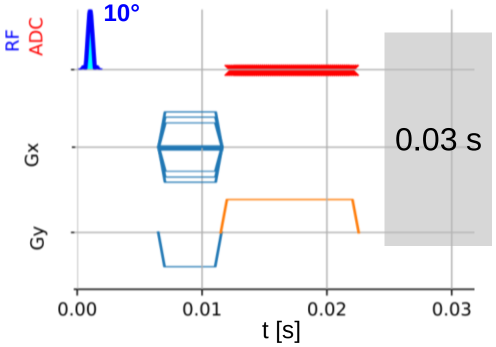


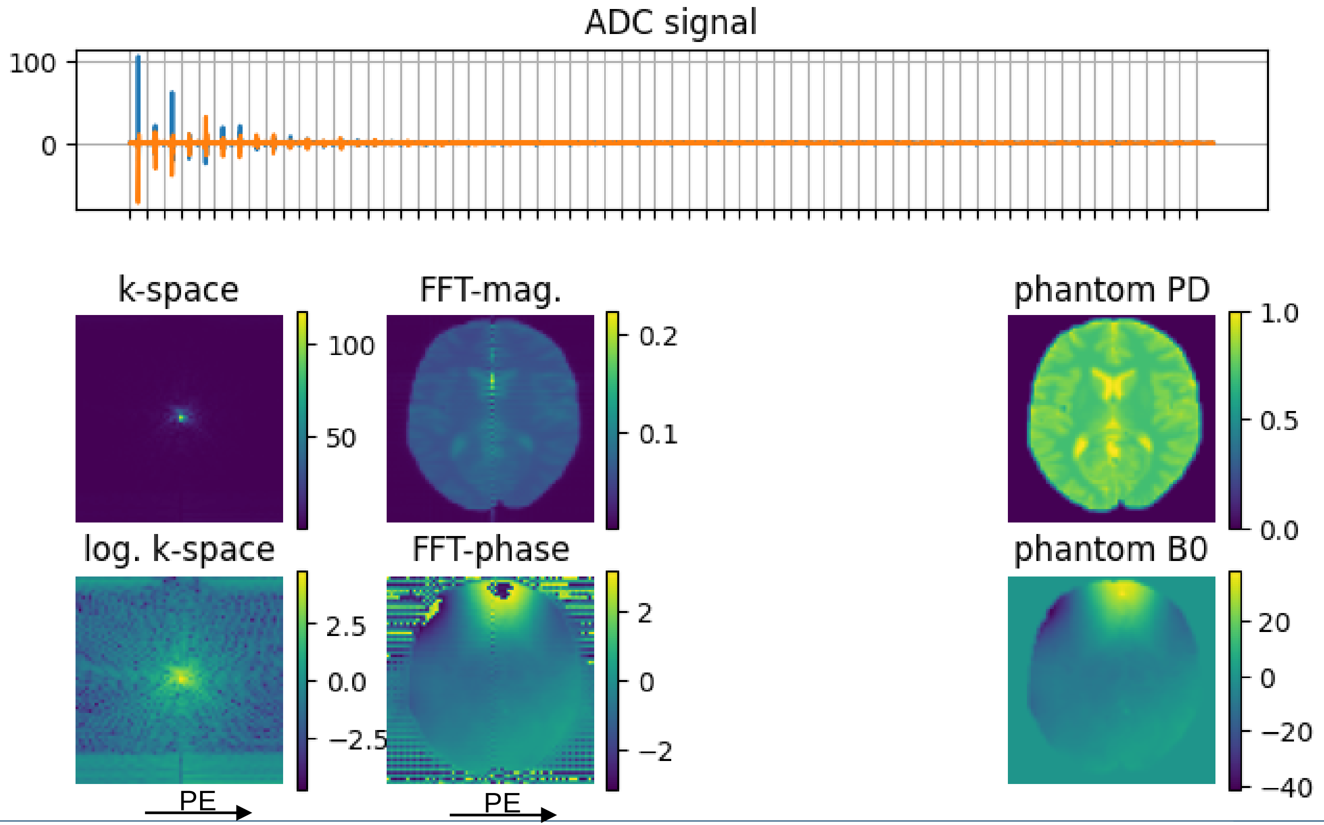
Delay 0.5 s, FA 10°



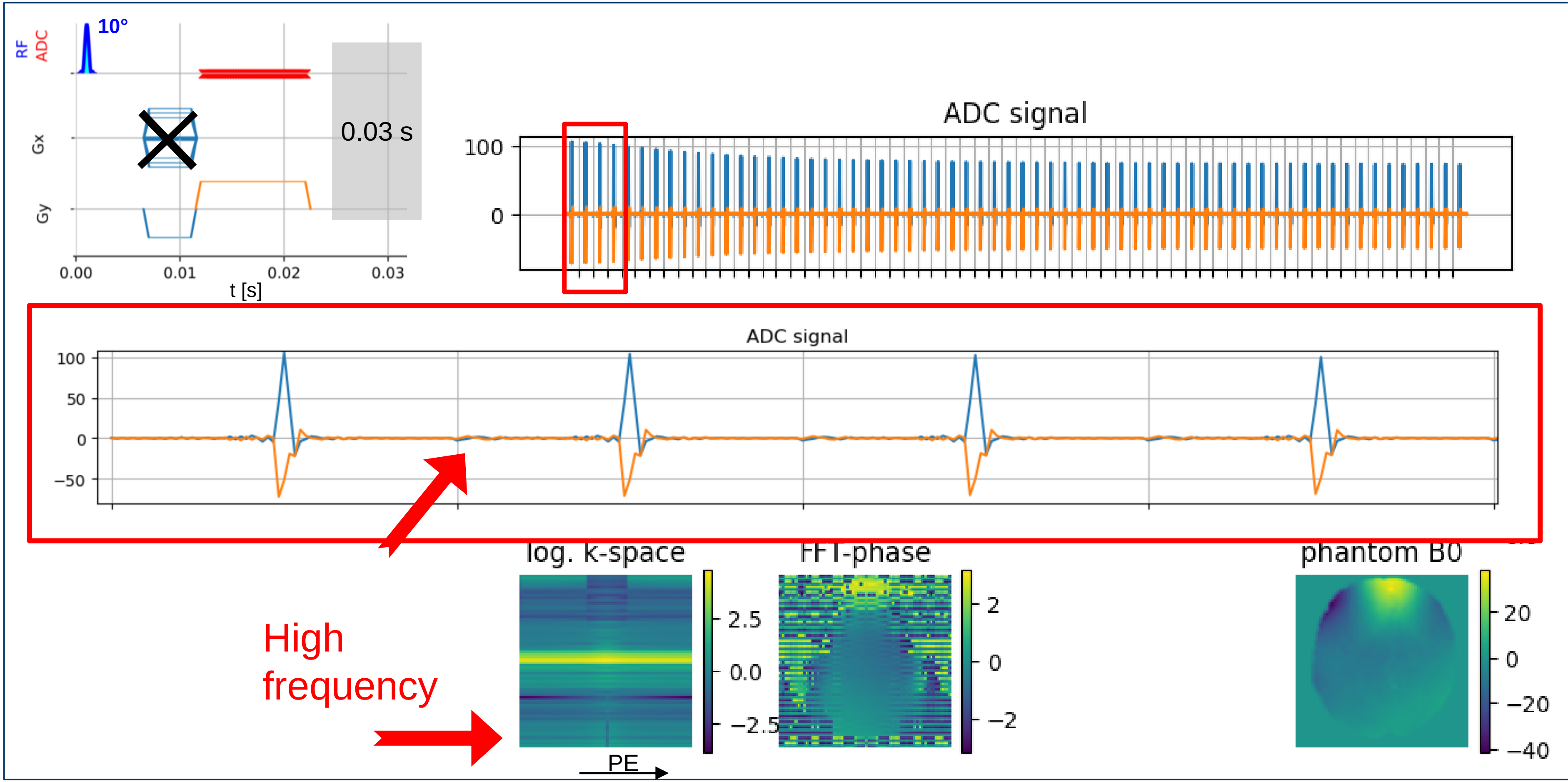


Delay 0.03 s, FA 10°

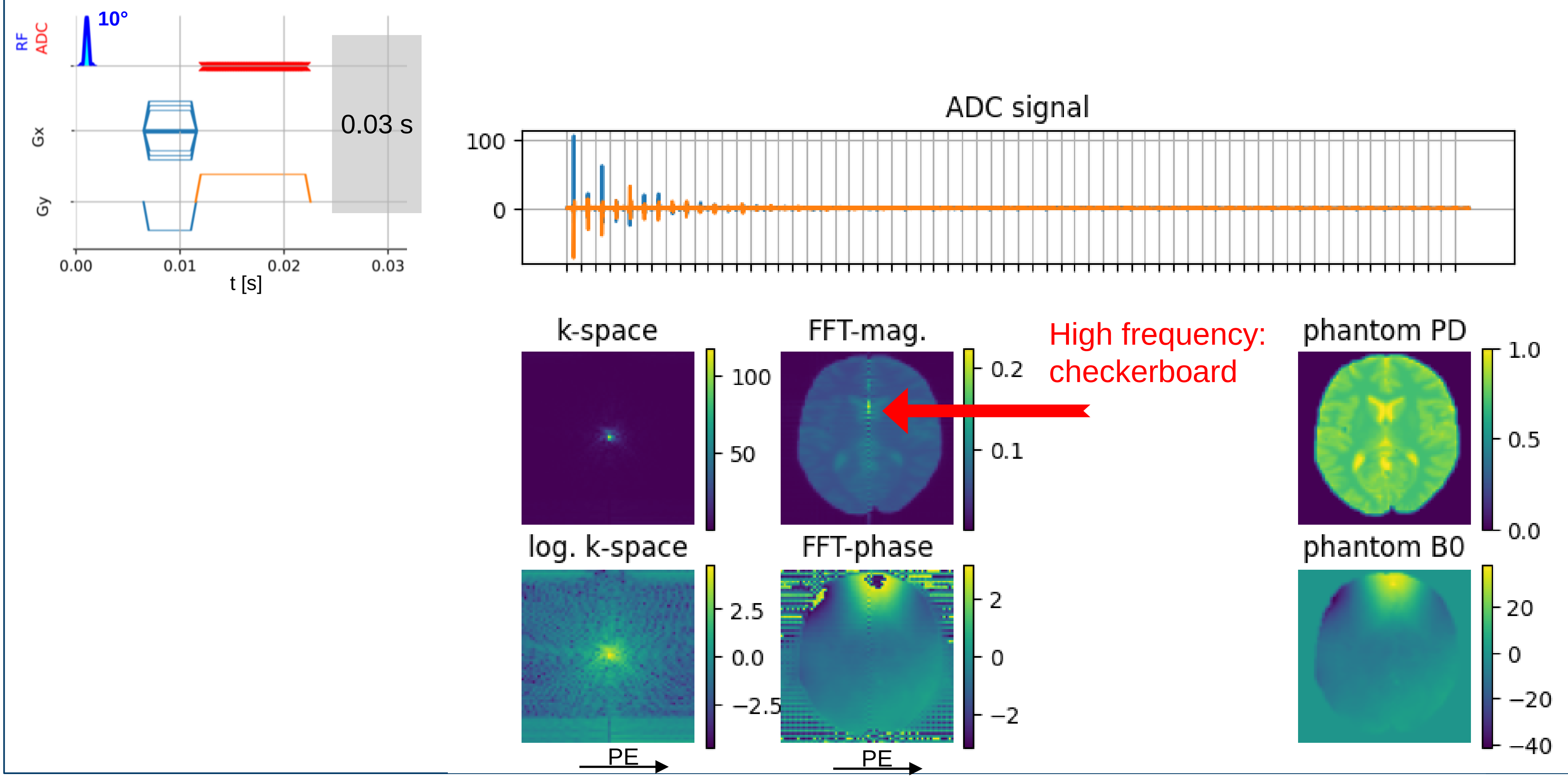




