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Overview of the Pulseq Approach

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Legacy approach to sequence programming

- Get a template sequence from the vendor

  Challenge: Time and paperwork

  Why? Implementation details even for basic things are often unknown

  Actual challenge: Generic opaqueness and secrecy in the MR field

- Implement additional features

  Challenge: complexity of product sequences

  Challenge: focus on a subset of features without breaking the whole thing

  Challenge: understanding / debugging is difficult due to reliance on libraries with inaccessible source code

- **Repeat from 0 for additional vendors or new software versions**

Pulseq Approach

- Minimize effort for implementation and support on hardware
  - Lean sequence-to-hardware interface
- Remove the thresholds in sequence programming
  - Make simple things truly simple
- Make researcher-oriented features accessible
  - Arbitrary gradients, arbitrary RF, free ordering, X-nuclei, …
- Prevent typical sources of (human) errors
  - Avoid timing errors with “overlapping” gradients
  - Make data flag and counter setting optional/unnecessary
- **Promote open-source thinking, sharing and exchange!**

Image source: wikipedia.org

What is *Pulseq*?

- *Pulseq* is a language to describe MR pulse sequences

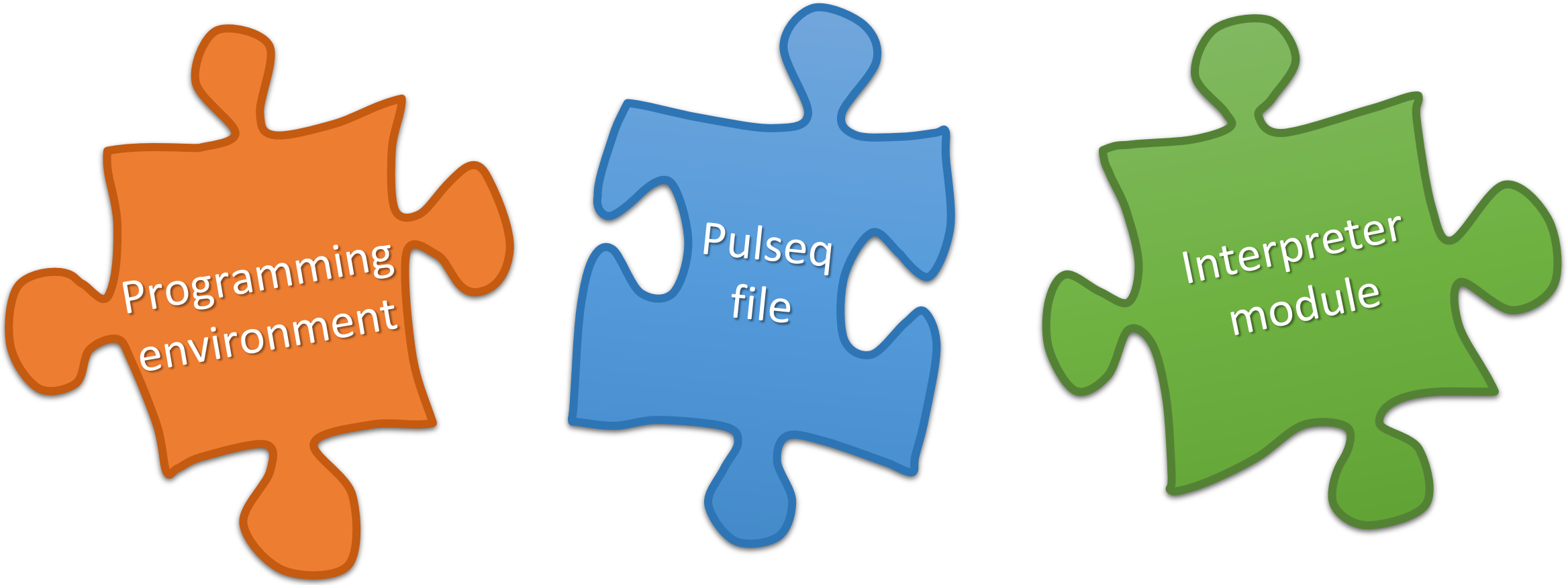
- *Pulseq* is the software to generate such pulse sequence descriptions

- *Pulseq* sequences are fixed successions of RF and gradient pulses and ADC events

- *Pulseq* scripts can re-generate *Pulseq* sequences to accommodate user input

Pulseq ecosystem includes sequences, software to generate them and software and hardware to consume them

