Pulseq Principles

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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

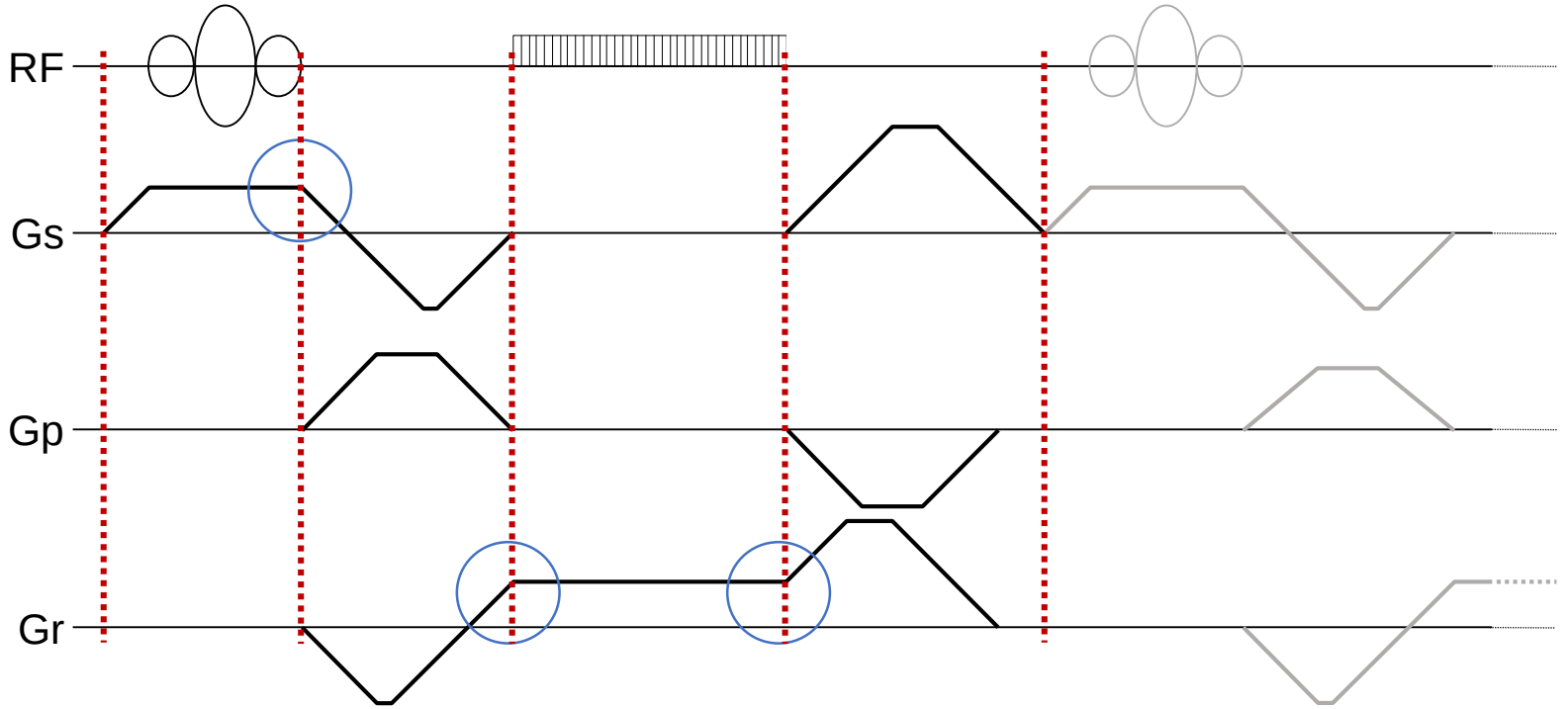
Pulseq ecosystem includes sequences, software to generate them and software and hardware to consume them

Pulseq 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

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

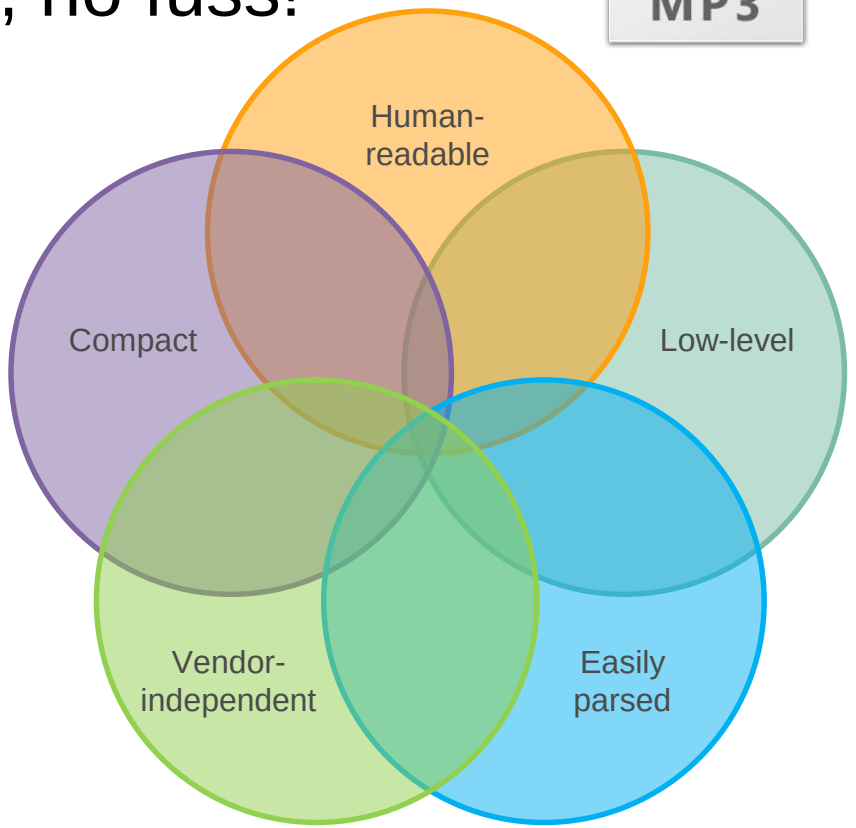
Pulseq block concept in detail

- 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 – 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