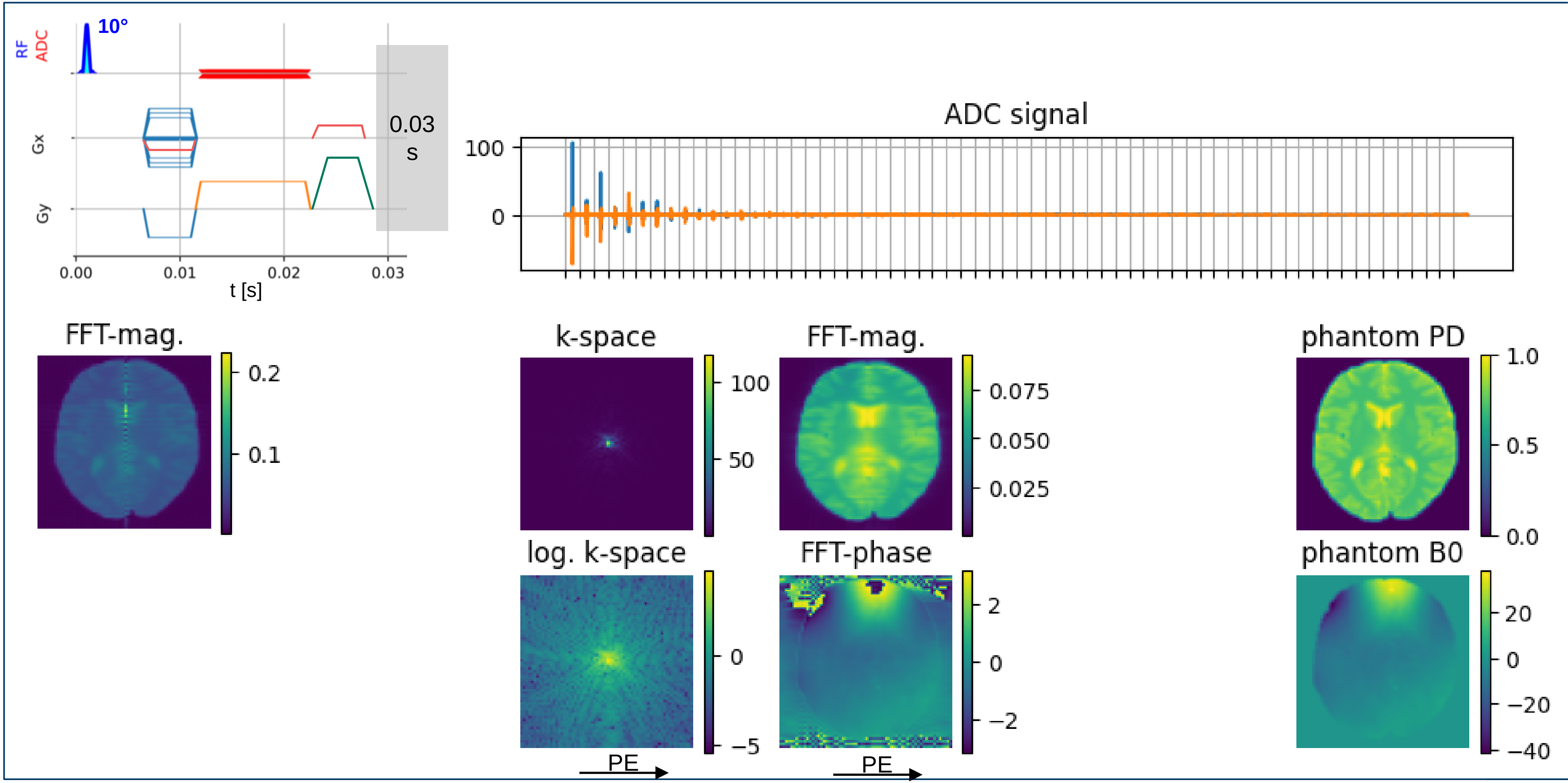
Delay 0.03 s, FA 10°



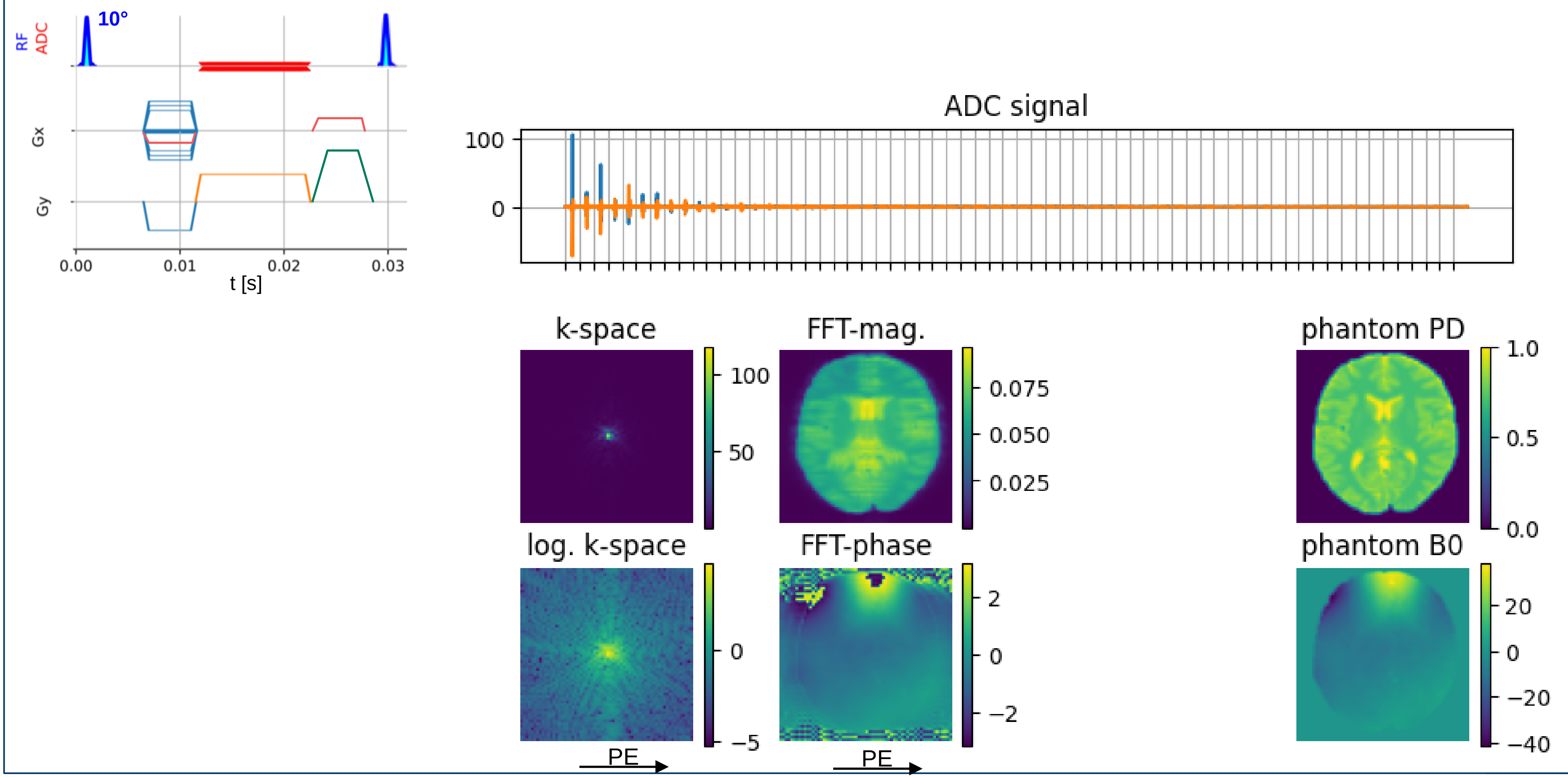
Delay 0.03 s, FA 10°



Delay 0.03 s, FA 10°, gradient spoiling



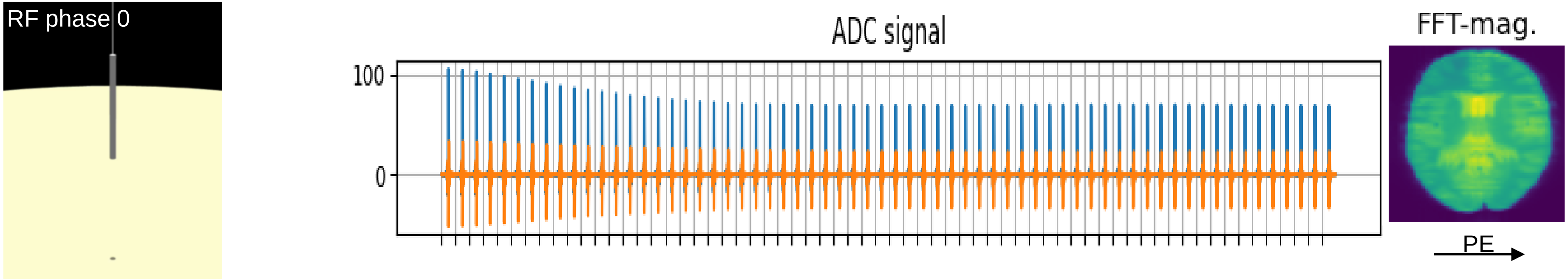
