

Pulseq Principles

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What is *Pulseq*?

- *Pulseq* is a language to describe MR pulse sequences
- *Pulseq* sequences are fixed successions of RF and gradient pulses and ADC events



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

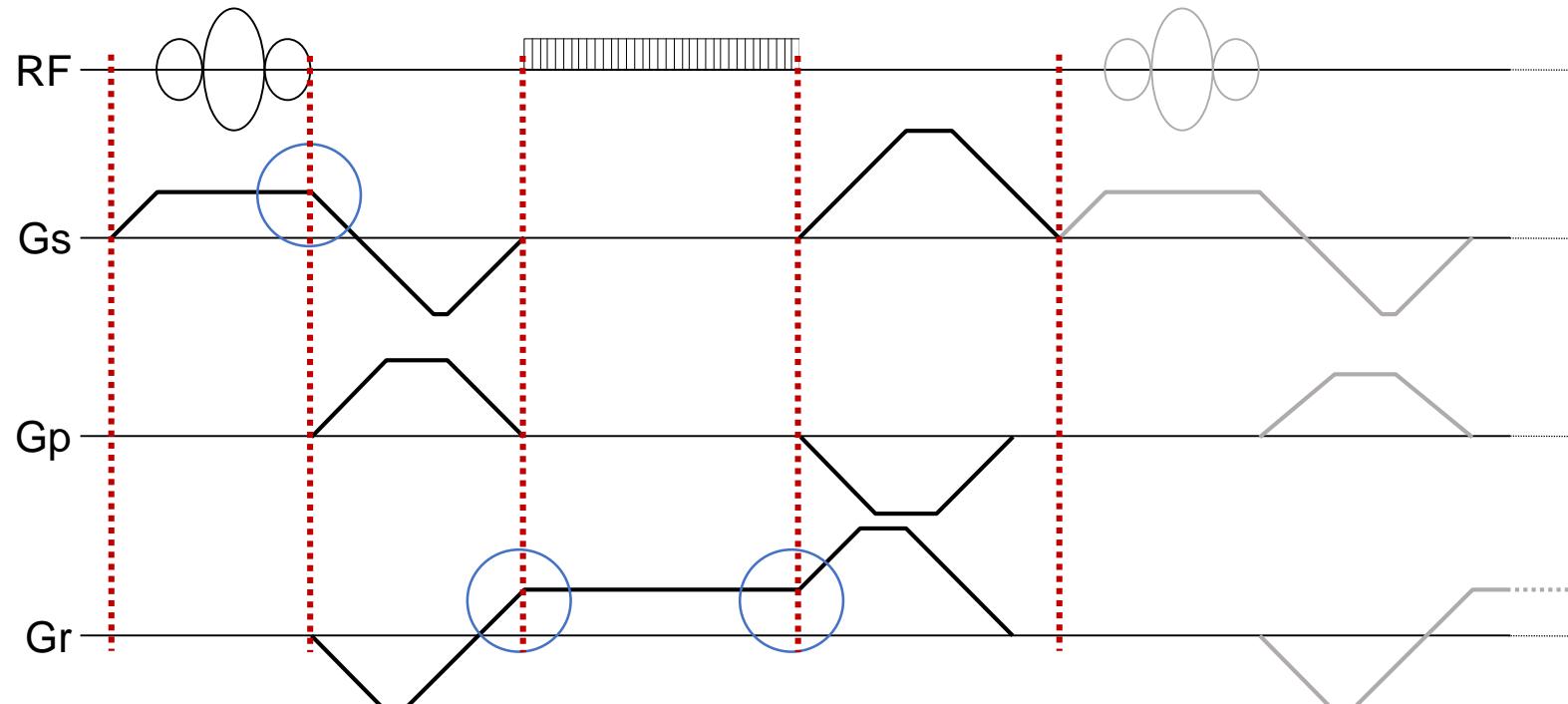
Pulseq Philosophy

- 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

Pulse sequence definition in *Pulseq*



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

- Sequence is a concatenation of non-overlapping blocks
- Gradients do not have to start or end at 0 at the block boundaries

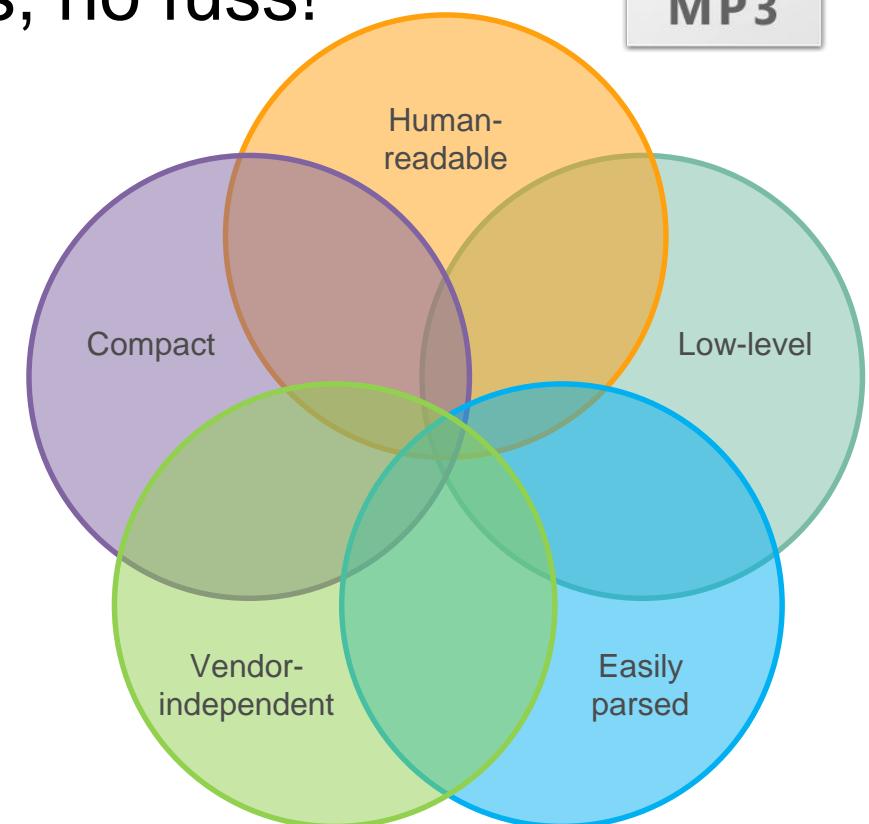
Pulseq block concept in detail

- 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 – like a recorded piece of music!



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 Extensions

- File format readily supports very flexible Extension objects
- Current extensions
 - Cardiac triggering
 - Digital-out (trigger) output
 - Data labeling
- Labels to control sequence execution
 - ONCE labels
 - NOPOS, NOROT, NOSCALE labels
- Labels may provide hints for the interpreter
 - New GE interpreter detects the “TR Loop” based on the TRID label



High-level programming environments

- Matlab *Pulseq* toolbox
- Python *PyPulseq* toolbox



- Further options
 - TOPPE is primarily targeted at GE but can import and export *Pulseq* files
 - GammaStar can export *pulseq* files
 - JEMRIS Bloch simulator can export *pulseq* files
 - CoreMRI Bloch simulator can export *pulseq* files
 - ...

Matlab *Pulseq* workflow

```
system = mr.opts('MaxGrad',30,'GradUnit','mT/m',...
    'MaxSlew',170,'SlewUnit','T/m/s');
seq=mr.Sequence(system);

fov = 220e-3; Nx=64; Ny=64; TE = 10e-3; TR = 20e-3;

[rf, gz] = mr.makeSincPulse(15*pi/180,system,'Duration',4e-3,...
    'SliceThickness',5e-3,'apodization',0.5,'timeBwProduct',4);

gx = mr.makeTrapezoid('x',system,'FlatArea',Nx/fov,'FlatTime',6.4e-3);
adc = mr.makeAdc(Nx,'Duration',gx.flatTime,'Delay',gx.riseTime);
gxPre = mr.makeTrapezoid('x',system,'Area',-gx.area/2,'Duration',2e-3);
gzReph = mr.makeTrapezoid('z',system,'Area',-gz.area/2,'Duration',2e-3);
phaseAreas = ((0:Ny-1)-Ny/2)*1/fov;

delayTE = TE - mr.calcDuration(gxPre) - mr.calcDuration(rf)/2 ...
    - mr.calcDuration(gx)/2;
delayTR = TR - mr.calcDuration(gxPre) - mr.calcDuration(rf) ...
    - mr.calcDuration(gx) - delayTE;
delay1 = mr.makeDelay(delayTE);
delay2 = mr.makeDelay(delayTR);

for i=1:Ny
    seq.addBlock(rf,gz);
    gyPre = mr.makeTrapezoid('y',system,'Area',phaseAreas(i),...
        'Duration',2e-3);
    seq.addBlock(gxPre,gyPre,gzReph);
    seq.addBlock(delay1);
    seq.addBlock(gx,adc);
    seq.addBlock(delay2)
end

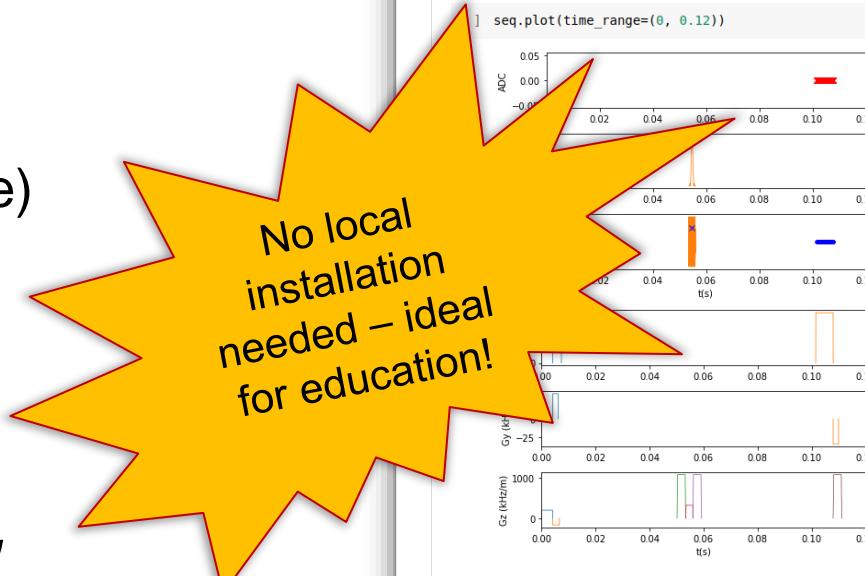
seq.write('*seq')
```

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

- 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
 - Duration of each block is defined by the duration of the longest event
 - *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!*



A screenshot of a Jupyter Notebook titled 'pypulseq_test.ipynb' running in Google Colaboratory. The code defines a sequence object, initializes it, and adds various RF and gradient blocks. It then plots the sequence timing and checks the timing. The plots show the sequence of pulses and gradients over time.

```
# (re)initialize the sequence object
seq = Sequence(system)
# Prepare RF offsets. This is required for multi-slice acquisition
delta_z = n_slices * slice_gap
z = np.linspace(-delta_z / 2), (delta_z / 2), n_slices) + rf_offset

for k in range(ns): # Averages
    for j in range(n_slices): # Slices
        # Apply RF offsets
        freq_offset = g290.amplitude * z[j]
        r290.freq_offset = freq_offset

        freq_offset = g180.amplitude * z[j]
        r180.freq_offset = freq_offset

        for i in range(Ny): # Phase encodes
            seq.add_block(rf90, g290)
            gy_pre = make_trapezoid(channel='y', system=system,
                                    area=phase_areas[-i - 1], duration=2e-3)
            seq.add_block(gx_pre, gy_pre, gz_reph)
            seq.add_block(delay1)
            seq.add_block(gz_spoil)
            seq.add_block(rf180, g180)
            seq.add_block(gz_spoil)
            seq.add_block(delay2)
            seq.add_block(gx, adc)
            gy_pre = make_trapezoid(channel='y', system=system,
                                    area=phase_areas[-j - 1], duration=2e-3)
            seq.add_block(gy_pre, gz_spoil)
            seq.add_block(delay_TR)

seq.plot(time_range=(0, 0.12))
seq.check_timing()
```



How to design a sequence in Pulseq

conceptual design steps

- Step 1: split 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, check hardware and PNS limits, mechanical resonances, etc...