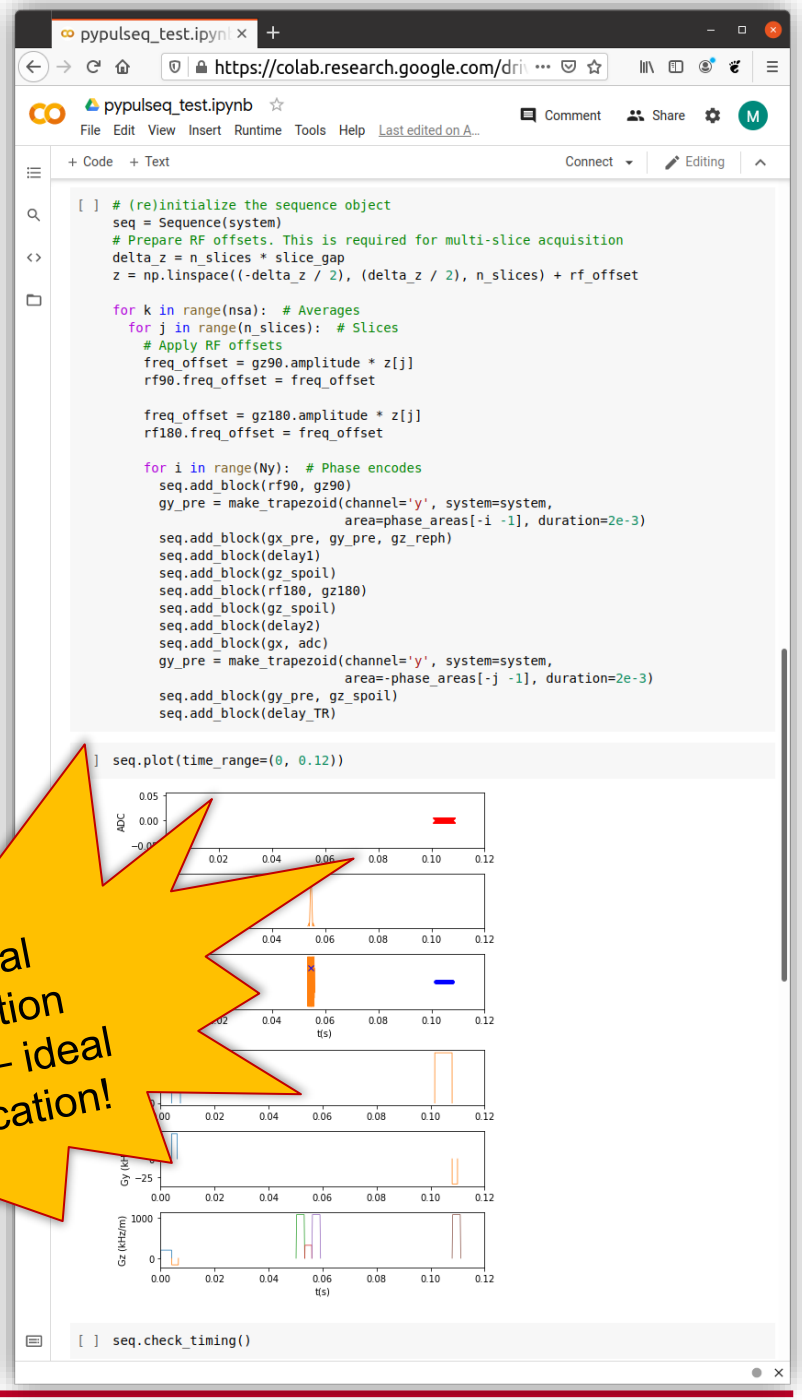
```
system = mr.opts('MaxGrad',30,'GradUnit','mT/m',...
    'MaxSlew',170,'SlewUnit','T/m/s');
seq=mr.Sequence(system);

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('gre.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!*



No local installation needed – ideal for education!

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, check hardware and PNS limits, mechanical resonances, etc…

Pulseq objects & blocks