Delay 0.0 s, FA 10°, gradient spoiling

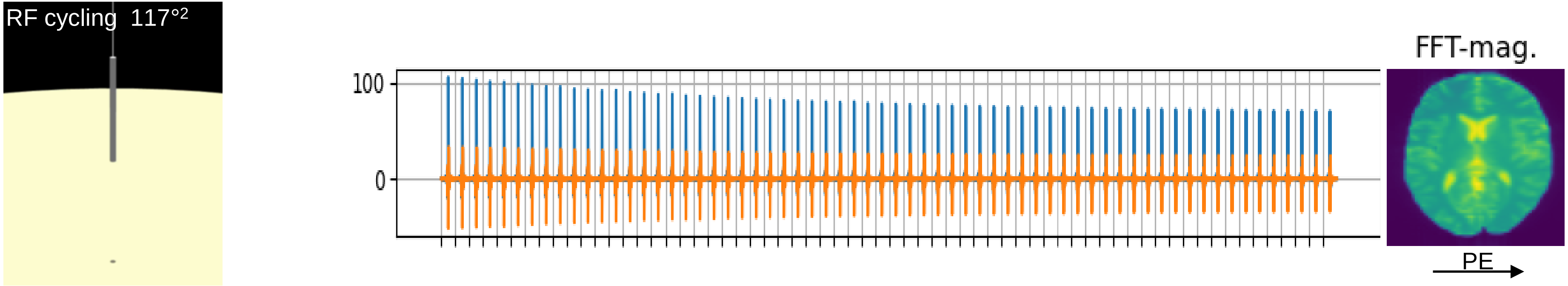


Delay 0.0 s, FA 10°, gradient spoiling, rf spoiling

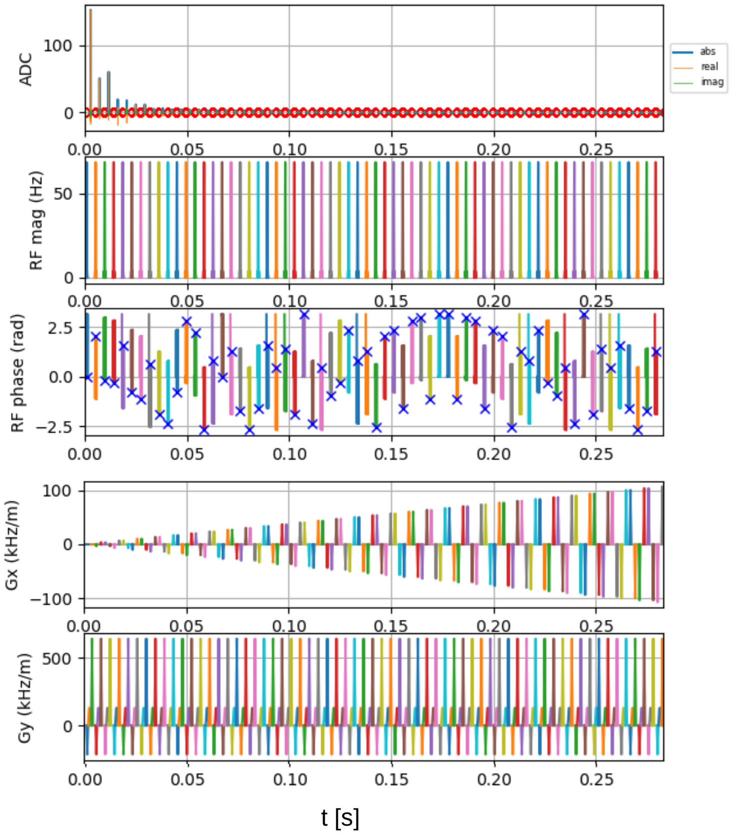
Artifact: Signal decay

Solution: rf cycling