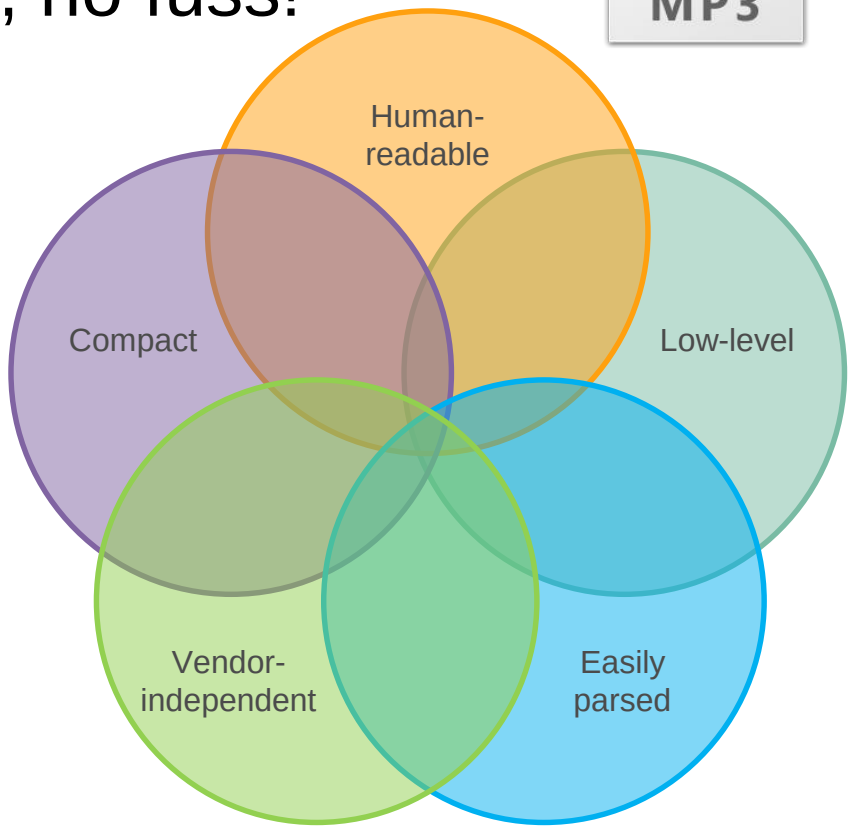
Pulseq : pieces of the puzzle



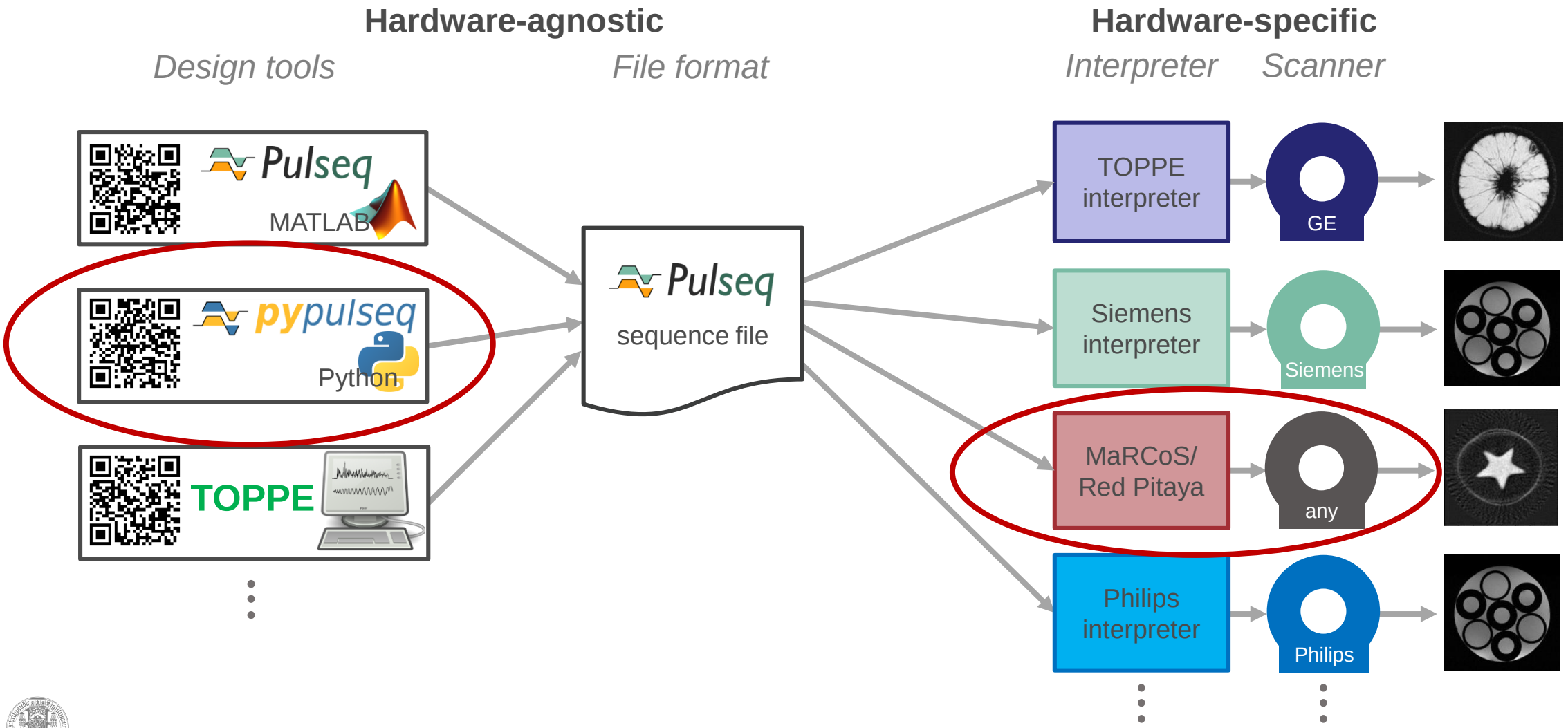
Pulseq file internals

- Explicit (low level) specification of the pulse sequence
  - Think of an MP3 file (or more precisely lossless FLAC)
- No loops, no parameters, no dependencies, no fuss!

- Text file (human-readable)
  - Simple hierarchy
    (RF pulses, gradients, shapes)
  - Event table keeps it together
  - See http://pulseq.github.io/specification.pdf
    for more details

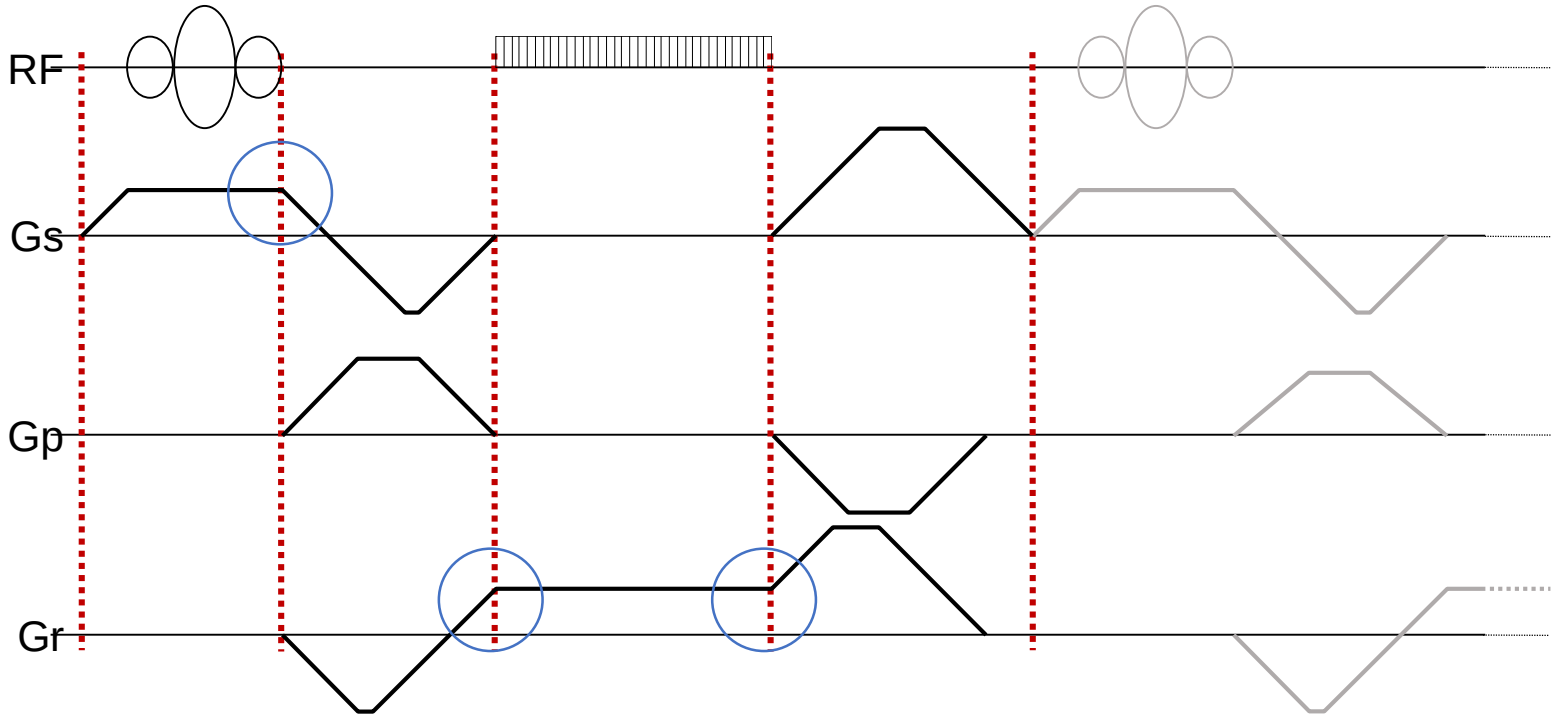


Pulseq framework overview



Pulse sequence definition in *Pulseq*

Concatenation of non-overlapping blocks



- Block 1:
  gradient and RF
- Block 2:
  only gradients
- Block 3:
  gradient and ADC
- Block 4:
  only gradients
- Block 5:
  gradient and RF …

Gradients do not have to start or end at 0 at the block boundaries

see http://pulseq.github.io/specification.pdf for more details

Pulseq block concept in detail

- Each block may contain following events:
  - One optional gradient pulse per axis
  - One optional RF pulse
  - One optional ADC event
- Individual events may define own start delays
- All events in the block overlap in time
- Duration of the block is defined by the longest event
  - Matlab/Python toolboxes use “dummy” delay objects to make blocks longer
- Explicit sequence description
  - No loops, no dependent parameters

How to design a sequence in *Pulseq*

conceptual design steps

- Step 1: spilt the time axis into blocks
- Step 2: assign events to the blocks

practical implementation steps

- Step 3: create/calculate all events
- Step 4: populate the blocks and add them to the sequence