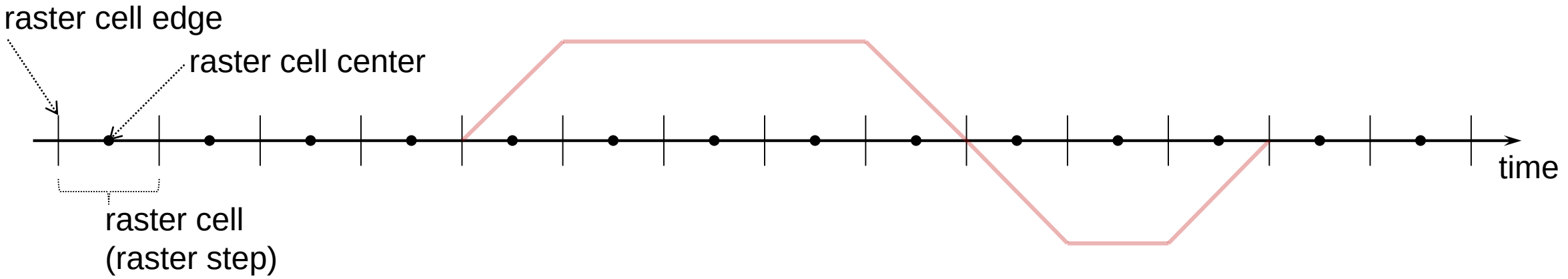
- *Pulseq* objects are created and then added to *Pulseq* blocks
  - Gradient & RF pulses

    mr.makeTrapezoid(…) or pp.make_trapezoid(…)

    mr.makeSincPulse(…) or pp.make_sinc_pulse(…)
  - ADC objects

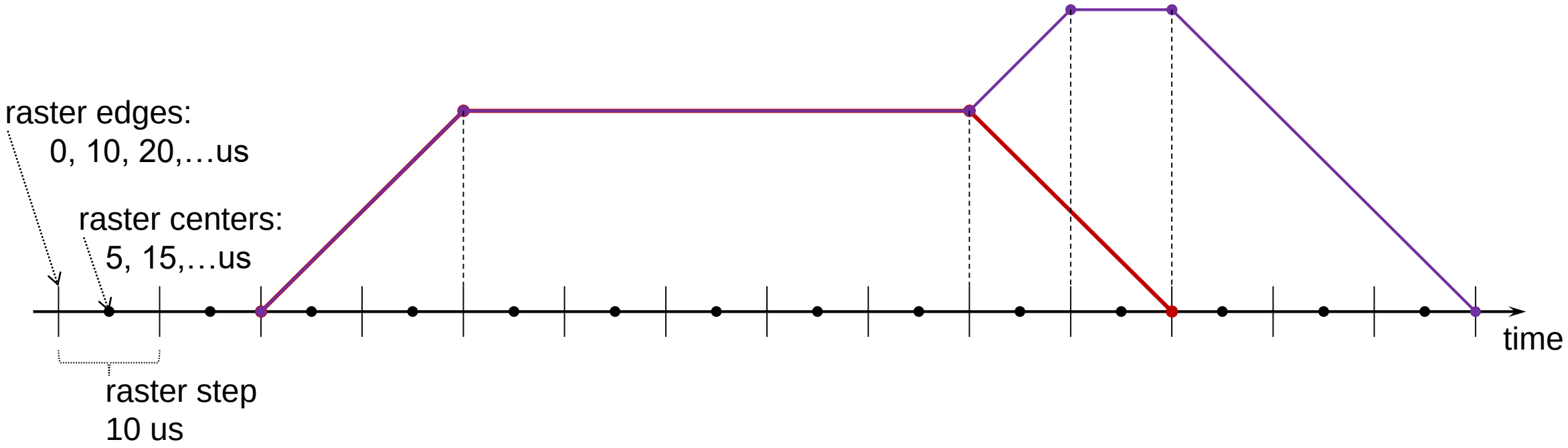
    mr.makeADC(…) or pp.make_adc(…)
  - Delays, extension objects, etc.
    (data labels, cardiac trigger directives, trigger pulses)
  - Use seq.addBlock(…) or seq.add_block(…) to add objects & blocks
- Block concept in *Pulseq* is probably the most demanding part