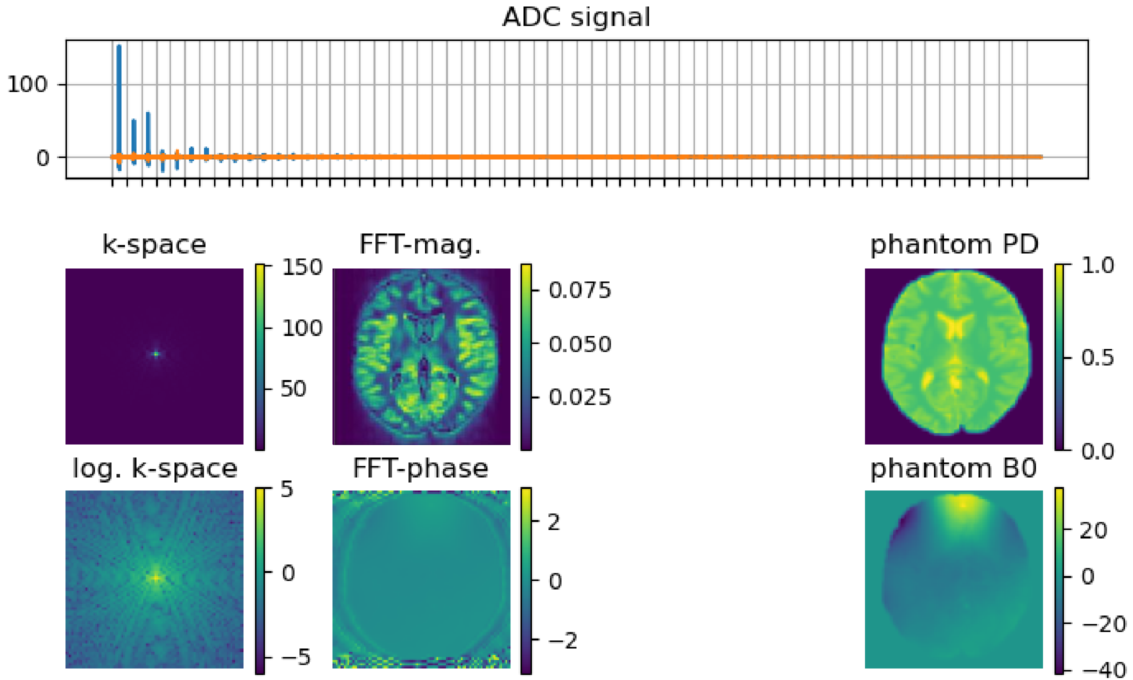


FLASH: Reduce TR to 5.5 ms and FA to 5°



Gradient and rf spoiled FLASH MRI
Fast low angle shot

600 s -> 0.3 s



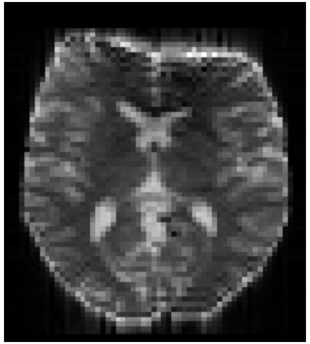
Simulation enables…

… fast feedback to find bugs / new techniques.

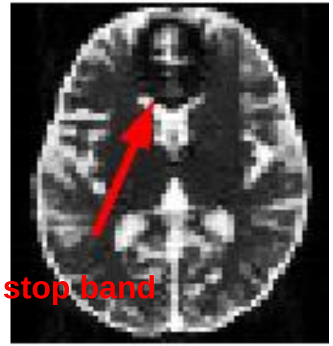
… to solve more mistakes before a real scan.

… to understand artifacts (encoded/non-encoded/recon-related)