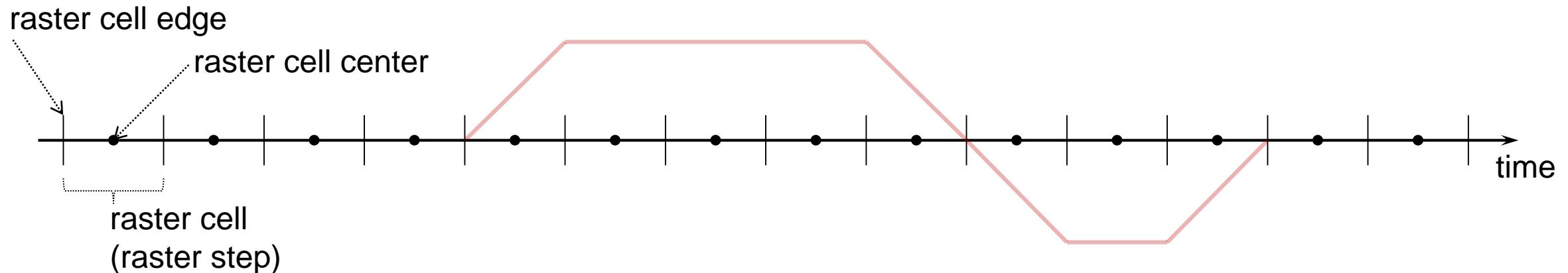


Pulseq objects & blocks

- *Pulseq* objects are created and then added to *Pulseq* blocks
 - Gradient & RF pulses
 - mr.makeTrapezoid(...) or pp.make_trapezoid(...)
 - mr.makeSincPulse(...) or pp.make_sinc_pulse(...)
 - ADC objects
 - mr.makeADC(...) or pp.make_adc(...)
 - Delays, extension objects, etc.
(data labels, cardiac trigger directives, trigger pulses)
 - Use seq.addBlock(...) or seq.add_block(...) to add objects & blocks
- Block concept in *Pulseq* is probably the most demanding part
 - Blocks and objects need to be aligned to raster times



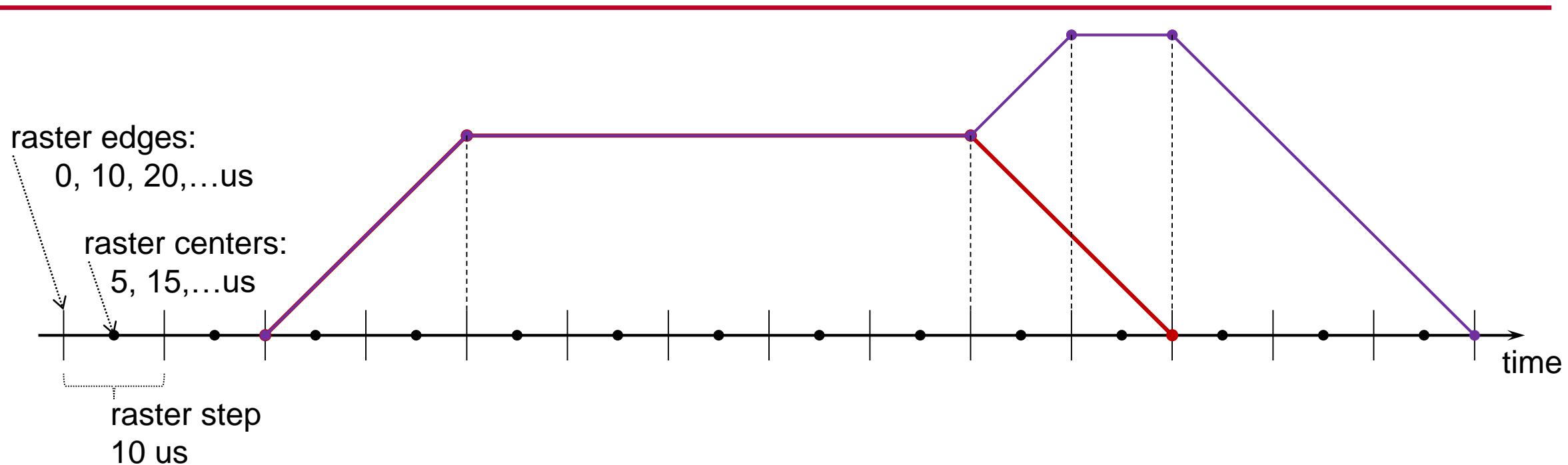
Shapes and Raster Times *Pulseq*



- Precise control of arbitrary gradient and RF waveforms
- Pulseq defines four types of raster times
 - adcRasterTime, rfRasterTime, gradRasterTime, blockDurationRaster
- Raster ‘thinking’ is probably one of the most demanding concepts in the practical pulse sequence programming
- Raster cells, edges and centers

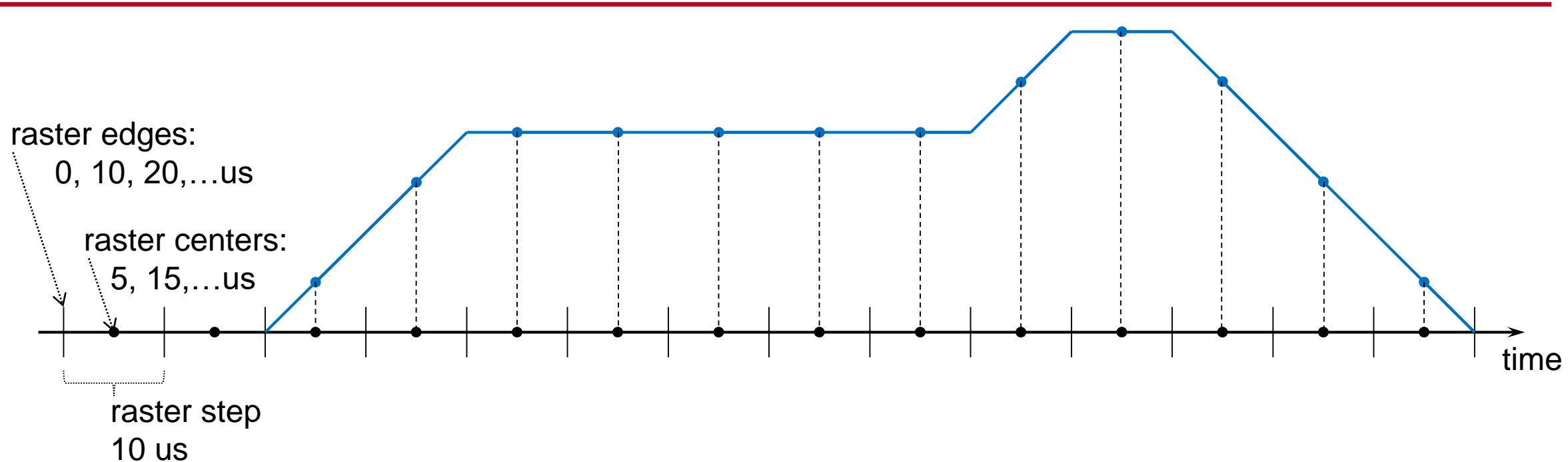


Gradient Raster and Shapes



- Gradient raster (10 us on Siemens)
- Trapezoid and extended trapezoids: vertices on raster edges

Gradient Raster and Shapes

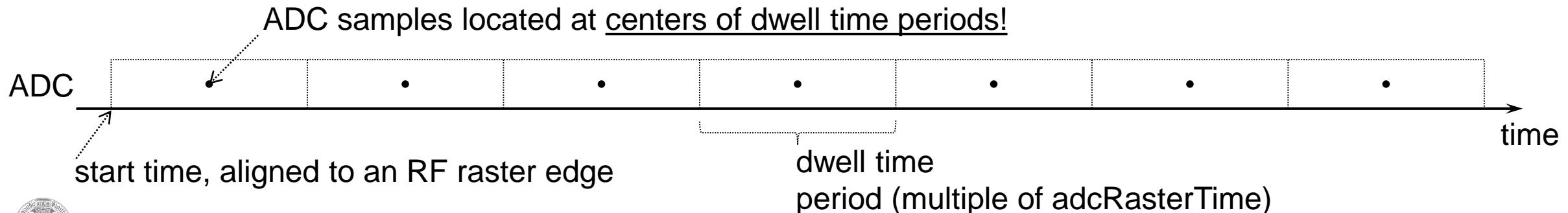


- Gradient raster (10 us on Siemens)
- Trapezoid and extended trapezoids: nodes on raster edges
- Sampled (arbitrary) gradients: samples on raster centers



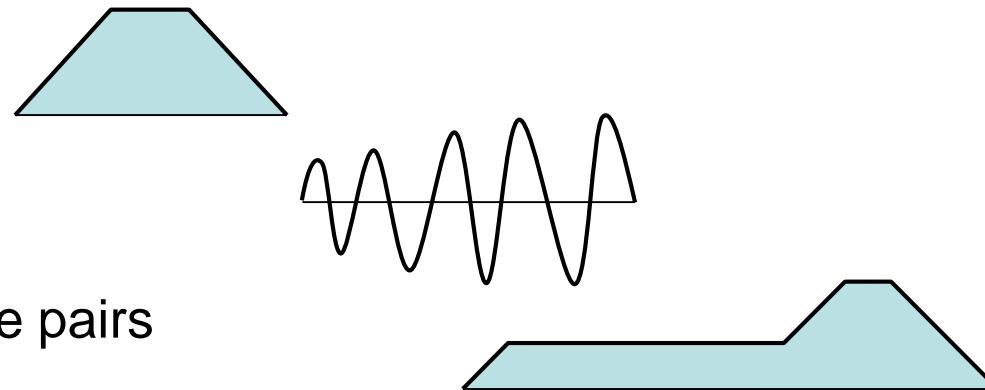
RF and ADC Raster Times

- RF objects can be either regularly sampled or defined by vertices
 - `mr.makeSincPulse()` defines a regularly sampled pulse
 - `mr.makeBlockPulse()` uses a shape with two points: $(0,1)$ and $(\text{dur},1)$
- `rfRasterTime` on Siemens: 1us
 - Dwell time for regularly-sampled pulses: multiple of `rfRasterTime`
- ADC start time must be aligned to `rfRasterTime`
 - ADC dwell time: multiple of `adcRasterTime` (100ns on Siemens)



Advanced topics

- Pulseq native unit for gradient and RF amplitude is Hz
- Three types of gradient events in Pulseq
 - Trapezoid pulses
ramp-up, flat top, ramp-down
 - Free shape defined on a regular raster (typically 10 us)
 - Extended Trapezoid: time-amplitude pairs
with linear ramps in between
- RF and ADC events cannot touch block boundaries (system-specific limits)
- RF pulses may define custom dwell time (default 1 us) to overcome duration limit due to the 8192 points shape limit on Siemens
- Semi-automatic ADC splitting to segments
(overcome 8192 points receive limit)



Post-export Changes to Sequences

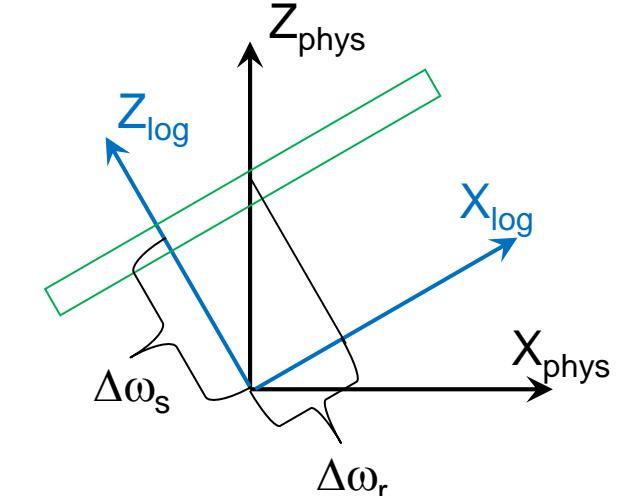
- A *Pulseq* sequence is completely defined in .seq file and is fixed
- Timing is always fixed with one exception:
 - Prospective (cardiac) triggering: actual repetition depends on the heartbeat

- Repetitions (with an optional delay)
 - Allows for additional variations due to the ONCE label
 - Gradient scaling
 - Pre-scales logical gradient prior to the execution
 - Includes gradient inversion and zeroing
 - Swapping nucleus
 - Sets base frequency and rescales gradients
 - FOV rotation & FOV positioning
 - See the next slide
- Interpreter-Specific Features**



FOV positioning physics

- Rotation matrix applied around the iso-centre
 - For safe operation, sequences must obey
 $\max(\text{abs}(\mathbf{G})) < \text{sys.G}_{\text{max}}$
- In traditional pulse sequence programming:
calculate $\Delta\omega_s$, $\Delta\omega_r$ & PE phase increment
- Pulseq relies on the method of Magland & Wehrli
(DOI:10.1002/mrm.20933)
- Continuously applies phase offsets to all RF and ADC objects
 - Integral form (publication): $\theta(t) = \int_0^t \mathbf{G}(\tau) \cdot \Delta\mathbf{r} d\tau$
 - Differential form (Siemens interpreter): $\Delta\omega(t) = \mathbf{G}(t) \cdot \Delta\mathbf{r}$