validation steps

- Step 5: check timing, verify k-space trajectory, hardware and PNS limits, etc

Matlab *Pulseq* workflow

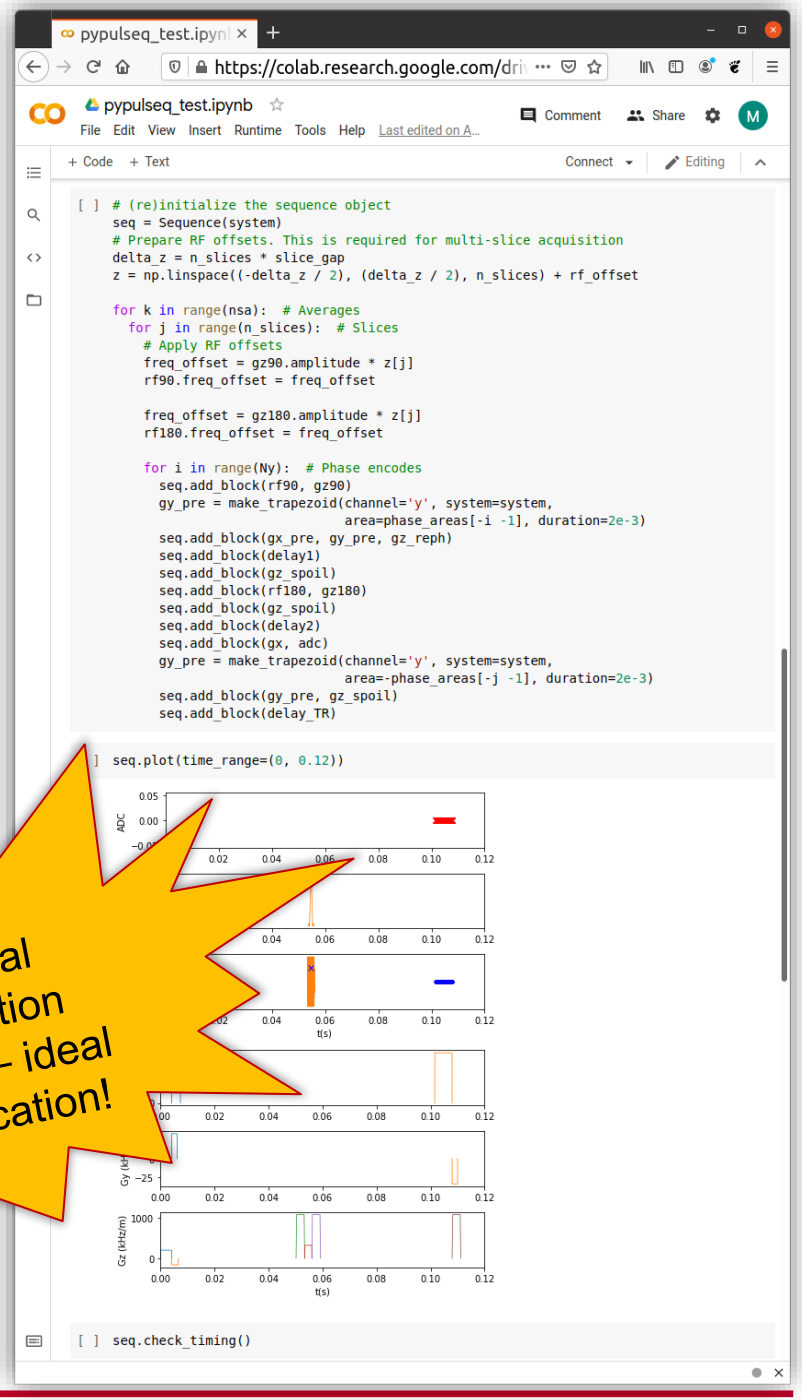
```
fov = 256e-3; slThck = 5e-3;
Nx = 128; Ny = Nx;
TE = 10e-3; TR = 20e-3; alpha=15;

sys = mr.opts('MaxGrad',20,'GradUnit','mT/m',...
    'MaxSlew',100,'SlewUnit','T/m/s',...
    'rfRingdownTime', 20e-6, 'rfDeadtime', 100e-6, 'setAsDefault', true);
seq=mr.Sequence(sys);

[rf, gz, gzReph] = mr.makeSincPulse(alpha*pi/180, 'Duration', 4e-3,...
    'SliceThickness', slThck, 'apodization', 0.5,'timeBwProduct', 4);

gx = mr.makeTrapezoid('x', 'FlatArea', Nx/fov, 'FlatTime', 6.4e-3);
adc = mr.makeAdc(Nx, 'Duration', gx.flatTime, 'Delay', gx.riseTime);
gxPre = mr.makeTrapezoid('x', 'Area', -gx.area/2, 'Duration', 2e-3);
gyPre = mr.makeTrapezoid('y', 'Area', Ny/2/fov, 'Duration', 2e-3);

phaseAreas = (0:Ny-1)/(Ny/2)-1;
delayTE = round((TE - mr.calcDuration(gxPre) - mr.calcDuration(gz)/2 ...
    - mr.calcDuration(gx)/2)/seq.gradRasterTime)*seq.gradRasterTime;
delayTR = round((TR - mr.calcDuration(gxPre) - mr.calcDuration(gz) ...
    - mr.calcDuration(gx) - delayTE)/seq.gradRasterTime)*seq.gradRasterTime;

for i=1:Ny
    seq.addBlock(rf, gz);
    seq.addBlock(gxPre, mr.scaleGrad(gyPre,phaseAreas(i)), gzReph);
    seq.addBlock(delayTE);
    seq.addBlock(gx, adc);
    seq.addBlock(delayTR);
end

seq.setDefinition('FOV', [fov fov slThck]);
seq.setDefinition('Name', 'mini_gre');

seq.write('mini_gre.seq')
```

a runnable gradient echo sequence code (similar to Siemens' example miniFlash)

- Define high-level parameters (convenience)
- Define the system properties
- Define pulses and ADC objects used in the sequence
- Calculate the delays and reordering tables
- Loop and define sequence blocks
  - Duration of each block is defined by the duration of the longest event
- Prepare sequence export and write it out
- *Copy '*.seq' to the scanner and run it!*

PyPulseq workflow

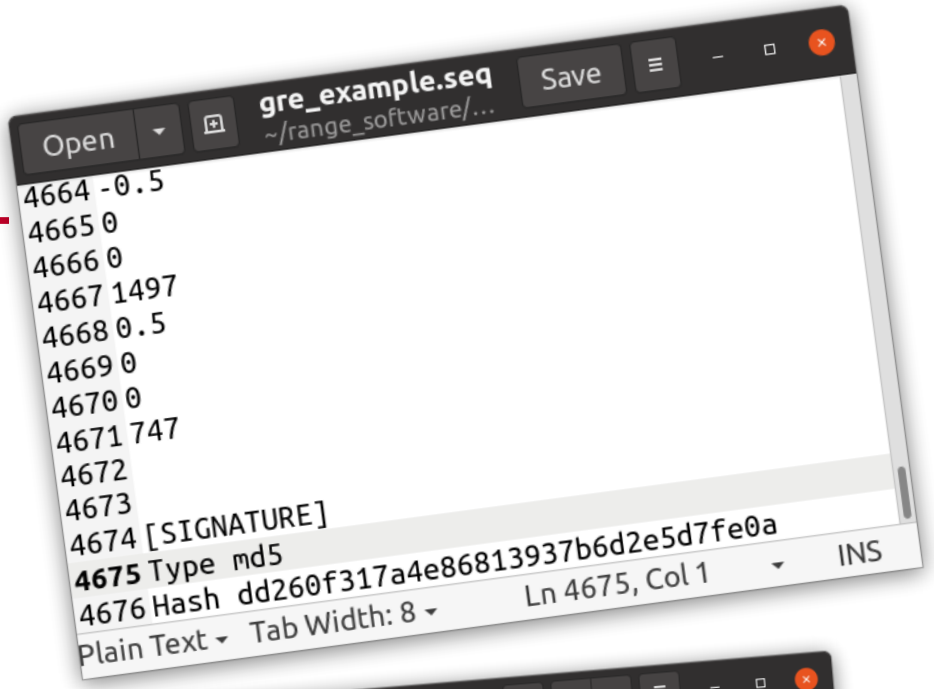
- ***PyPulseq*** is a close replica of the original Pulseq toolbox that does not require a MATLAB license
- Runs in many Python environments, e.g. as notebook in Jupyter (http://jupyter.org/) or Google Colaboratory
- Identical workflow:
  - Define the system properties
  - Define high-level parameters (convenience)
  - Define pulses and ADC objects used in the sequence
  - Calculate the delays and reordering tables
  - Loop and define sequence blocks
  - *Download '*.seq' to the scanner and run it!*