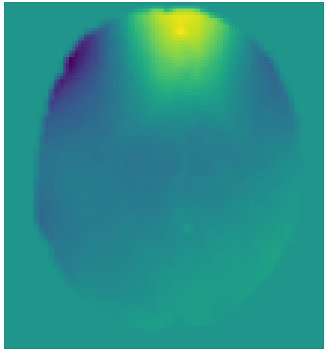
SE-EPI



bSSFP

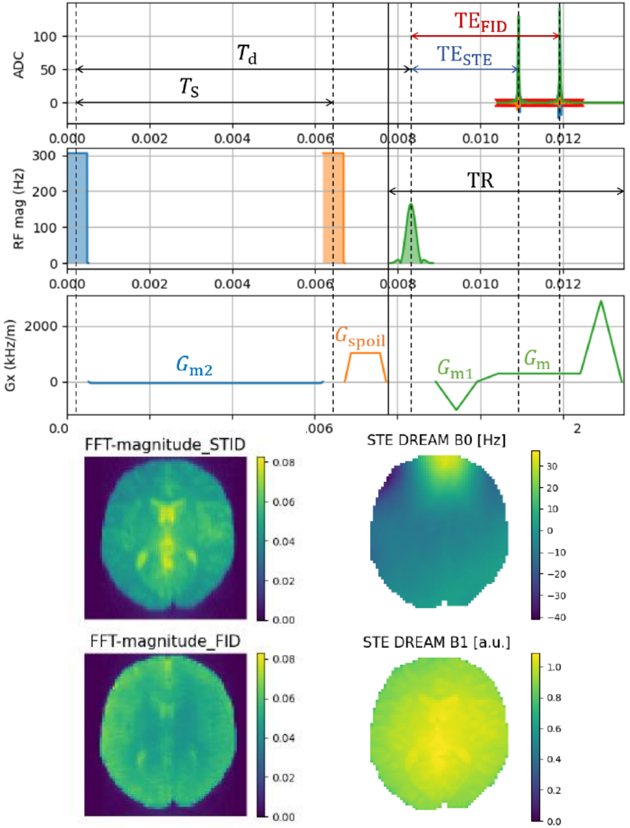


phantom B0

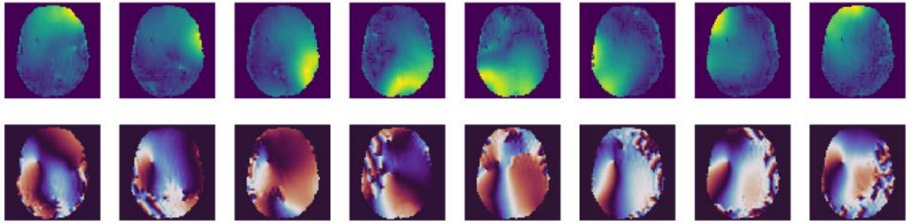


Towards research: prototyping

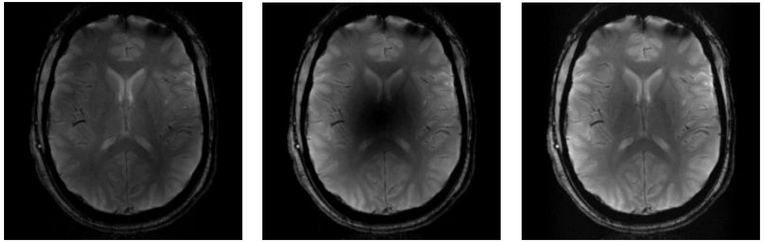
STE / DREAM



Pulseq-pTx extension



→ .seq-file



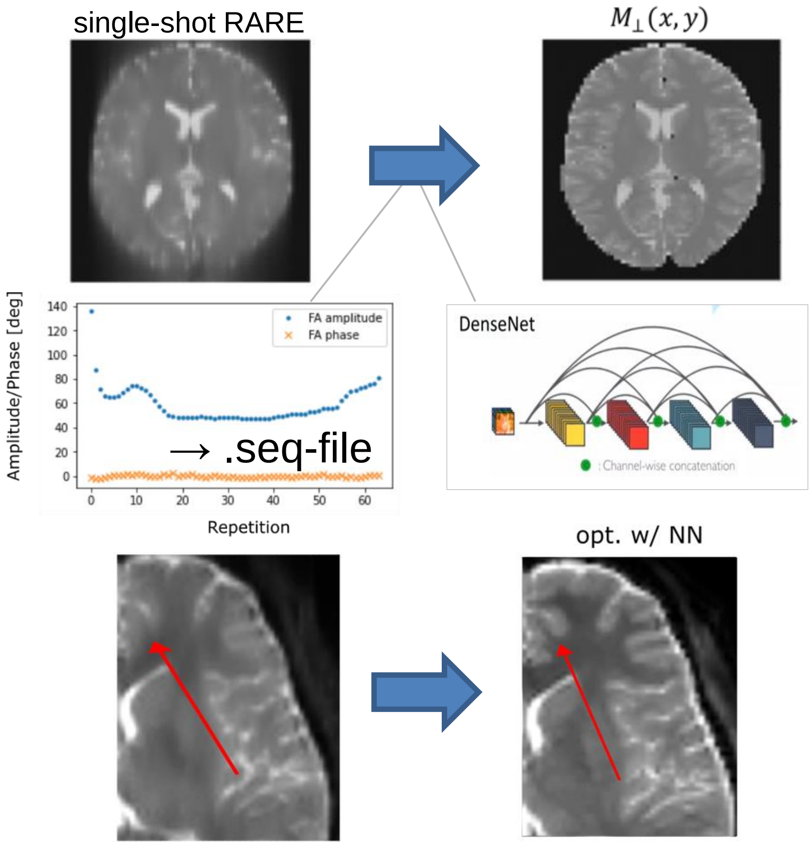
(d) Brain CP (d) Brain EP (f) Brain TIAMO.seq