Possible Future Format Extensions

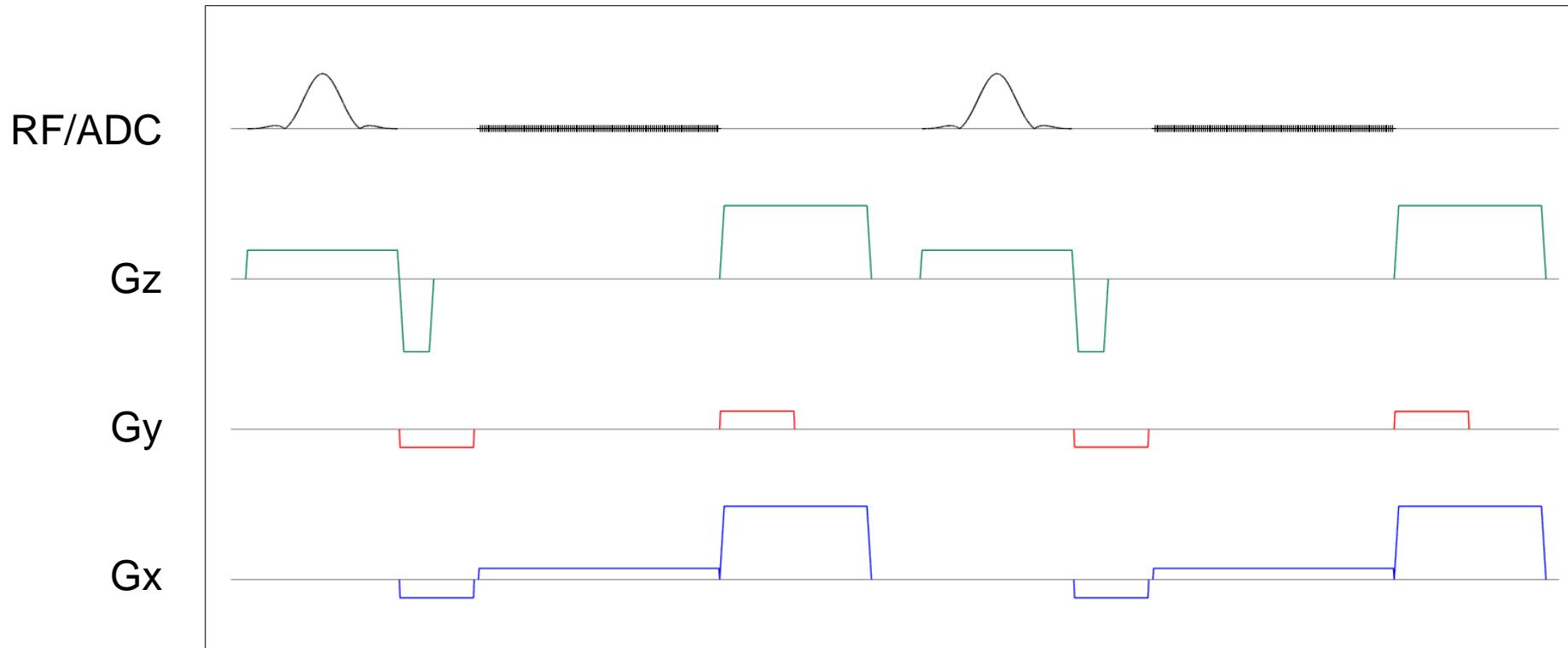
- “Sub-volume” objects
 - Parts of the sequence with independent slice position and orientation
- Or better “sub-sequence” objects
 - E.g. slice position or orientation...
 - Which other properties should be changeable? Nucleus?
- Higher-level control structure (meta-block tables)?
- Streaming Pulseq version
 - No complete generation of the sequence necessary
 - Interesting challenges for “garbage collection”, etc...
- *Open to further ideas*



Sequence examples



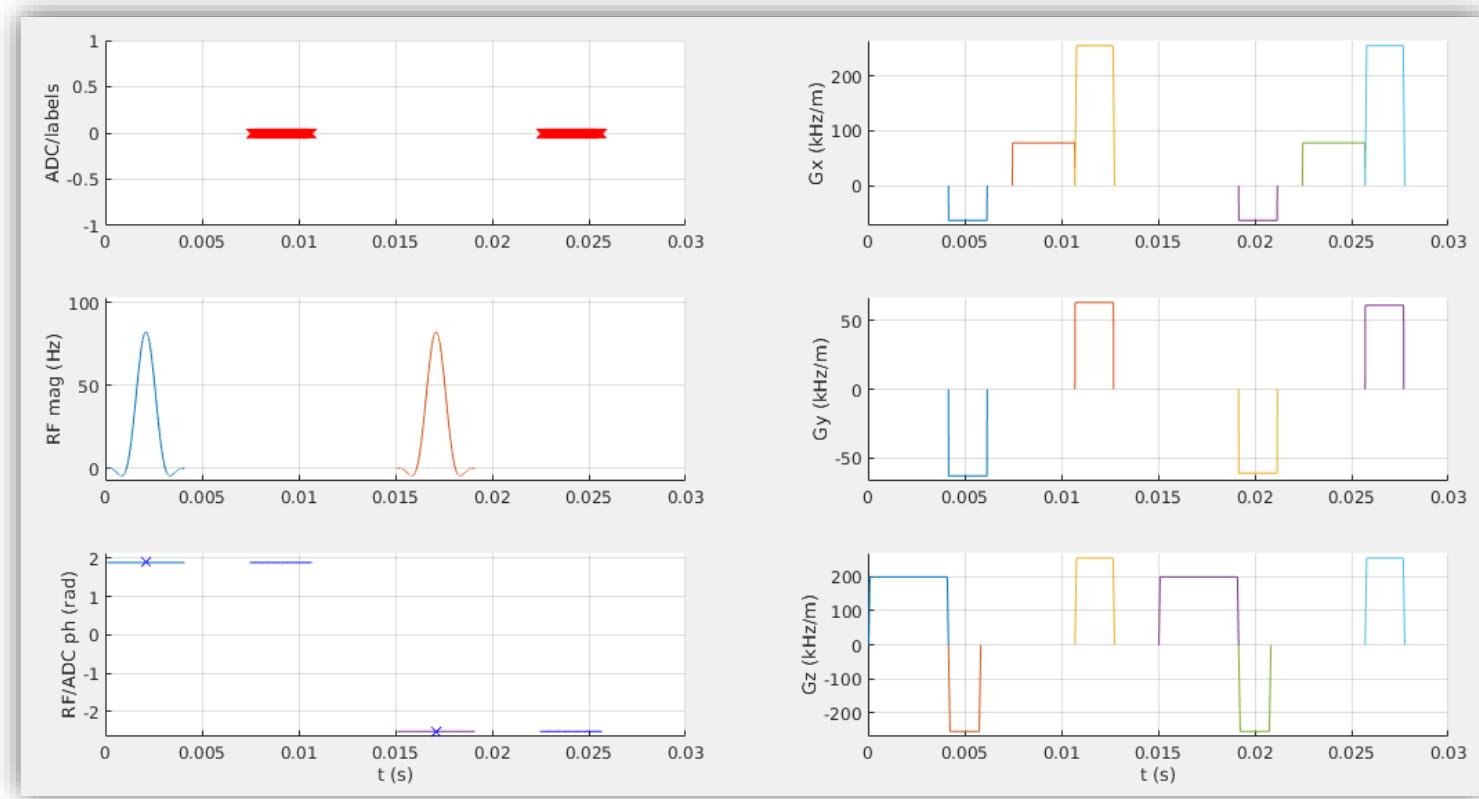
Example 1: simple gradient echo



- No overlapping gradient ramps on different axes
- Events are clearly separated



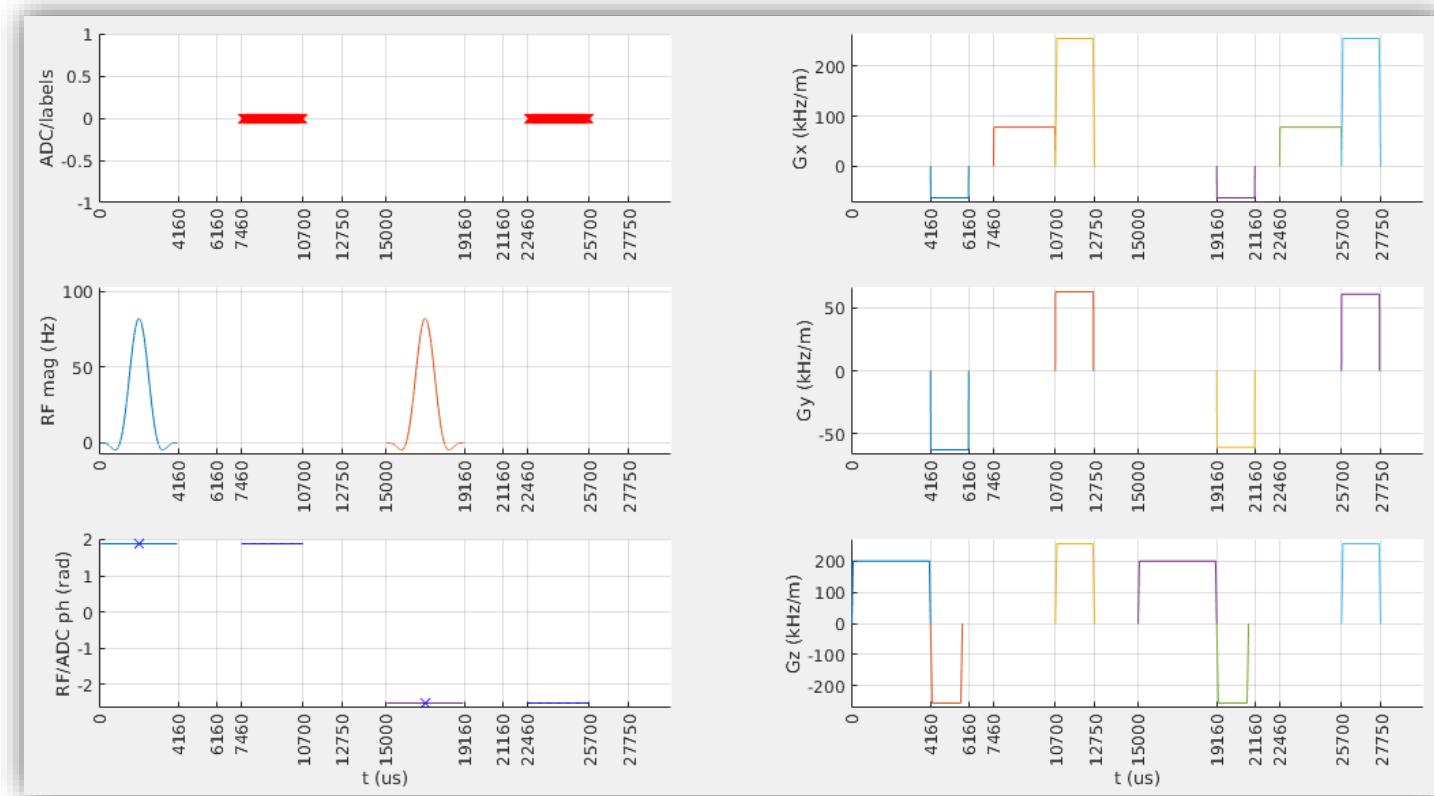
Example 1: basic sequence display options



- Pulseq 6-panel plot: seq.plot()
 - ADC, RF magnitude, RF phase, G_x, G_y, G_z
 - Each event plotted in its own color