  - Blocks and objects need to be aligned to raster times

Shapes and Raster Times *Pulseq*



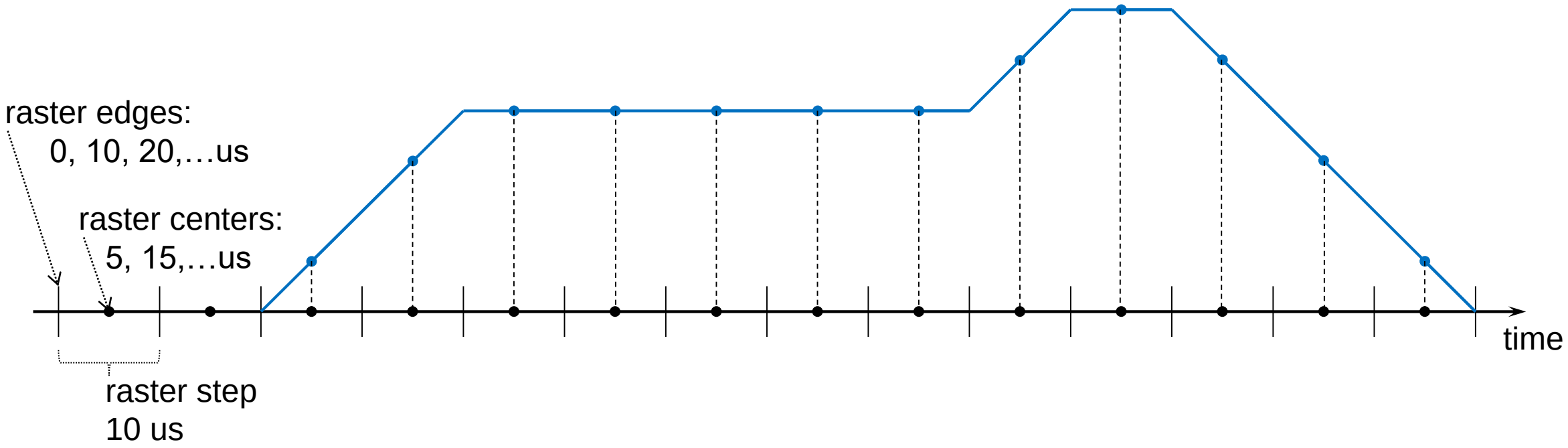
- Precise control of arbitrary gradient and RF waveforms
- Pulseq defines four types of raster times
  - adcRasterTime, rfRasterTime, gradRasterTime, blockDurationRaster
- Raster ‘thinking’ is probably one of the most demanding concepts in the practical pulse sequence programming
- Raster cells, edges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

Gradient Raster and Shapes