CEST-MP-DREAM, Baum,Weinmüller et al. ESMRMB 2023

Freudensprung et al. ESMRMB 2023

Towards research: optimization

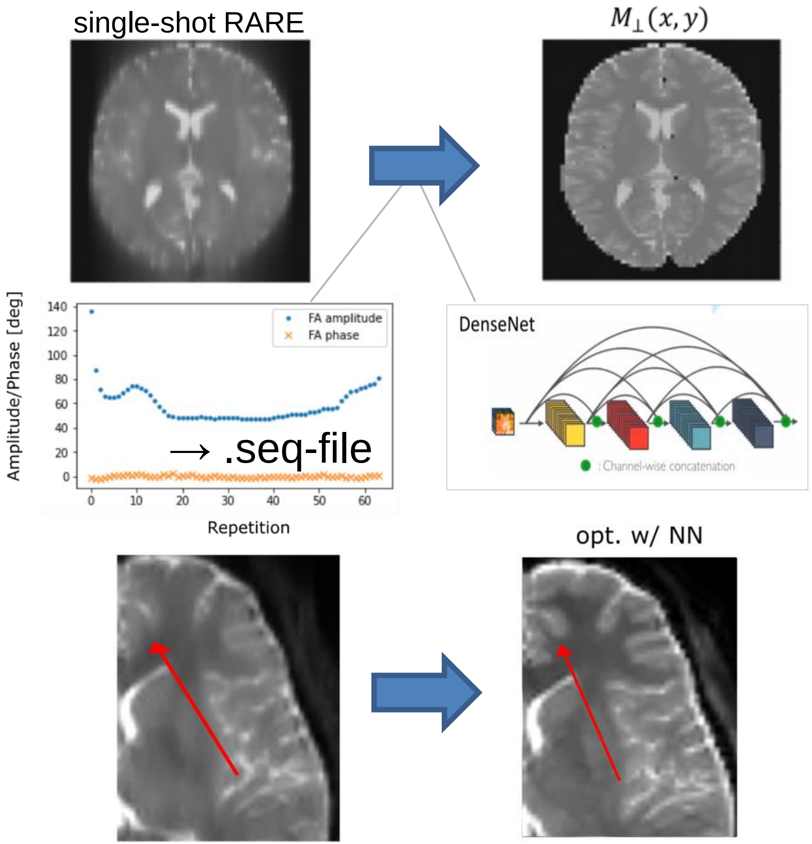
TSE flip angle train optimization



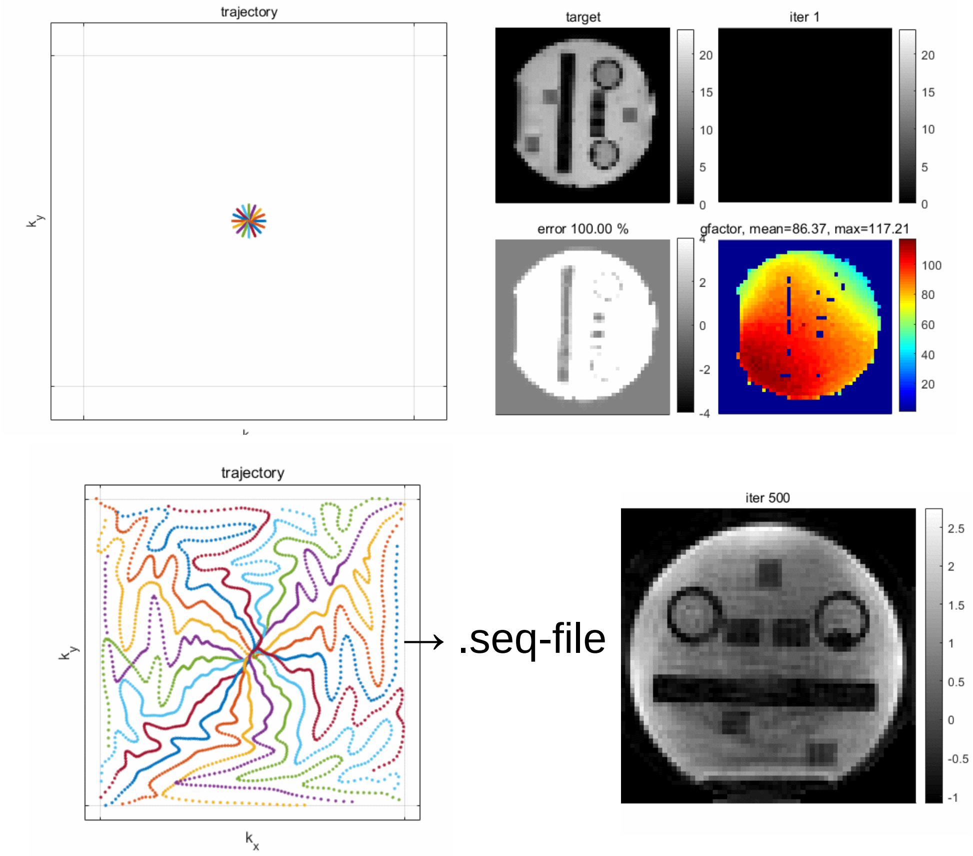
Dang et al. MRM 2023 FLASH: Weinmüller et al. DS-ISMRM 2022

Towards research: optimization

TSE flip angle train optimization



k-space trajectory optimization



Dang et al. MRM 2023 FLASH: Weinmüller et al. DS-ISMRM 2022 Glang et al. ISMRM 2021

How to do it:

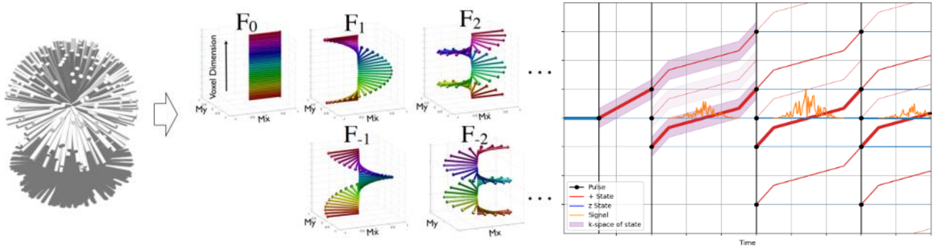
- **Features and limits of our simulation**
- **Hands on Coding example**

  https://mrzero-core.readthedocs.io/en/latest/playground_mr0/overview.html

Features and Limitations of our simulation

Limits

- **EPG-based simulation**
  - arbitrary timing
  - encoding



Jonathan Endres

- Instantaneous pulses (center pulse assumed)
  - no slice profile, no rf off-resonance, no SMS ->mr.simRf.m ->KOMA.jl

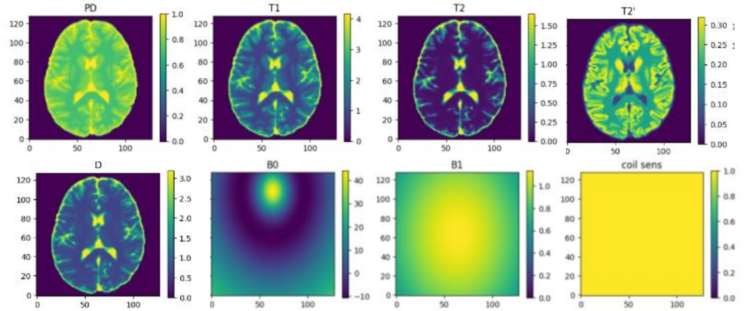
- Pulseq standard >1.2 required, tested until 1.4
- Newest versions? / New loop structures? / Extensions? - > Delay!

Endres J, Dang N, Glang F, Loktyushin A, Weinmüller S, Zaiss M.
Phase distribution graphs for differentiable and efficient simulations of arbitrary MRI sequences. In: Proc. ISMRM 30, 2022

Features and Limitations

Features

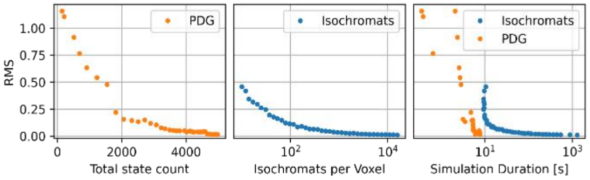
- PD, T1, T2, T2’, D(isotropic), B0, B1 (all static)
    - compartments possible
- 1D/2D/3D possible, mimicking MRS is possible
- Differentiable