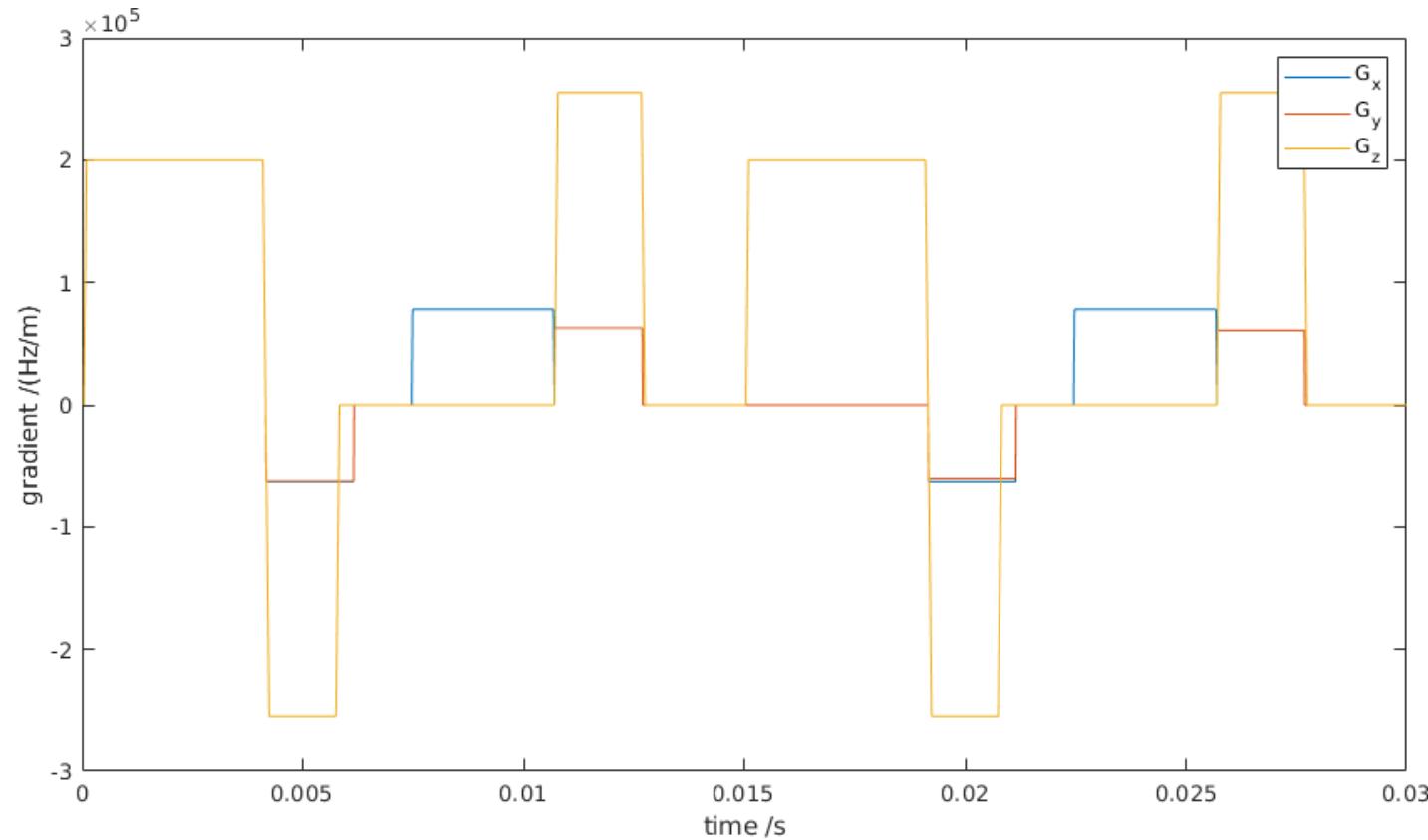


Example 1: display block structure



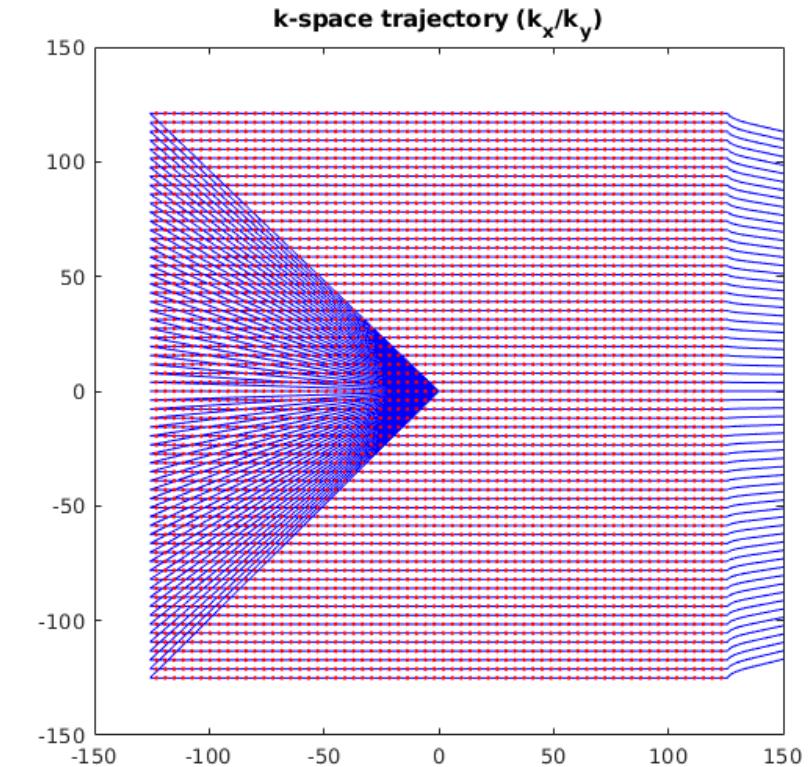
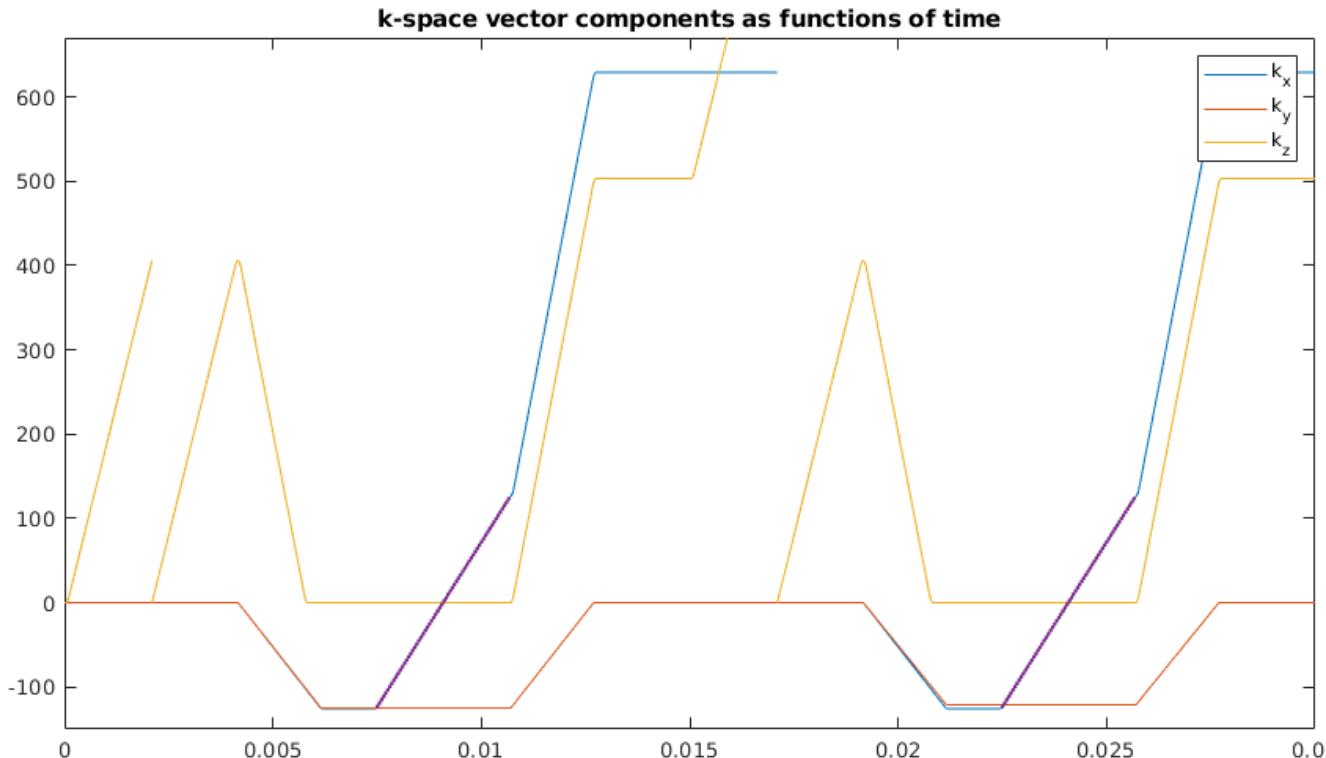
- Advantageous to separate PE & PR gradients into different blocks
- To visualize block structure:
 - `seq.plot('showBlocks',true,'timeDisp','us');`

Plot gradient waveforms



- Plot entire waveforms for all axes
 - Native gradient unit in *Pulseq*: Hz/m

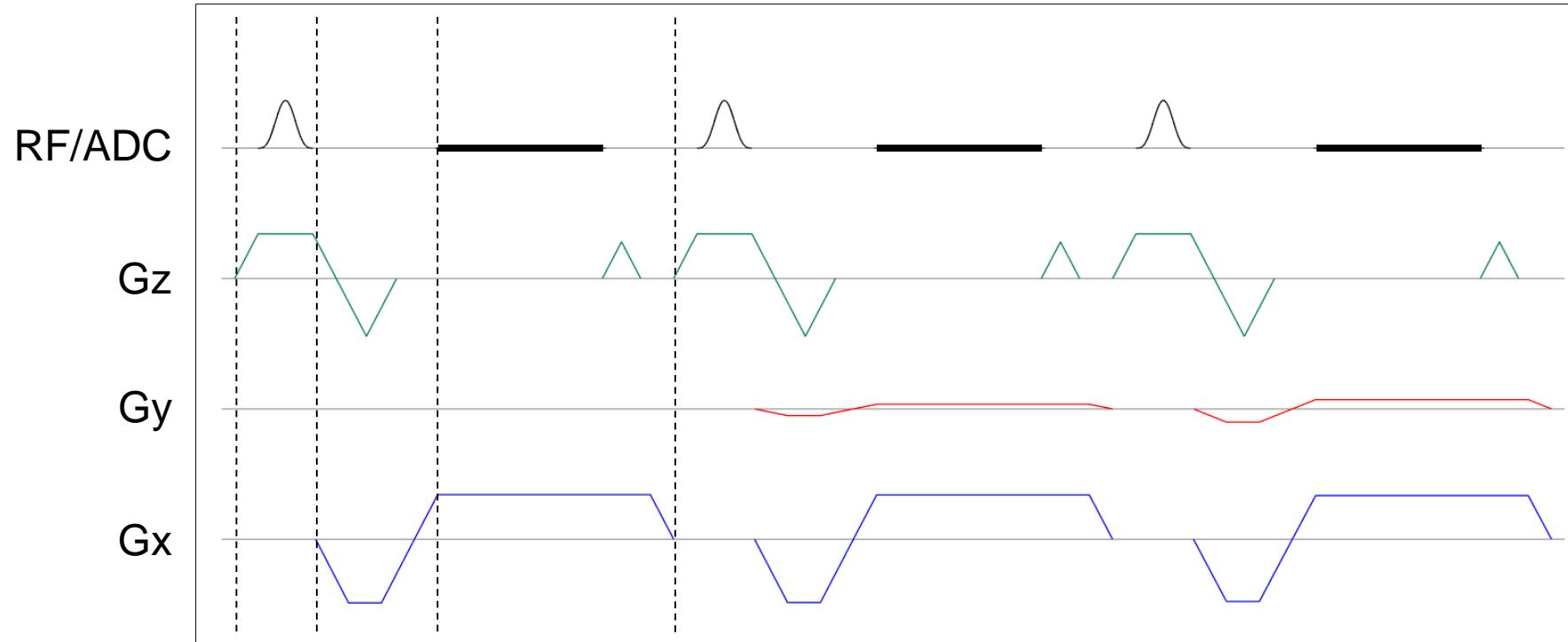
Basic sequence display options: k-space



- Plot k-space time evolution or 2D (or even 3D) trajectories
 - Native k-space unit in *Pulseq*: m^{-1}