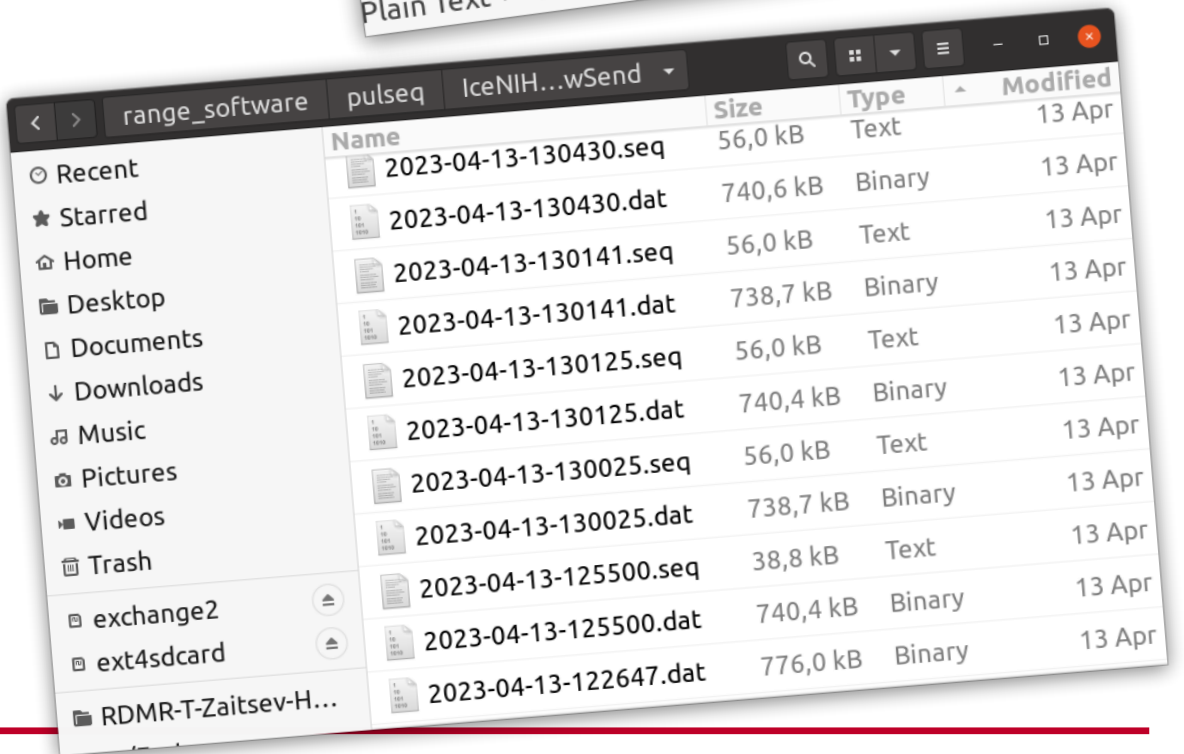


No local installation needed – ideal for education!

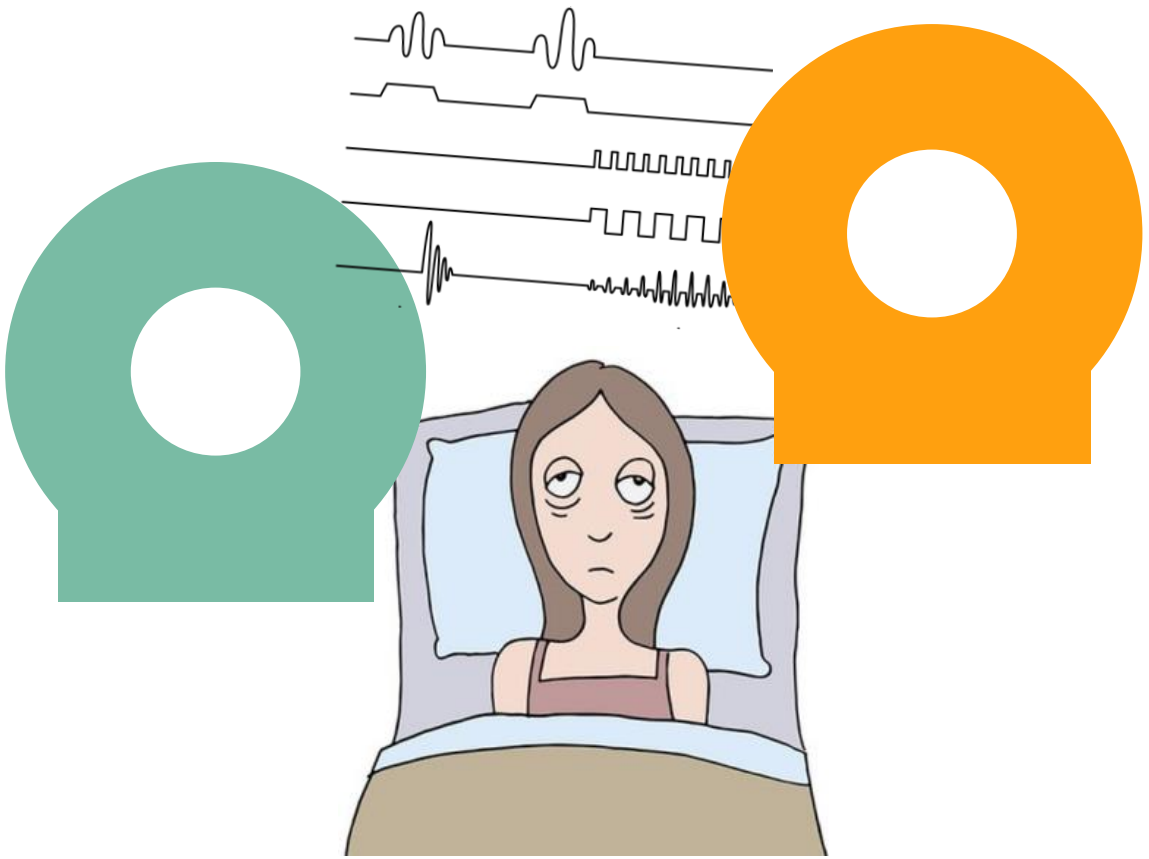
Reproducibility with *Pulseq*

- All Pulseq sequences are signed with a 128-bit hash
- Siemens RAW data contain the Pulseq hash
  - Verify where the data were acquired with the given sequence
- In practice: always archive sequences along with the data
  - Tutorial recon scripts use .seq files to extract k-space trajectories and reordering information