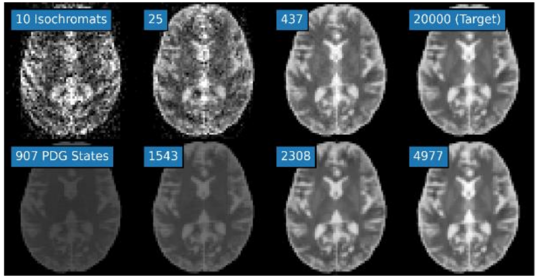


Features and Limitations

Features

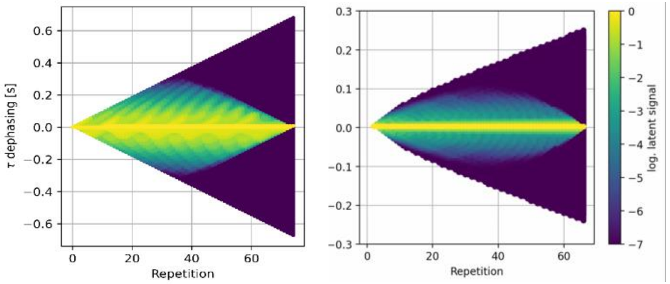
- PD, T1, T2, T2’, D(isotropic), B1, B0   (all static)
    - compartments possible
- 1D/2D/3D possible, mimicking MRS is possible
- Differentiable
- Faster than isochromat solutions
- EPG state analysis possible
- Recon: Adjoint, FFT, soon: GRAPPA/SENSE





phase graphs: graph.plot()

bSSFP RARE



How to do it:

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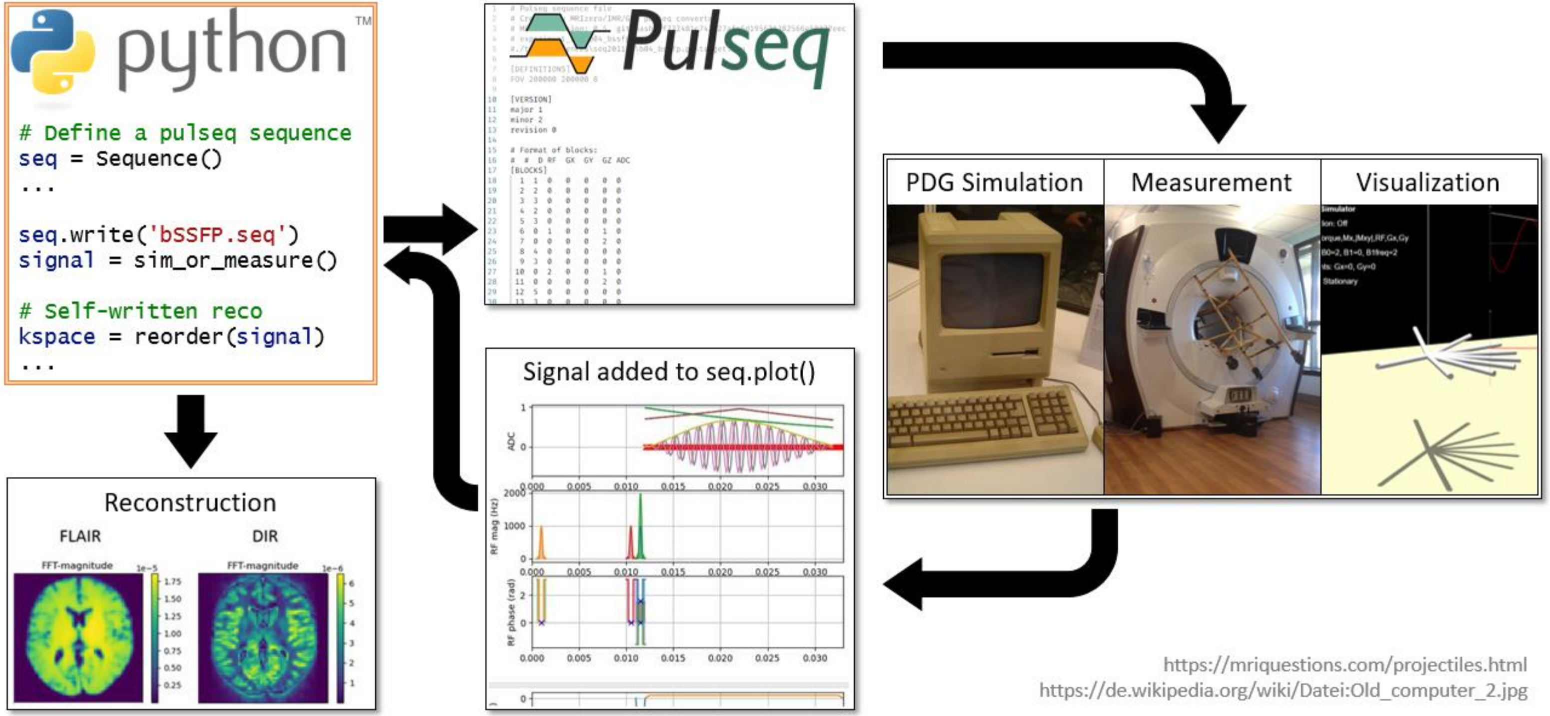
- **Hands on Coding example**

  https://mrzero-core.readthedocs.io/en/latest/playground_mr0/overview.html

MRI-Pulseq course at FAU, Erlangen



https://mriquestions.com/projectiles.html
https://de.wikipedia.org/wiki/Datei:Old_computer_2.jpg

Thanks!

- **Jonathan Endres, Simon Weinmüller, Nam Dang, Martin Freudensprung**
- **Felix Glang, Sebastian Müller, Alex Loktyushin, Kai Herz**

- **Thanks for Pulseq and PyPulseq!**

pypulseq

Pulseq

Thank you for your attention!

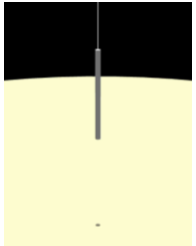
- **Open source course script + exercises + simulator:**
  https://github.com/mzaiss/MRTwin_pulseq

- **Simulation Core**
  https://github.com/MRsources/MRzero-Core

- **Documentation and Notebooks**
  https://mrzero-core.readthedocs.io

- **Direct links to demo colabs of this talk:**
  .seq-upload: https://colab.research.google.com/github/MRsources/MRzero-Core/blob/main/documentation/playground_mr0/mr0_upload_seq.ipynb
  GRE2FLASH: https://colab.research.google.com/github/MRsources/MRzero-Core/blob/main/documentation/playground_mr0/mr0_GRE_to_FLASH.ipynb

- **Lars Hansons Bloch-Simulator** https://www.drcmr.dk/BlochSimulator/
  - Extended for Pulseq(1.3)-file input: https://asd2511.xyz/BlochSimWeb/



moritz.zaiss@fau.de
@altustro

www.mr-physik.med.fau.de/ag-zaiss