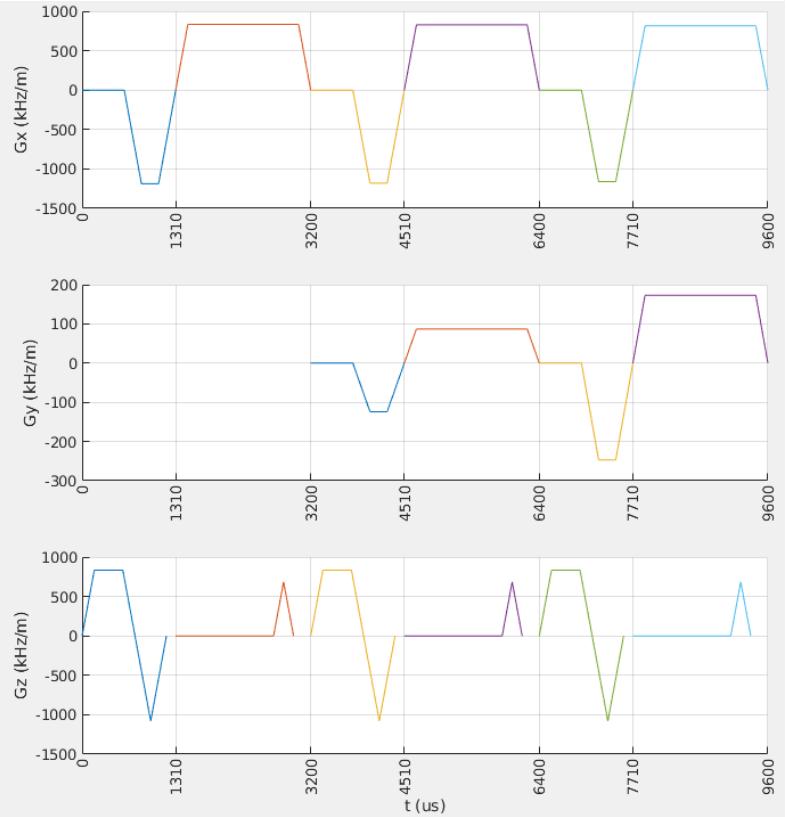
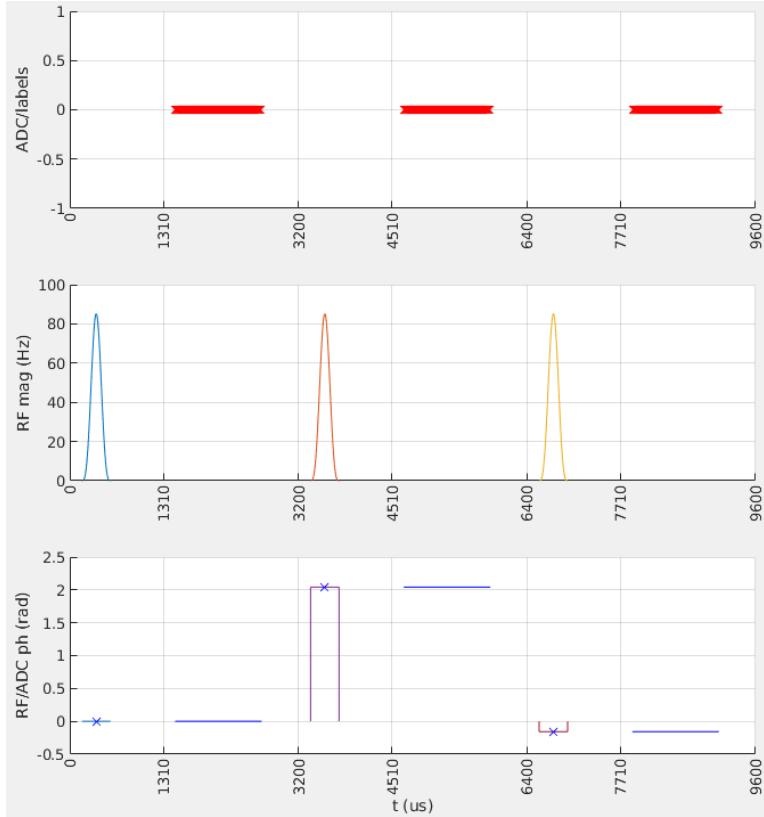
Example 2: fast radial gradient echo



- Block separation is less obvious
 - Merging all into one block is possible, but this would make Z spoiler a part of a shaped gradient....

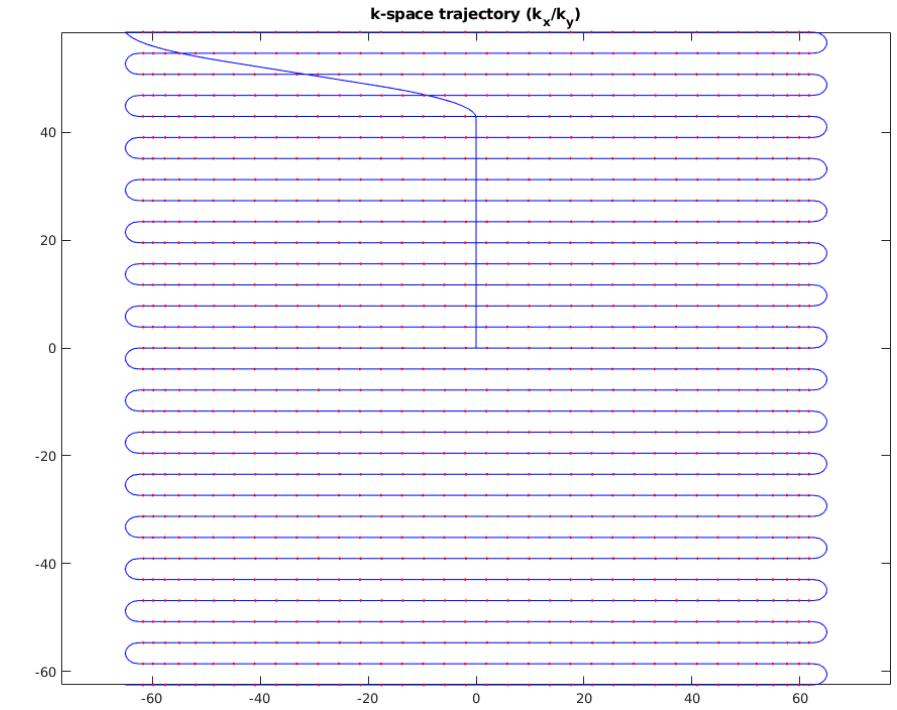
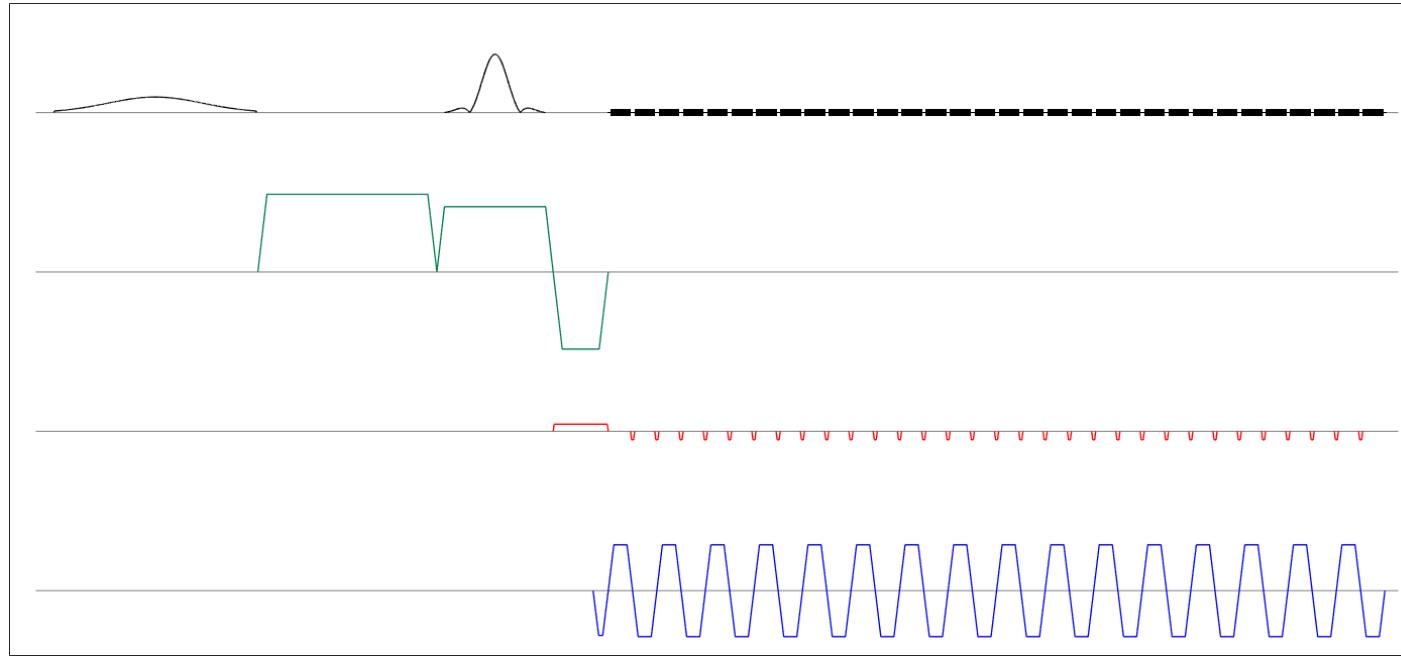


Fast radial gradient echo block structure



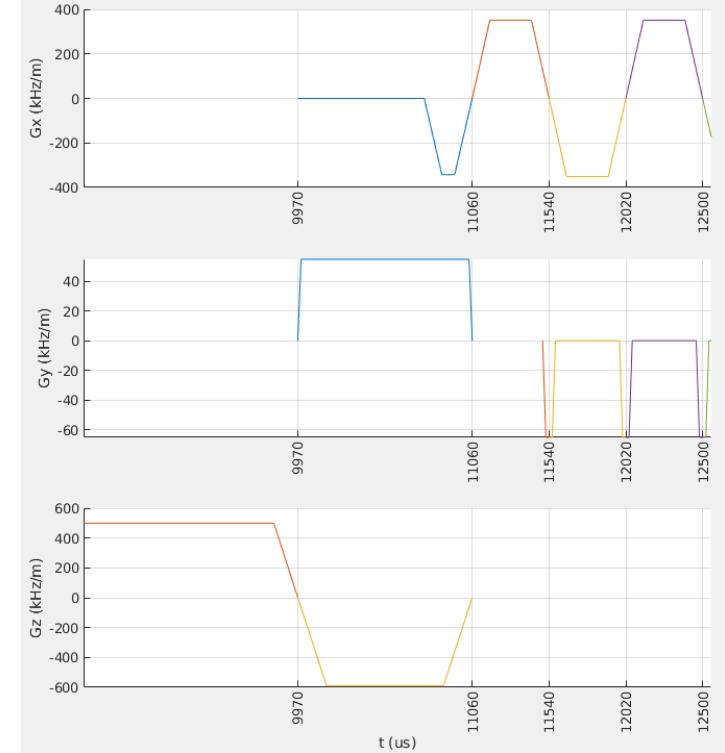
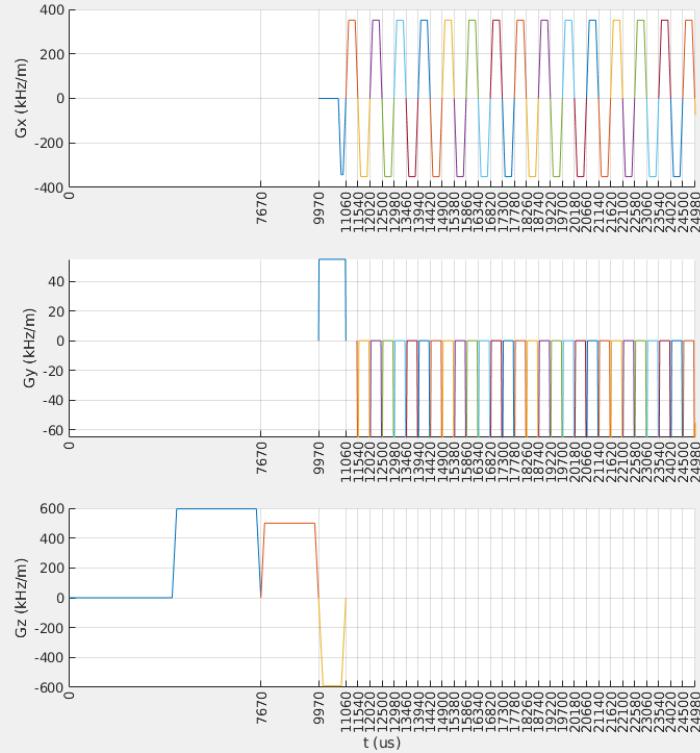
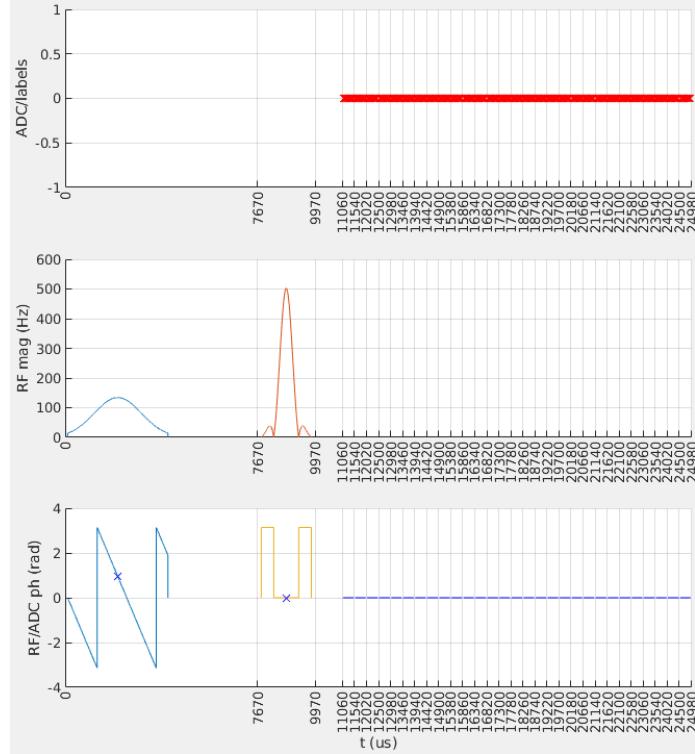
- This is one of many possible solutions
 - Many options work, but your Pulseq file size may vary