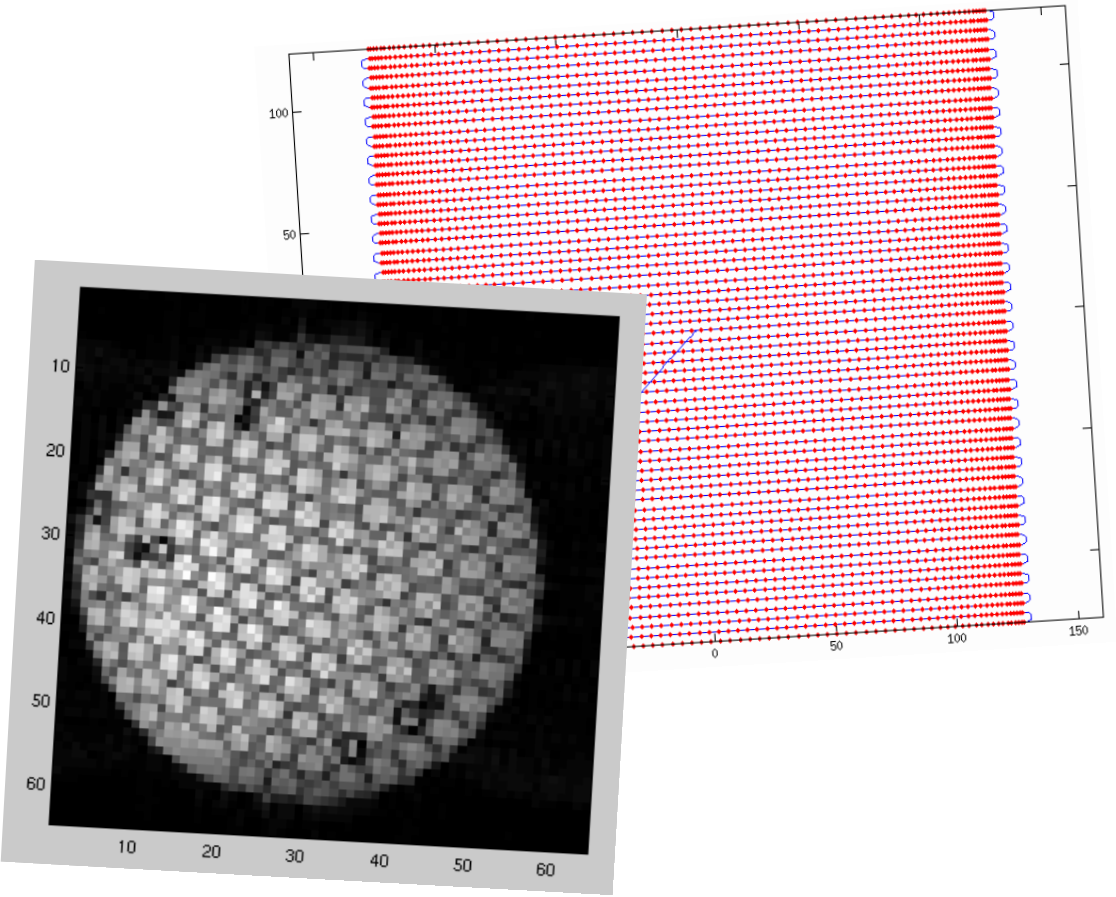




Prototyping from scratch in *Pulseq*



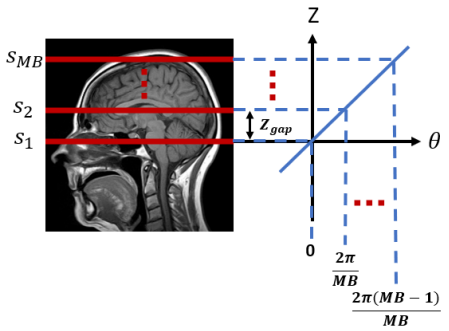
…dream of a sequence in the morning…

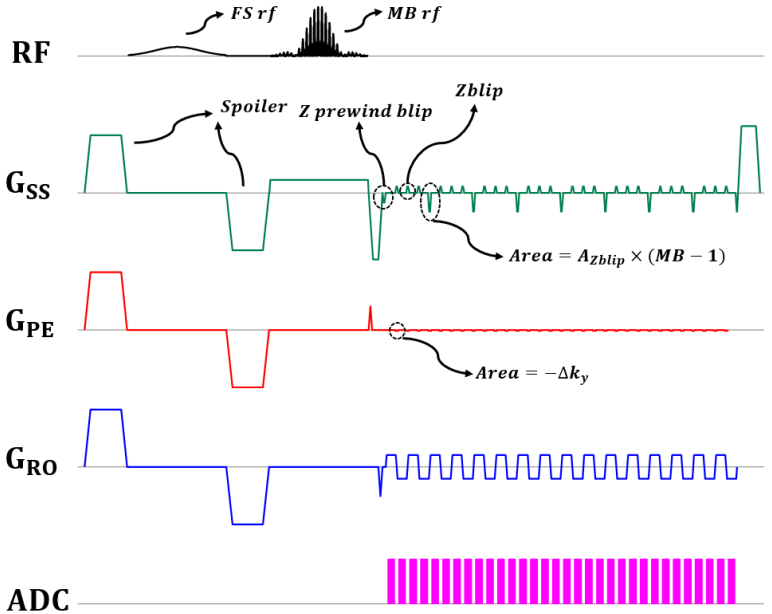


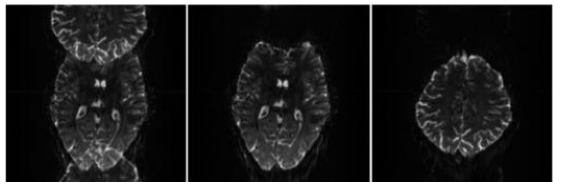
…check your data in the afternoon!

Educational SMS EPI with CAIPI

- Echo-planar imaging with simultaneous multi-slice excitation
- Complete calibration, acquisition and reconstruction scripts
- To be presented at the ESMRMB 2024 in Barcelona*



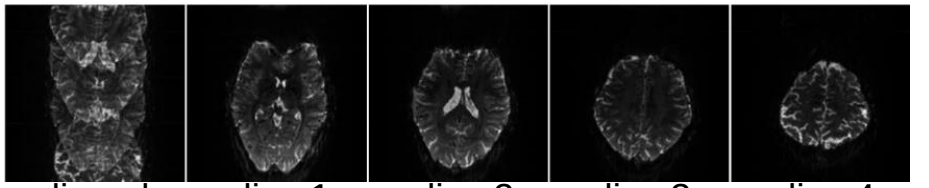




aliased image | slice 1 | slice 2

SMS-EPI
SMS=2

SMS-EPI, SMS=4



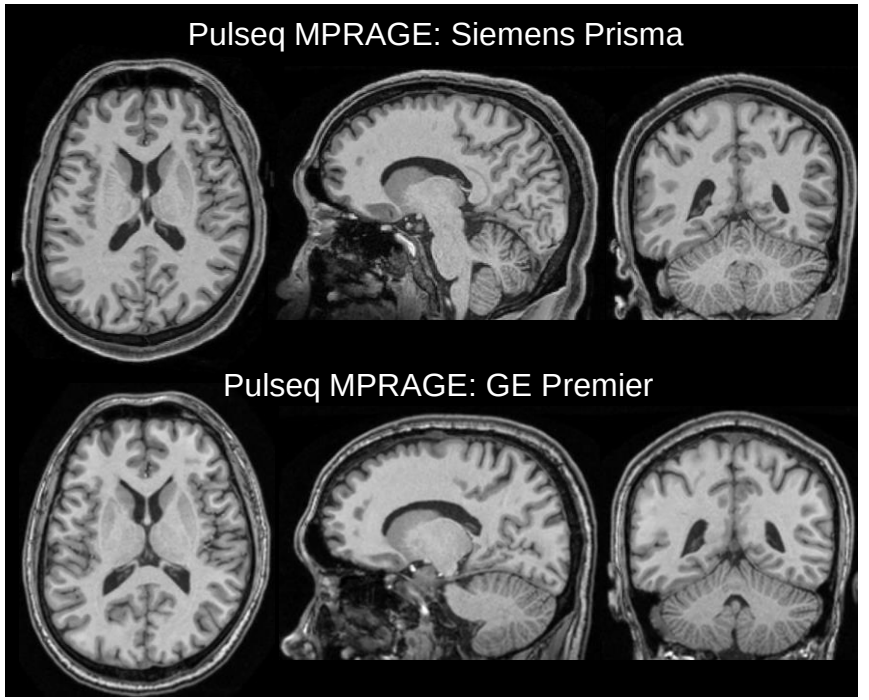
aliased image | slice 1 | slice 2 | slice 3 | slice 4

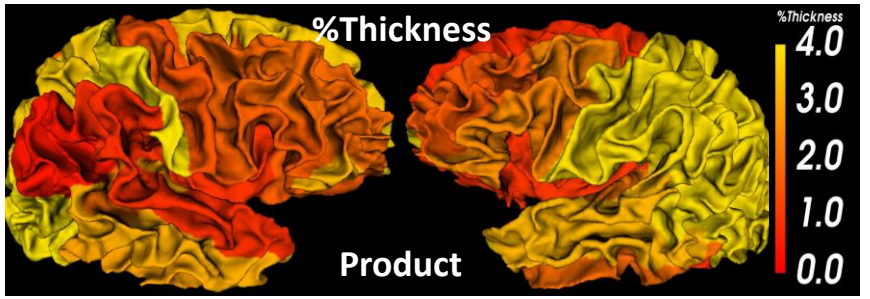
*Shafiekhani M et al, ESMRMB 2024 proceedings #118

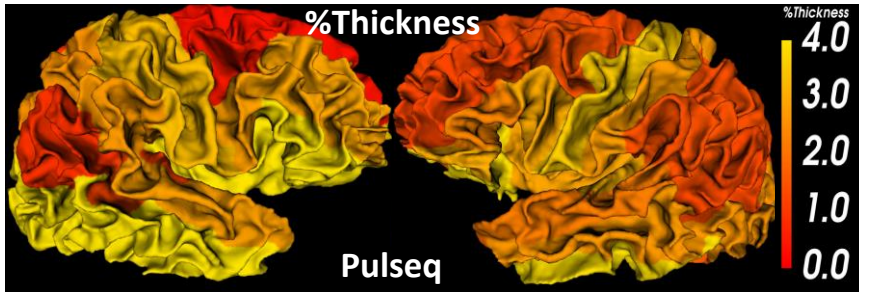
Pulseq is not a toy

- Growing user community
  - Over 150 labs worldwide
- Great not only for prototyping
  - Education
  - Multi-center MRI studies

- Identical 3D MPRAGE on Siemens & GE
  - Pulseq reduces cortical thickness variance
    Rathi Y, Nielsen JF, Zaitsev M, Ning L, Chiou JR, Kim T, Grissom W, Gagoski B, Bilgic B, ISMRM 2022, #1618

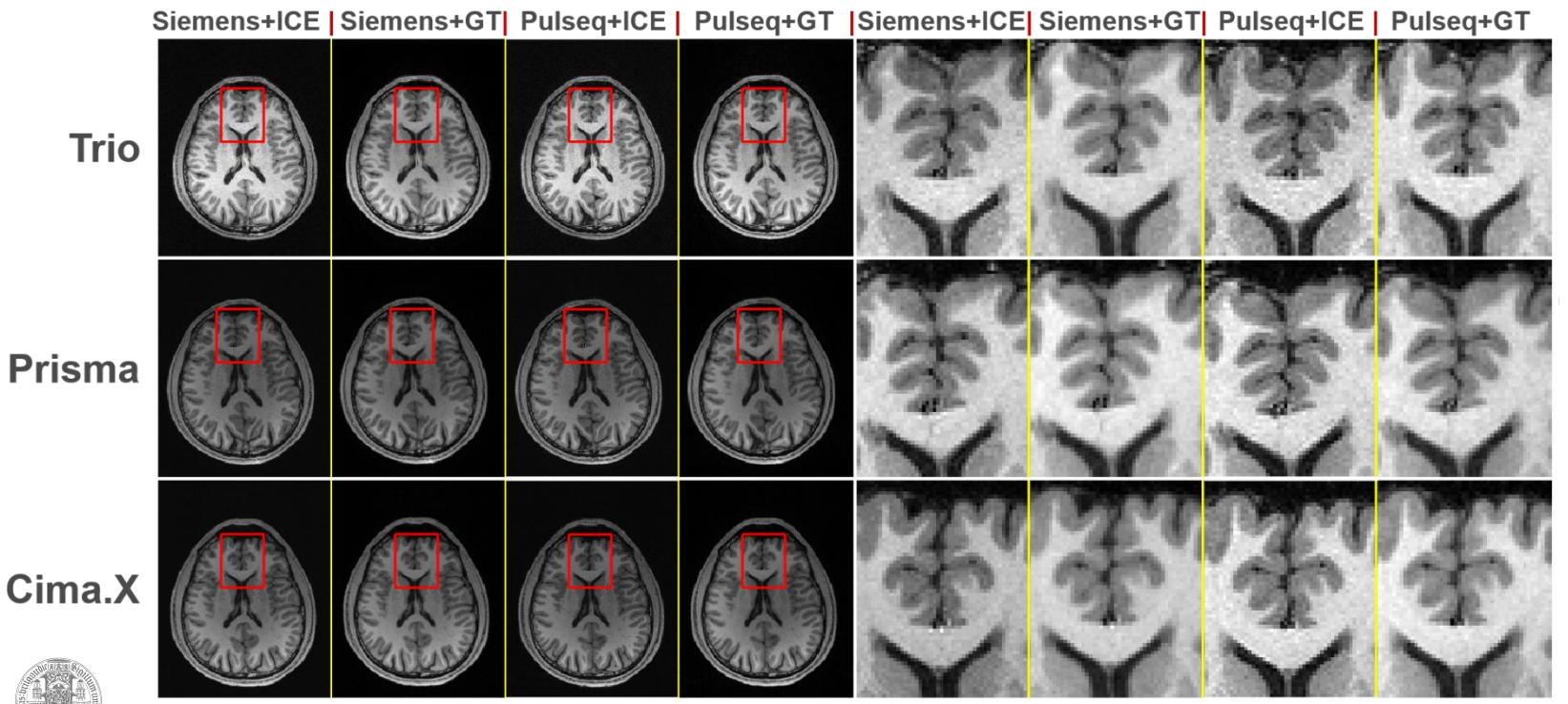


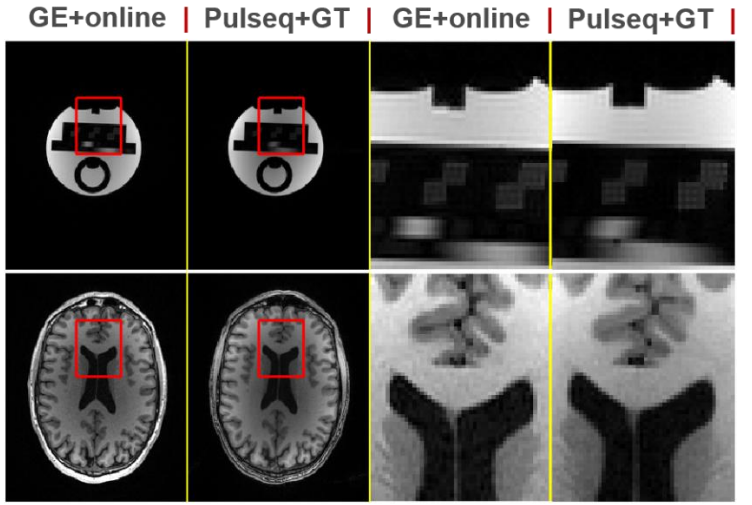




MPRAGE with GRAPPA

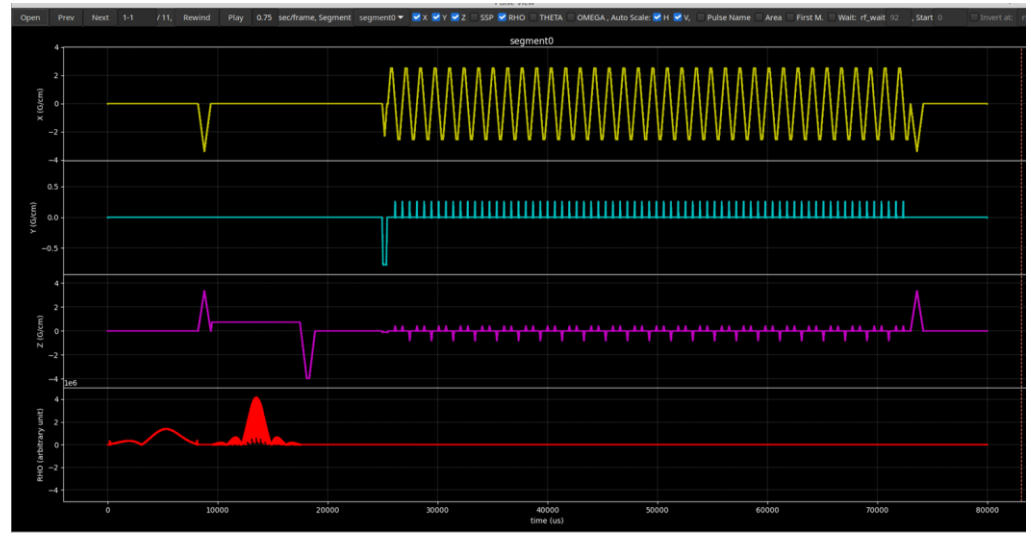
- ISMRM reproducibility challenge 
- 3 sites, 2 vendors, 4 scanner models
- Image recon: either integrated Siemens (ICE) or Gadgetron



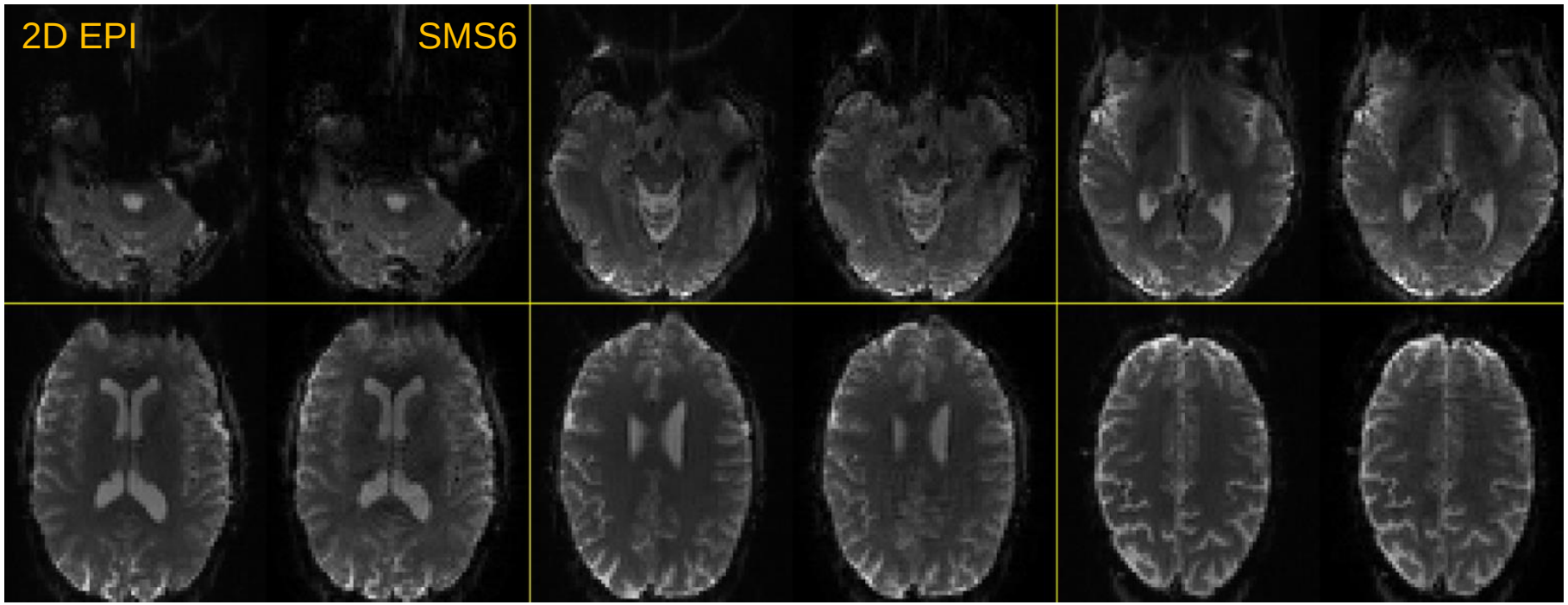


fMRI-ready SMS EPI

- Target multicenter fMRI studies
  - Implemented ABCD-like fMRI protocol (SMS factor 6; 2.4 mm iso)
  - Tested on Siemens and GE



Pulseq SMS-EPI sequence simulated in GE's Pulse Studio



Pulseq
2D-EPI vs. SMS-EPI
Left: non-SMS (2D) EPI
Right: EPI with SMS=6

Pulseq is fun!