Example 3: echo planar imaging (EPI)



- Two RF pulses need to be in separate blocks
- Each ADC event needs to be in a separate block
 - Challenge with blips, readout ramp and optimal sampling window

EPI block structure



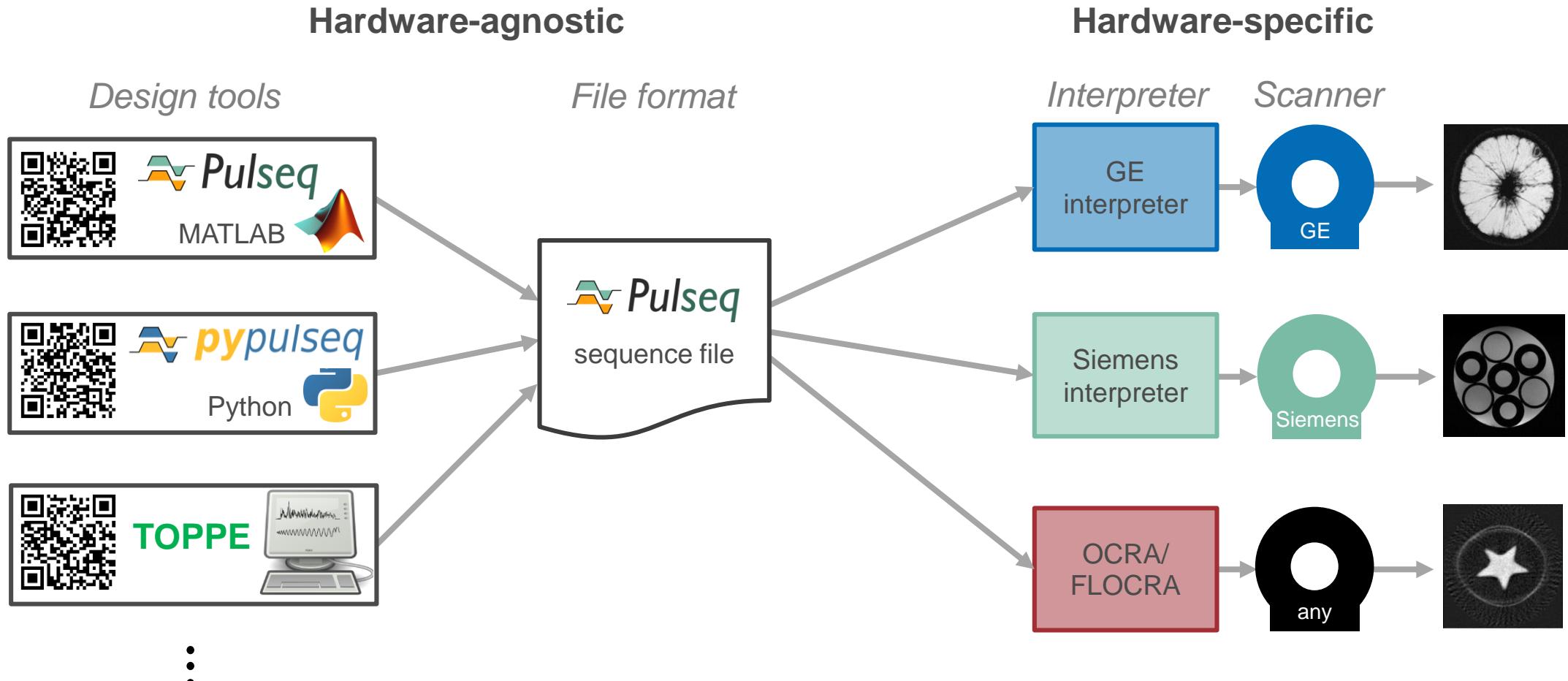
- One possible solution:
 - Keep readout gradient as trapezoid
 - Convert blips to shapes and split them at the center

Pulseq blocks summary

- Block concept takes some time to get used to
- Blocks help to organize events and eliminate timing errors
- There is a lot of flexibility
 - Different strategies possible
- Some interpreters expose additional limitations
 - Explicit and implicit delays, number of ADCs per TR, etc...
- **Blocks make it easier for the interpreter to play things out**



Pulseq framework overview



Before you start on the scanner

- Peripheral nerve analysis
- Avoiding acoustic resonances (for fast sequences)