- mrMusic library for creating gradient music
- Located in demoUnsorted
  (lib + 5 demo scripts)
- Really easy to create nice 3-voice tunes
- Many more options available (explore examples)
  - Sound quality settings (wave vs. sawtooth)
  - Temperaments, Staccato & Legato
  - **Tuning for avoiding mechanical resonances**
- **Enjoy responsibly!**

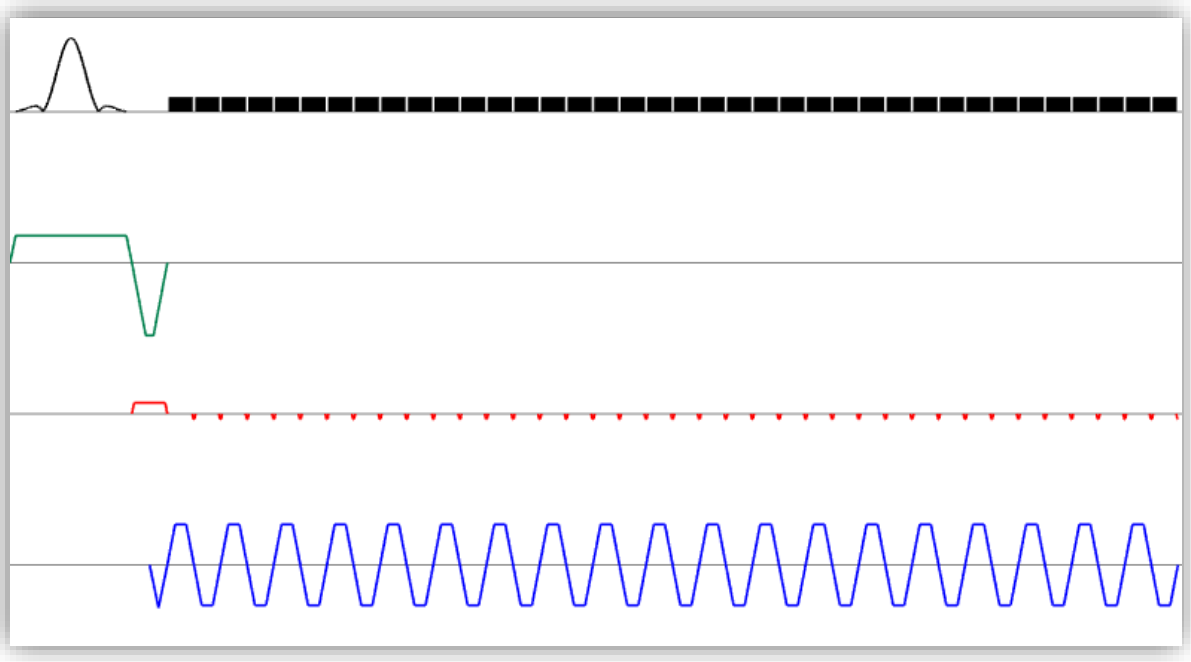
What's new in *Pulseq*

(Matlab Pulseq)

- Requested block duration in addBlock
- max RF amplitude as system property / RF amplitude warning
- (relative) SAR calculation
- Moments and b-factor calculation
- New display options: paperPlot() and plot('stacked')
- Plotting & debugging functions for labels & counters

(Siemens Interpreter)

- Install arbitrary number of sequences in different sub-directories



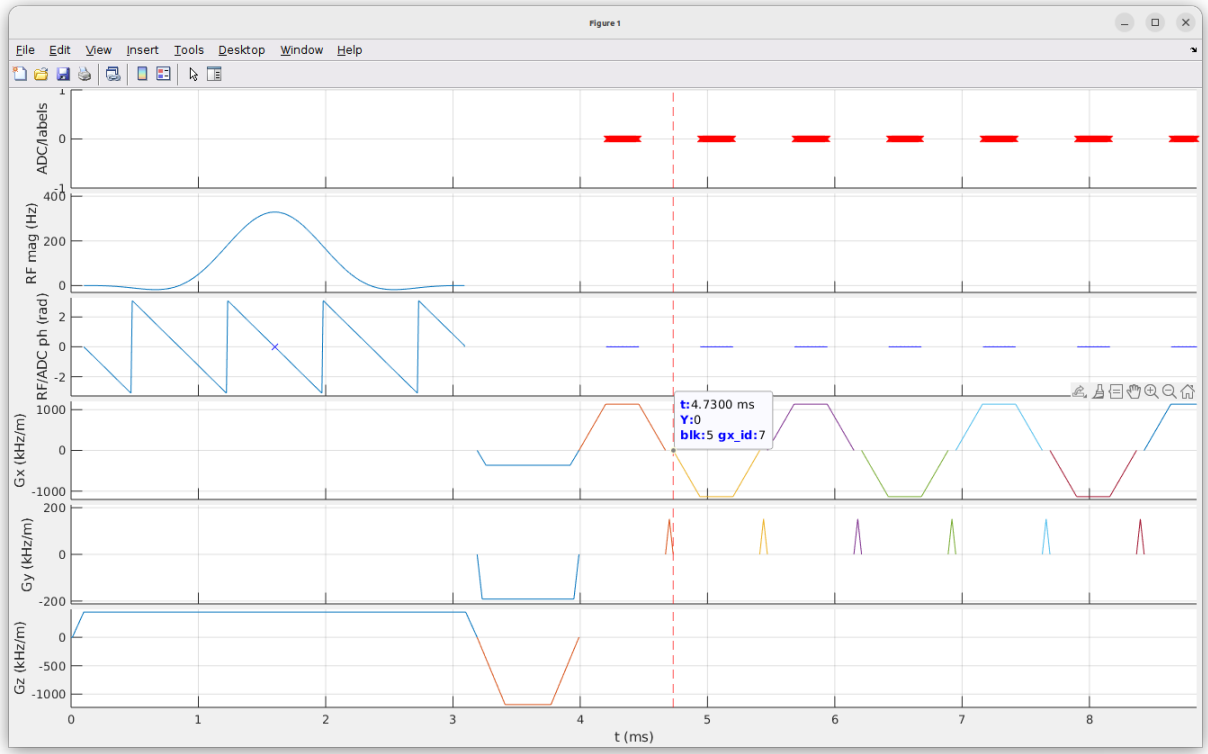


Figure 1
File Edit View Insert Tools Desktop Window Help
ADC/labels
RF mag (Hz)
RF/ADC ph (rad)
Gx (kHz/m)
Gy (kHz/m)
Gz (kHz/m)
t:4.7300 ms
Y:0
blk:5 gx_id:7
t (ms)

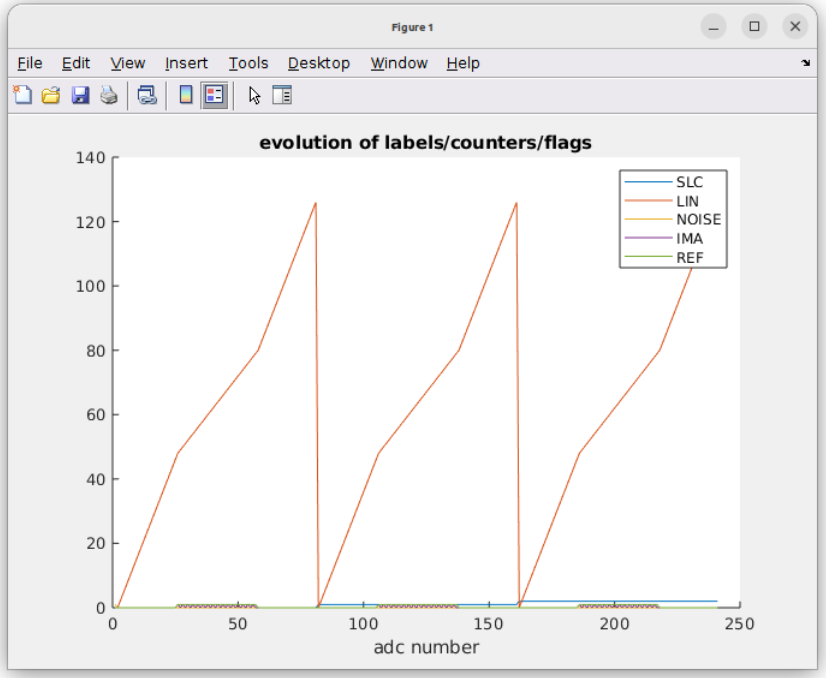
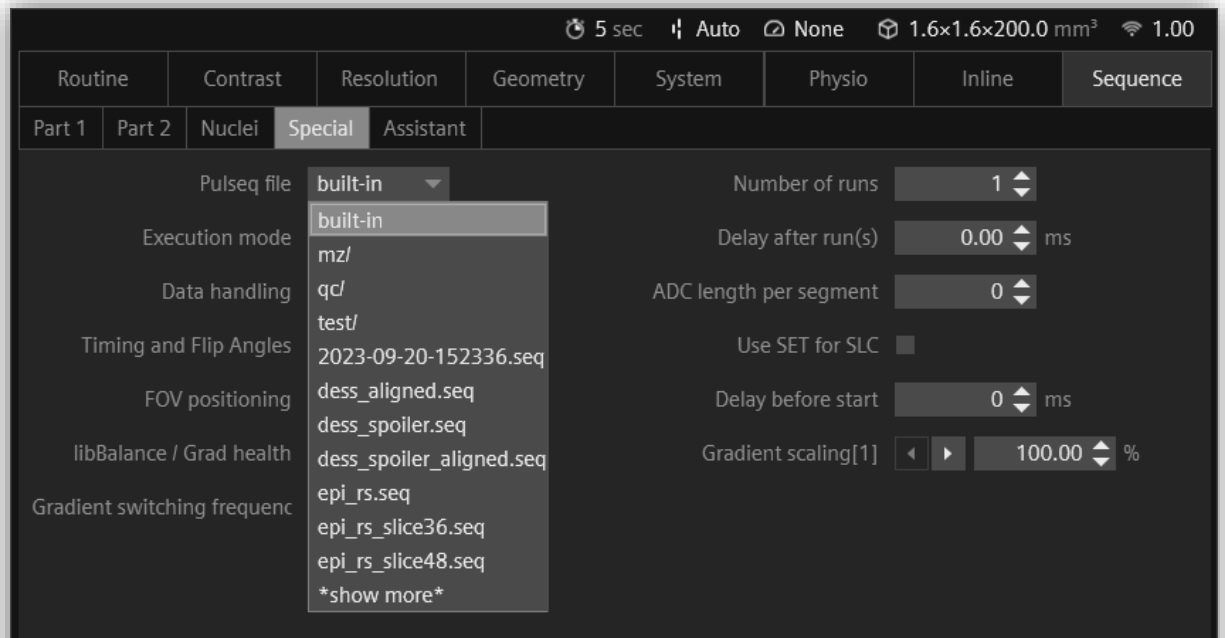


Figure 1
File Edit View Insert Tools Desktop Window Help
evolution of labels/counters/flags
SLC
LIN
NOISE
IMA
REF
adc number


5 sec
Auto
None
1.6×1.6×200.0 mm³
1.00
Routine
Contrast
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Geometry
System
Physio
Inline
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Part 1
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Nuclei
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Pulseq file
built-in
Execution mode
Data handling
Timing and Flip Angles
FOV positioning
libBalance / Grad health
Gradient switching frequenc
built-in
mz/
qc/
test/
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dess_aligned.seq
dess_spoiler.seq
dess_spoiler_aligned.seq
epi_rs.seq
epi_rs_slice36.seq
epi_rs_slice48.seq
show more
Number of runs
1
Delay after run(s)
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ms
ADC length per segment
0
Use SET for SLC
Delay before start
0
ms
Gradient scaling[1]
100.00
%

Pulseq on Siemens platforms

- Over 150 C2P sites
- *Pulseq* works well on:
  - All Numaris4 platforms (tested on vb15…ve12u) and numerous hardware platforms (Symphony, Trio, 7T, 3T Connectom, Skyra, Prisma,Cima.X…)
  - All released NumarisX versions (xa11, xa20, xa30, xa40, xa5x, xa6x …)



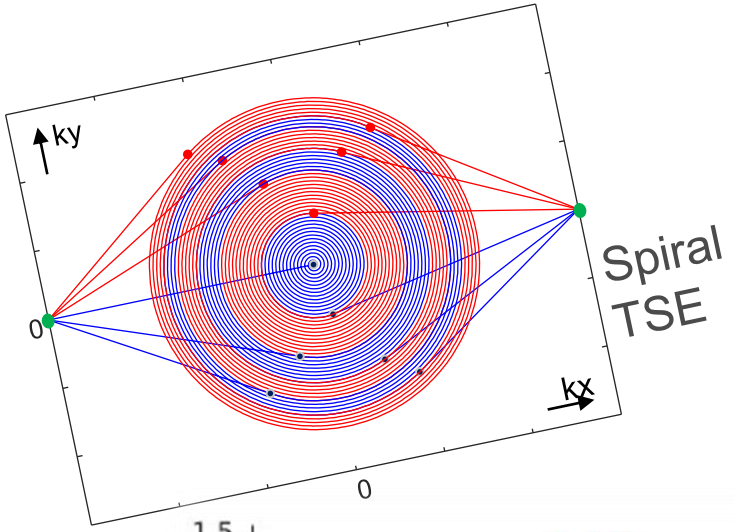


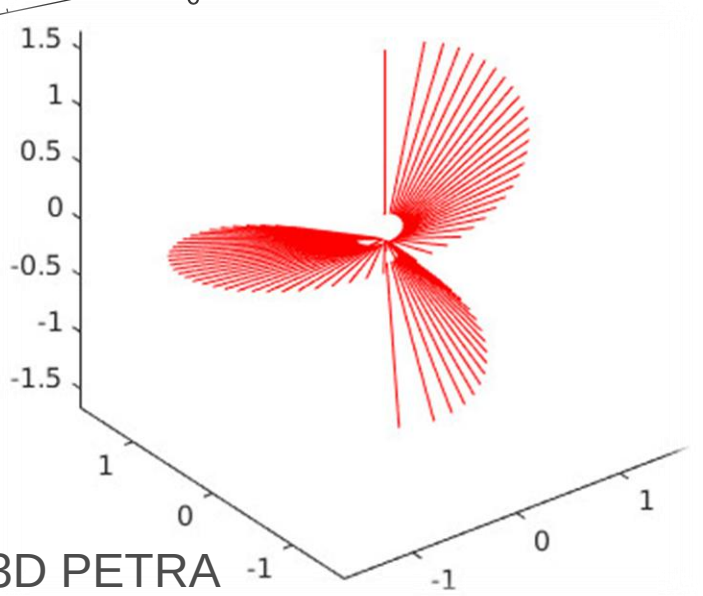
Pulseq on Other Platforms

- Works very well on GE (Thanks to Jon-Fredrik Nielsen)
- MaRCoS / Red Pitaya / Portable System → → → → →
- Reportedly works on United Imaging
- Two Philips interpreters @ISMRM2024

Cross-platform sequences with *Pulseq*

- MR physics-oriented workflow
  - Write your sequences from scratch
  - Non-Cartesian readouts, user-defined gradient shapes and custom RF pulses
  - Advanced visualization and analysis tools
  - Automatic k-space calculation
- Play out on many scanners
  - Siemens, GE, UI, Marcos…
  - Philips : ready to start
  - *Bruker : we are talking to them…*
- **Focus on sharing and open science**





Berkin Bilgic
Borjan Gagoski
Douglas Noll
Feng Jia
Imam Shaik
Jeff Fessler
Jon-Fredrik Nielsen
Juergen Hennig
Lukas Winter
Marten Veldmann
Moritz Zaiss
Naveen Murthy
Niklas Wehkamp
Philipp Amrein
Qiang Liu
Qingping Chen
Scott Peltier
Sebastian Littin
Tony Stoecker
Will Grissom
Yogesh Rathi

THANK YOU FOR YOUR ATTENTION!

Pulseq MATLAB

pypulseq Python

harmonized MRI

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METROLOGY PARTNERSHIP
EURAMET
EURAMET 22HLT02 A4IM