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

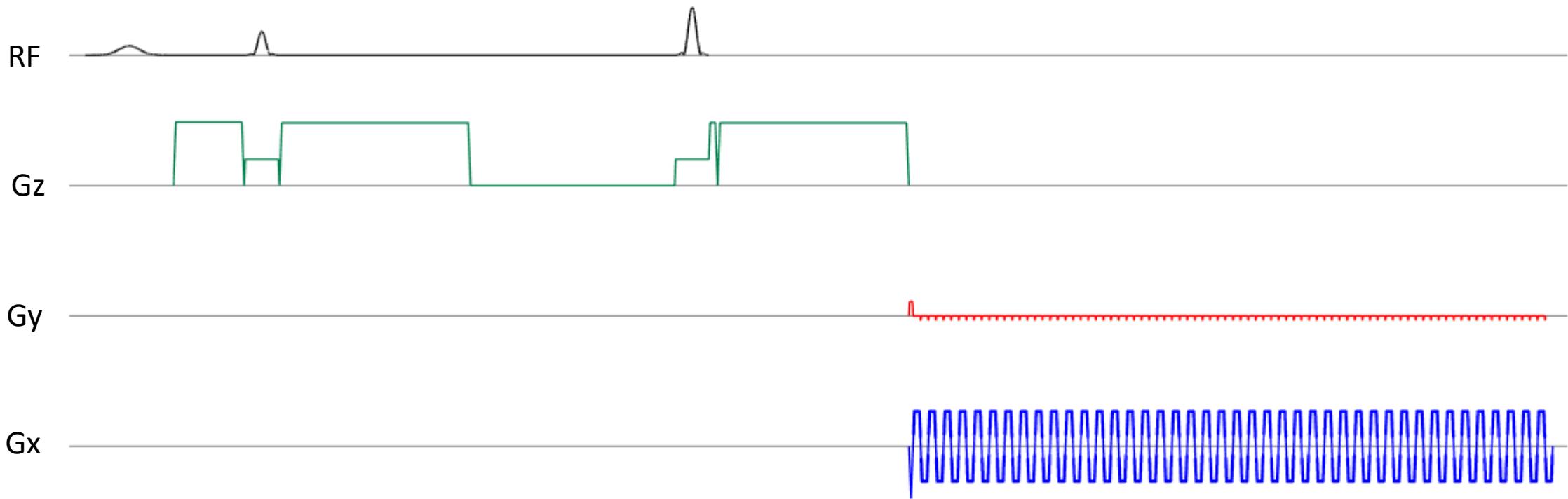


Caveat & Solution

- 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

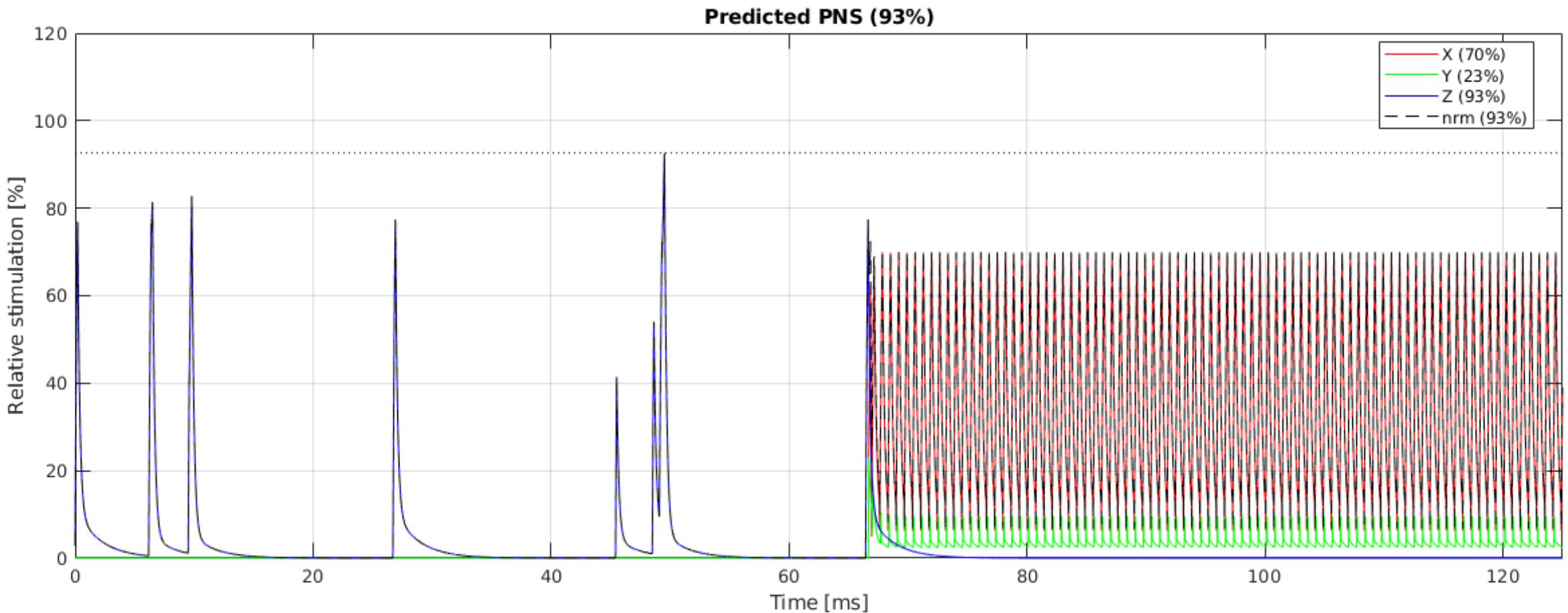
Example: DW-EPI

- 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');
```

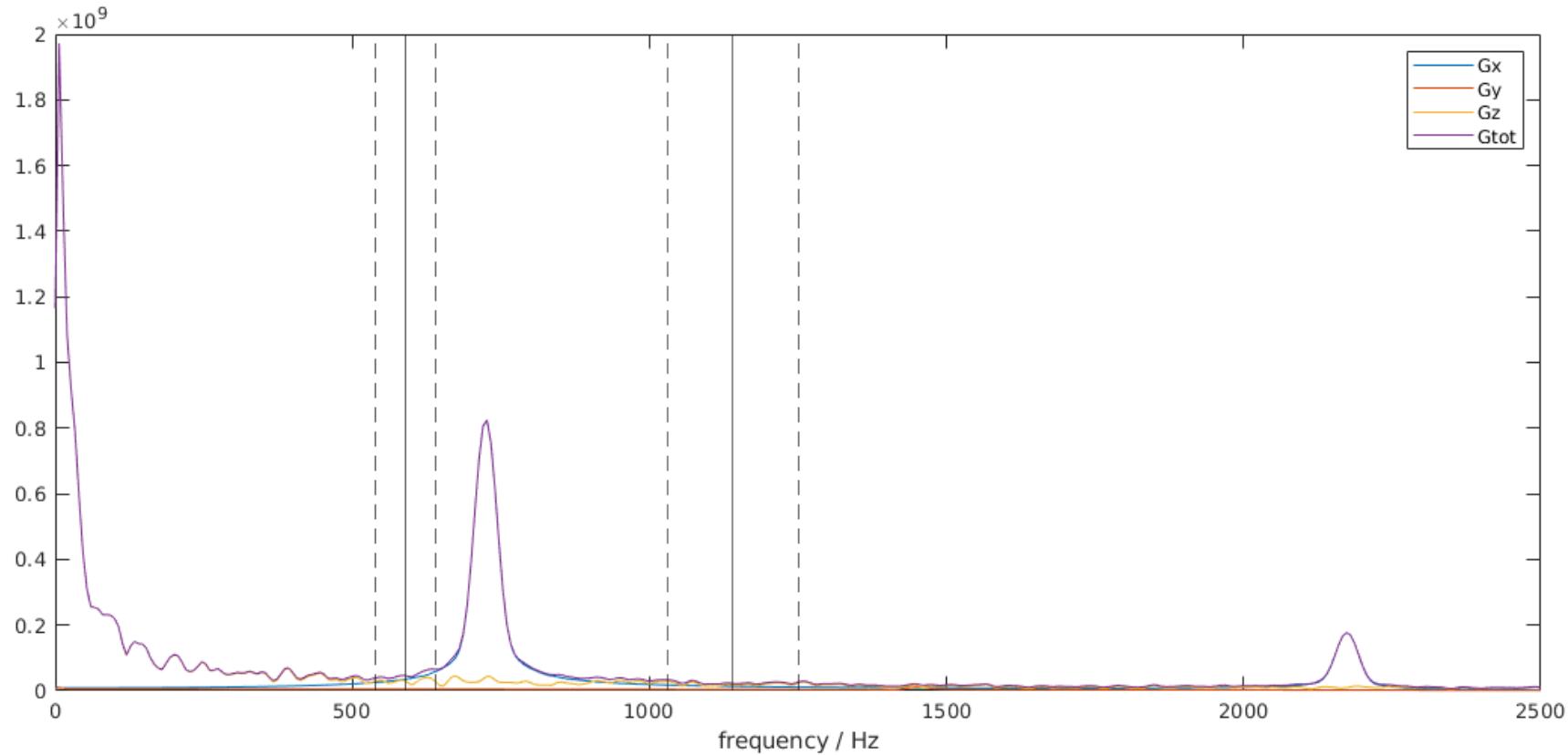


Acoustic resonance analysis

- 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



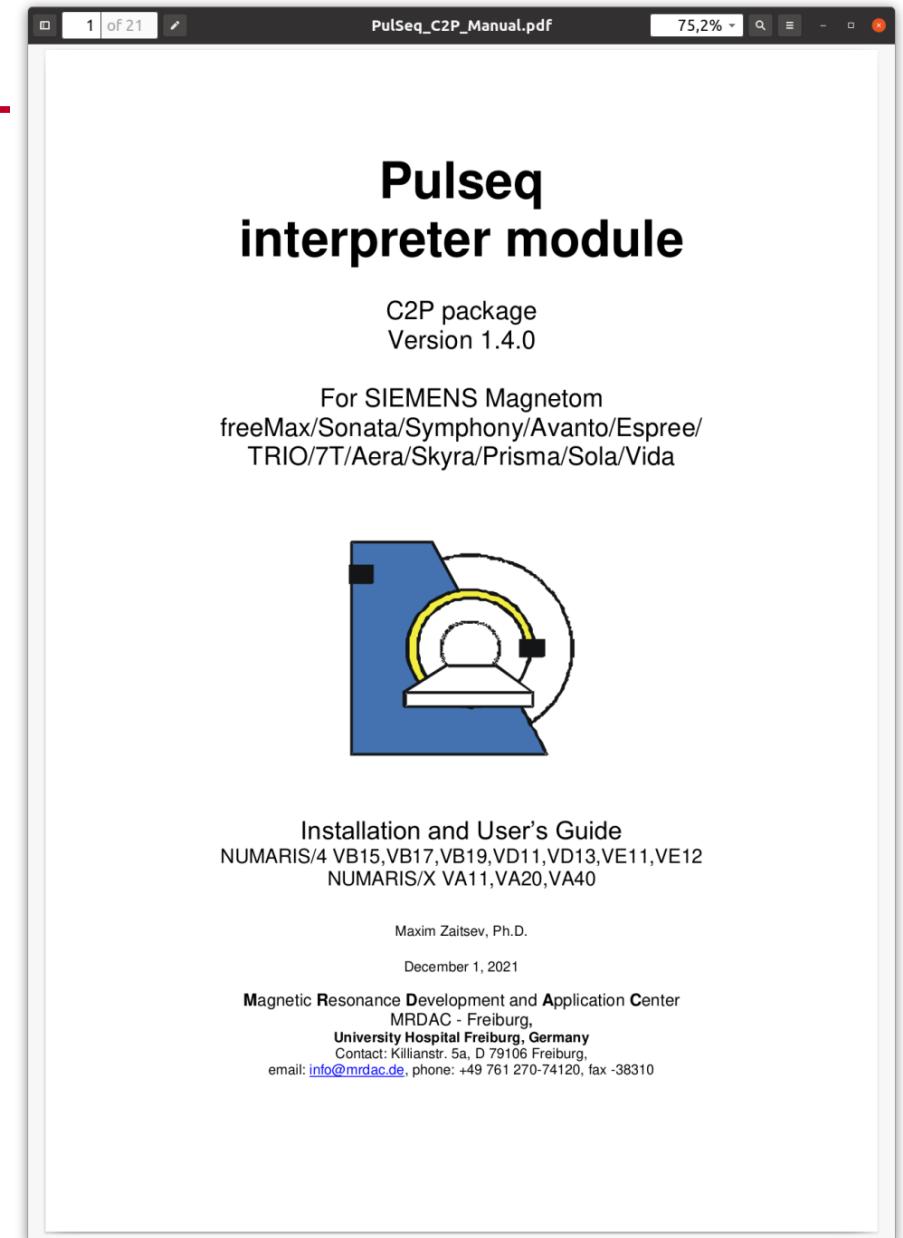
Acoustic analysis: DW-EPI



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

Pulseq Siemens interpreter

- Just a “normal” sequence
 - Loads its “content” from a Pulseq file
 - Almost all aspects of the sequence are pre-defined in the Pulseq file
 - FOV positioning and rescaling possible
- Based on miniFlash
 - No product code
 - No hacks, no backdoors
- Distributed as a C2P package in **source form**
- Standard SAR calculation
- “Gradient Health” libBalance applicable to all sequences
- PNS and acoustic resonance analysis possible in Matlab
- **Safety equal or higher than a typical IDEA sequence**



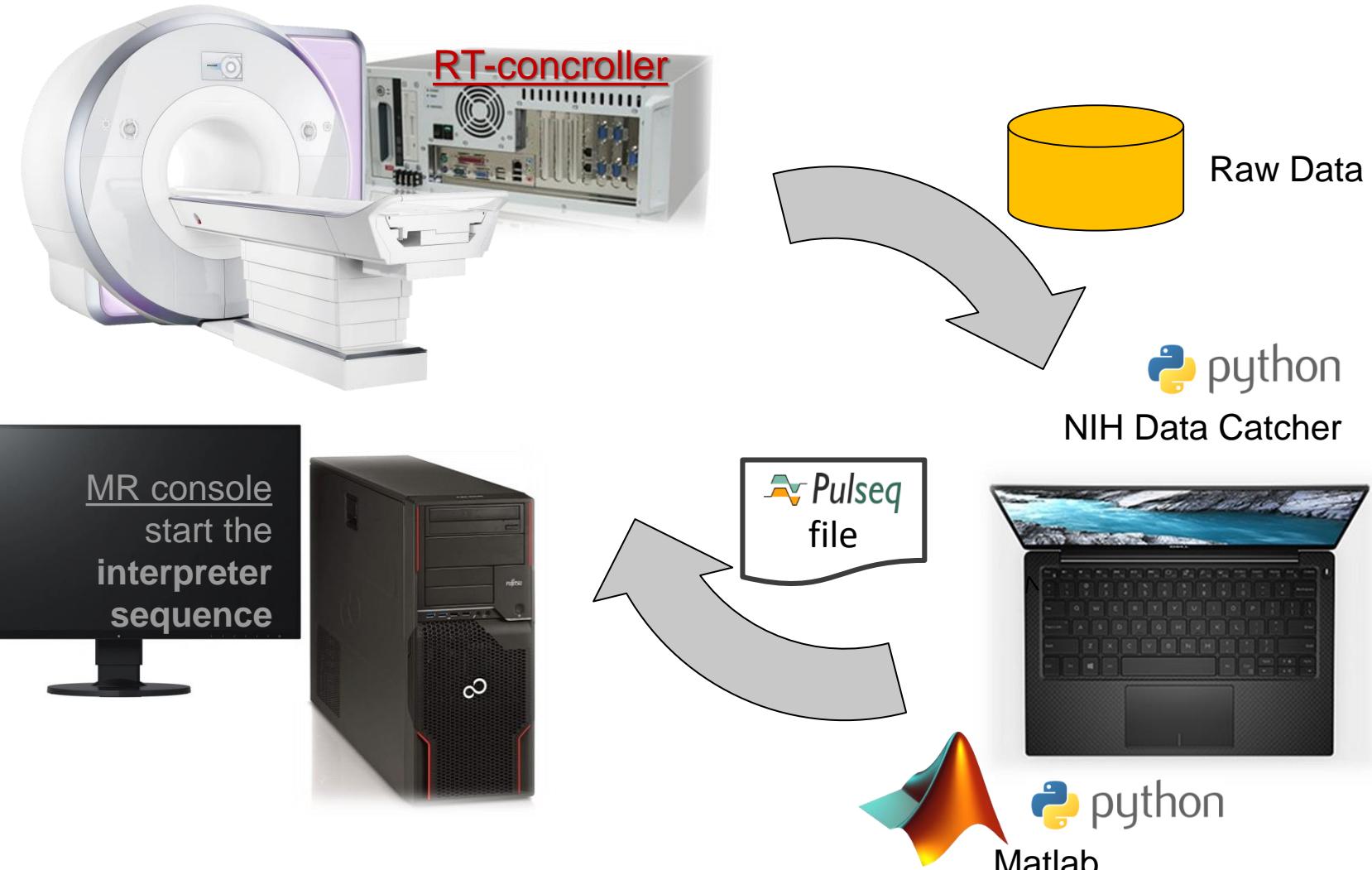
Pulseq on Siemens platforms

- Over 100 C2P sites
- *Pulseq* works well on:
 - All Numaris4 platforms (tested on vb15...ve12u) and numerous hardware platforms (Symphony, Trio, 7T, 3T Connectom, Skyra, Prisma,...)
 - All released NumarisX versions (xa11, xa20, xa30, xa40, xa5x, xa6x ...)



Pulseq on Siemens scanners

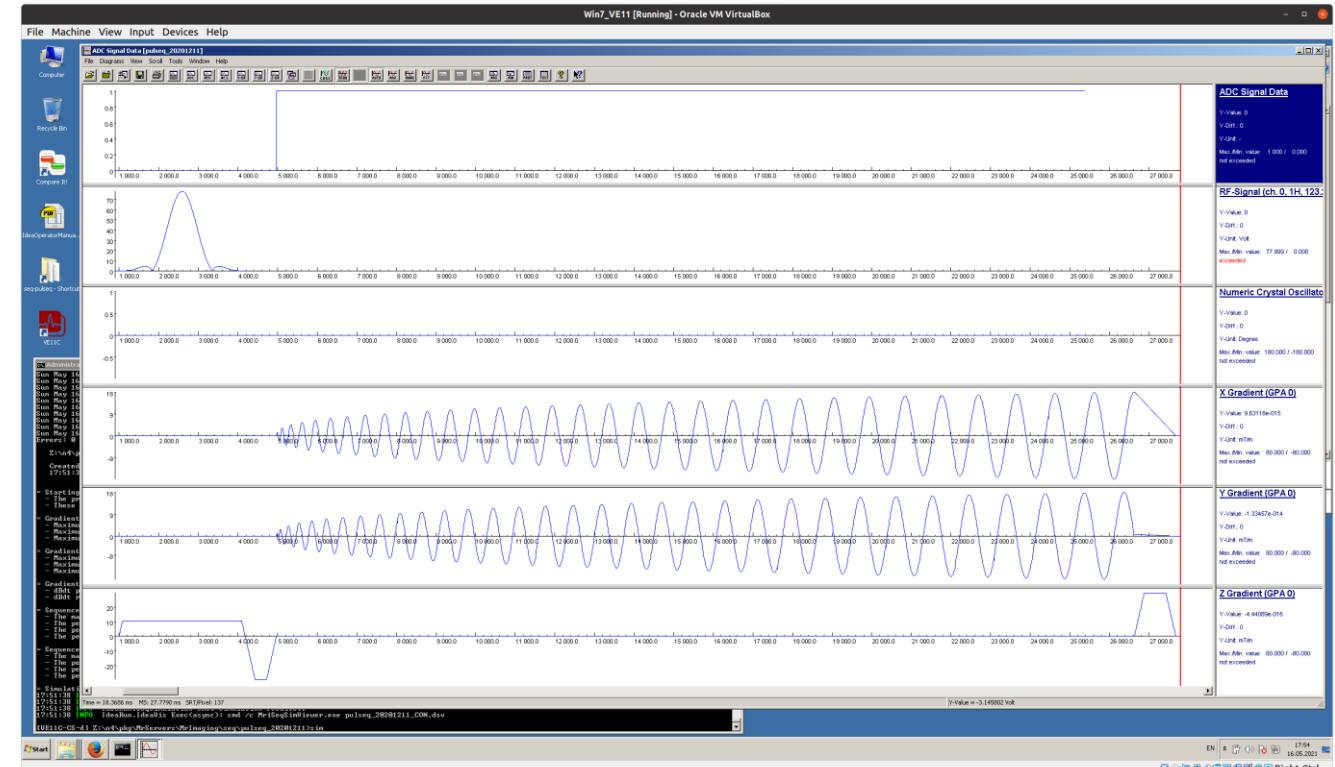
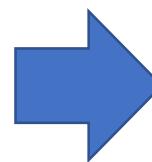
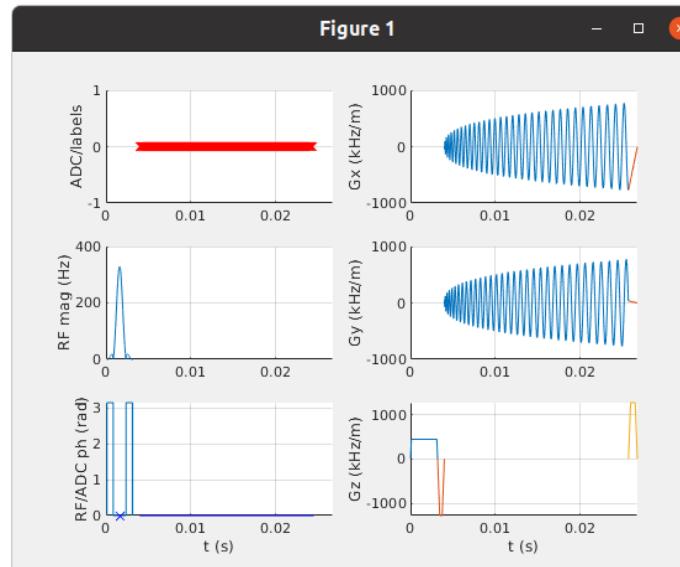
- *Optional initial step:
connect your
PC to the scanner*
- Save the .seq file on the scanner as external.seq
- Run the interpreter_sequence on the scanner
- *Optional step:
stream raw data
to your PC with
NIH_DataCatcher*
- or export raw data manually



IDEA simulation with *Pulseq*

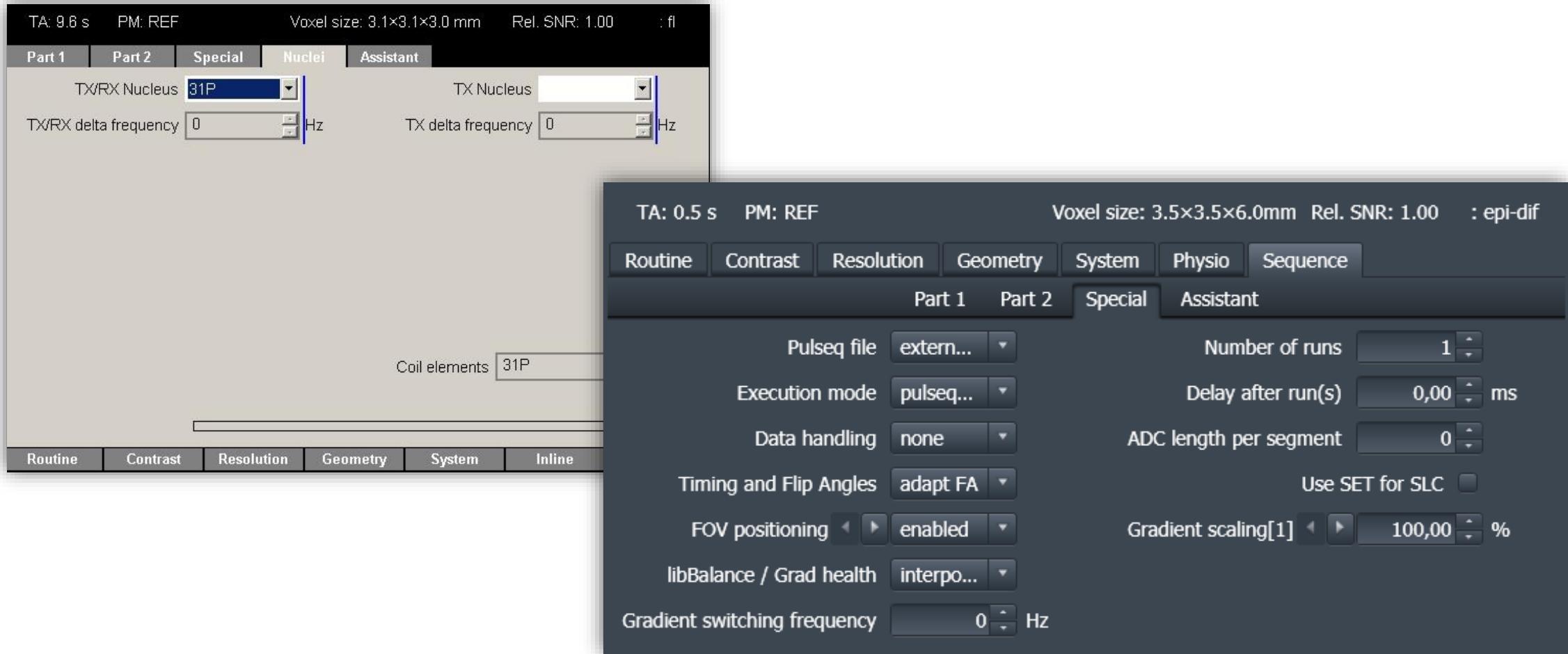
Pulseq interpreter sequence can also be used with the Siemens' IDEA

1. Save your .seq file as %CustomerSeq%/Pulseq/external.seq
2. In the IDEA command run
sim



Pulseq interpreter parameters

- Yes, you can still change few things on the console



Pulseq for Siemens: image recon

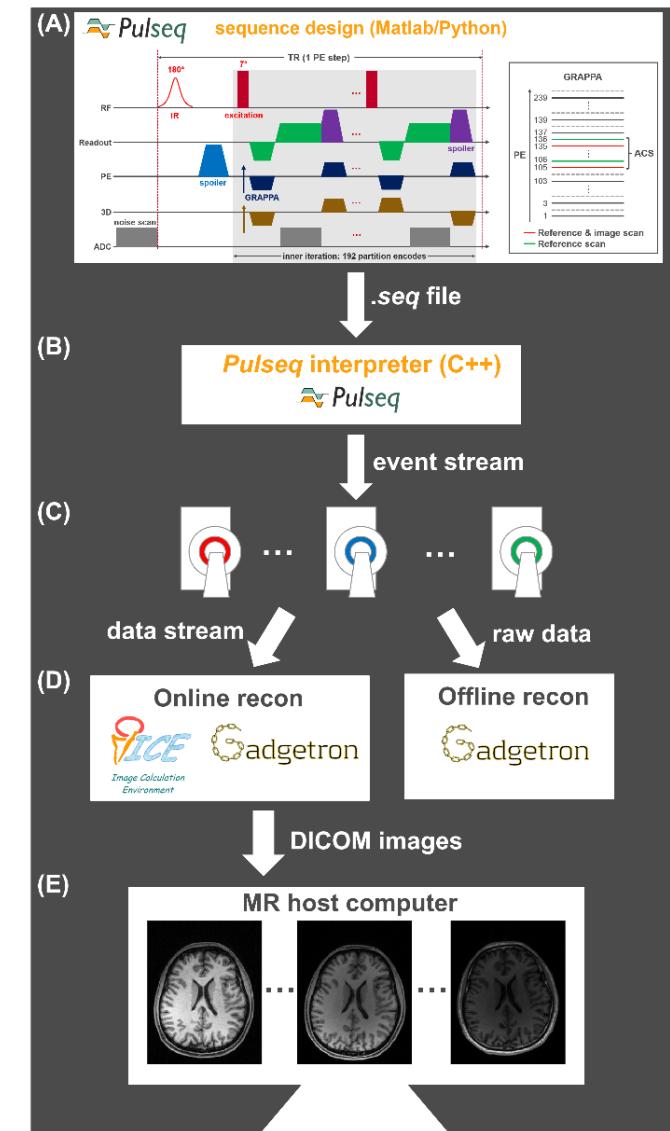
- Image reconstruction is up to the researcher
- Integration with ICE is possible for some sequences
 - 2D GRE
 - 2D EPI with ramp sampling
 - 3D MPRAGE with GRAPPA
- Online & offline reconstruction with Gadgetron for some sequences
- Offline reconstruction in Matlab & Python
 - Examples for 2D / 3D Cartesian reconstruction
 - Simple gridding reconstruction
 - Example of automated BART reconstruction
- All-in-one FIRE solution : Marten Veldmann et all, MRM 2022, doi:10.1002/mrm.29384

Qingping Chen @
ISMRM



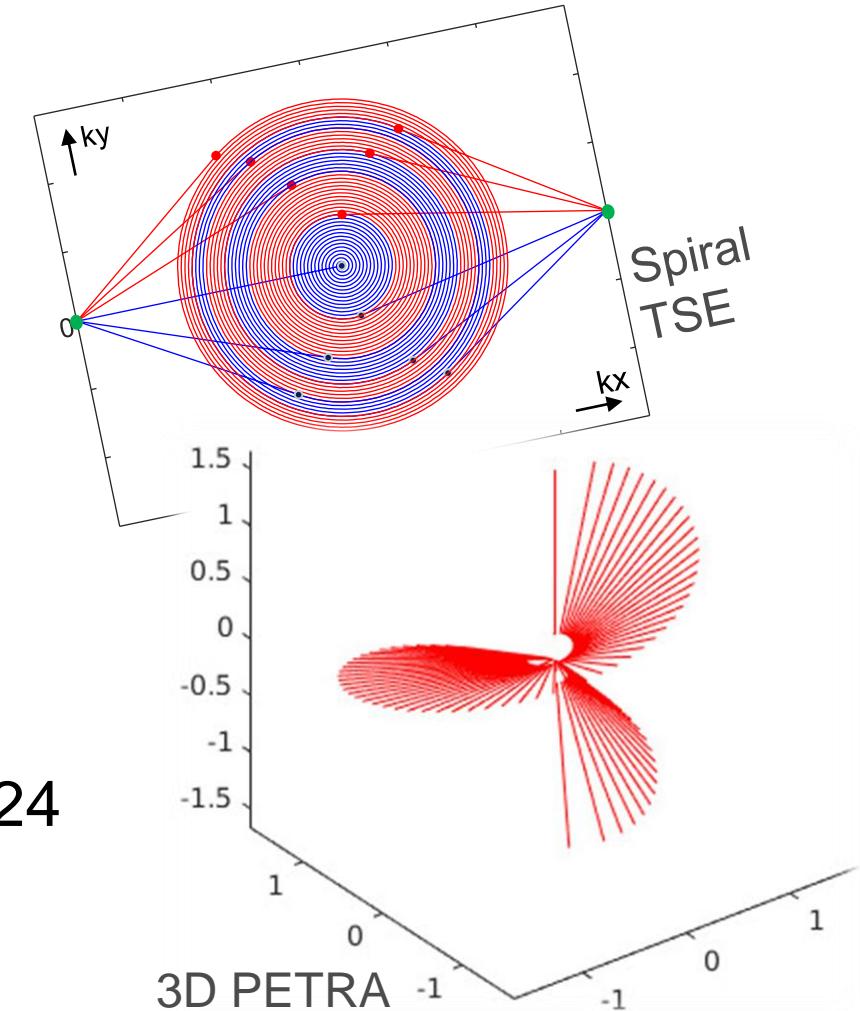
Pulseq for Siemens: online recon with label

- Workflow for data acquisition and image reconstruction
- Extended Pulseq interpreter
 - Load ADC labels and sequence definitions
 - Link to ICE and/or Gadgetron
- How to enable ICE online reconstruction
 - ADC labeling & label debugging. E.g. Label the first PE line
`mr.makeLabel('SET', 'LIN', 0)`
 - Sequence definitions. E.g. 2D multi-slice mode:
`seq.setDefinition('SlicePositions', 0) ;
seq.setDefinition('SliceThickness', sliceThickness) ;
seq.setDefinition('SliceGap', sliceGap) ;`
 - Interface setting. E.g:
Sequence->Special Card->Data handling ->ICE 2D



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
- Pulseq files play out on many scanners
 - Siemens & GE : works
 - Philips : two working interpreters @ISMRM24
 - *Bruker* ???
- New release v1.4.2 (Dec 2023)



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