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

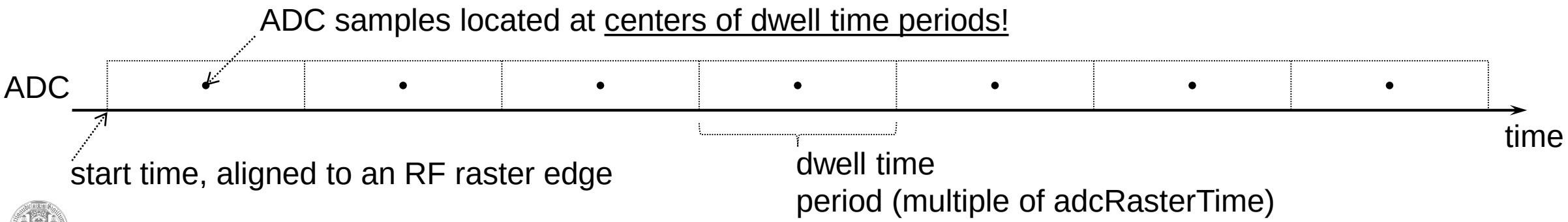
Gradient Raster and Shapes



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

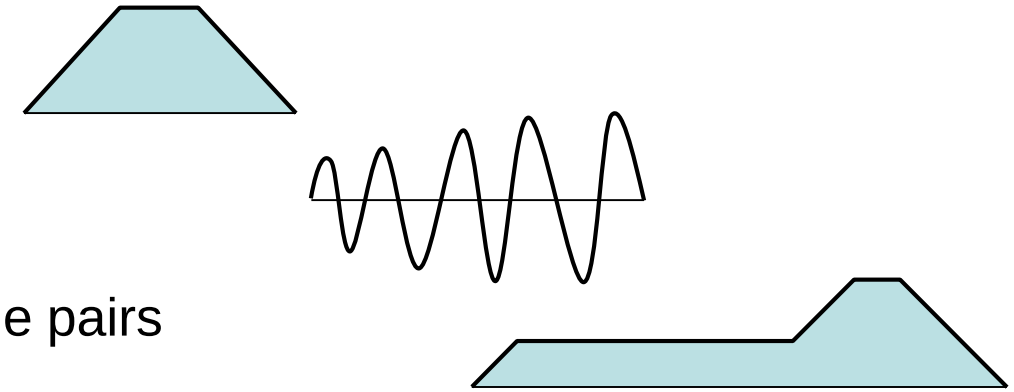
RF and ADC Raster Times

- 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 (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

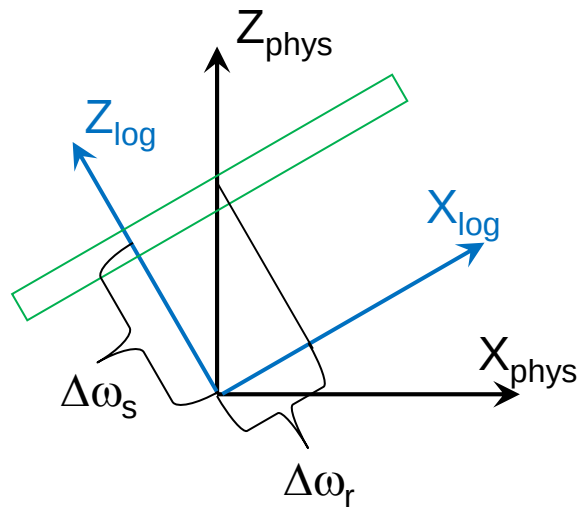
- A *Pulseq* sequence is completely defined in .seq file and is fixed
- Timing is always fixed with one exception:
  - Prospective (cardiac) triggering: actual repetition depends on the heartbeat

Interpreter-Specific Features

- 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

FOV positioning physics

- Rotation matrix applied around the iso-centre
  - For safe operation, sequences must obey
    max(abs(**G**))<sys.G_{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): $\Delta\omega(t) = \mathbf{G}(t) \cdot \Delta\mathbf{r}$

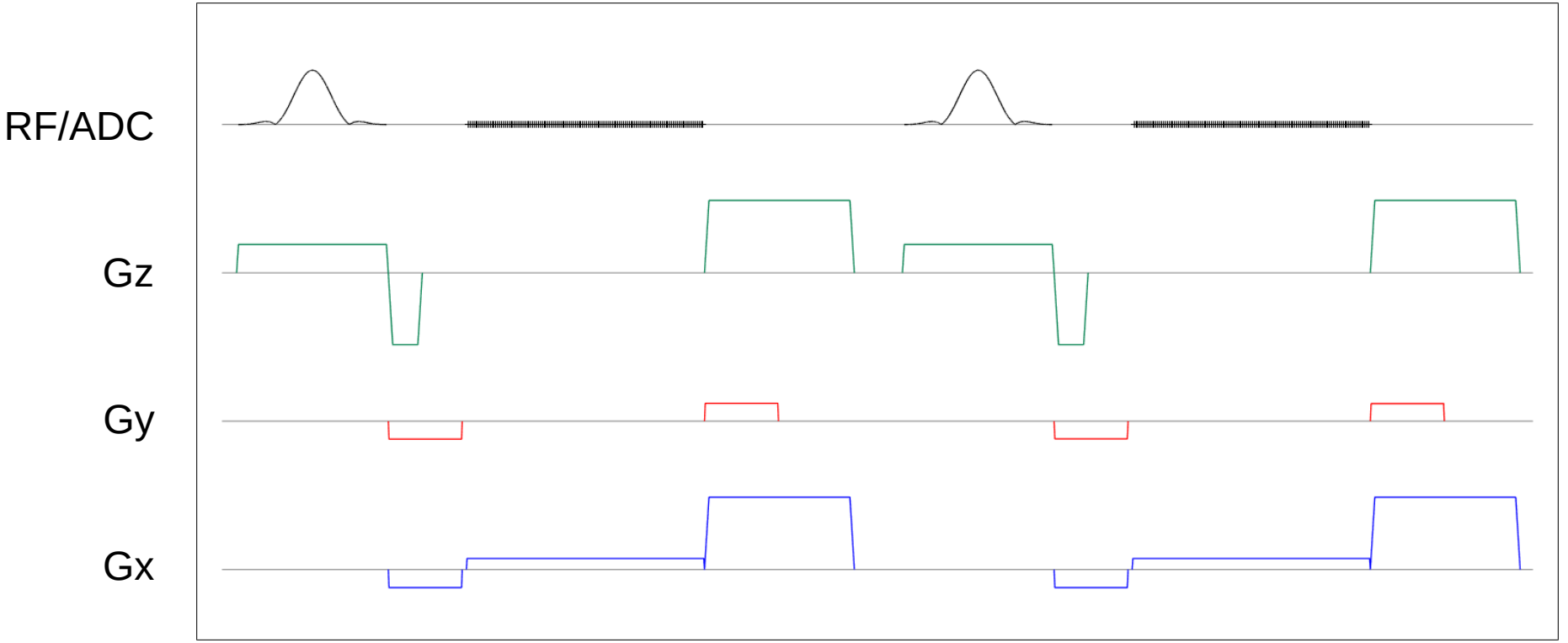


Possible Future Format Extensions

- “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*

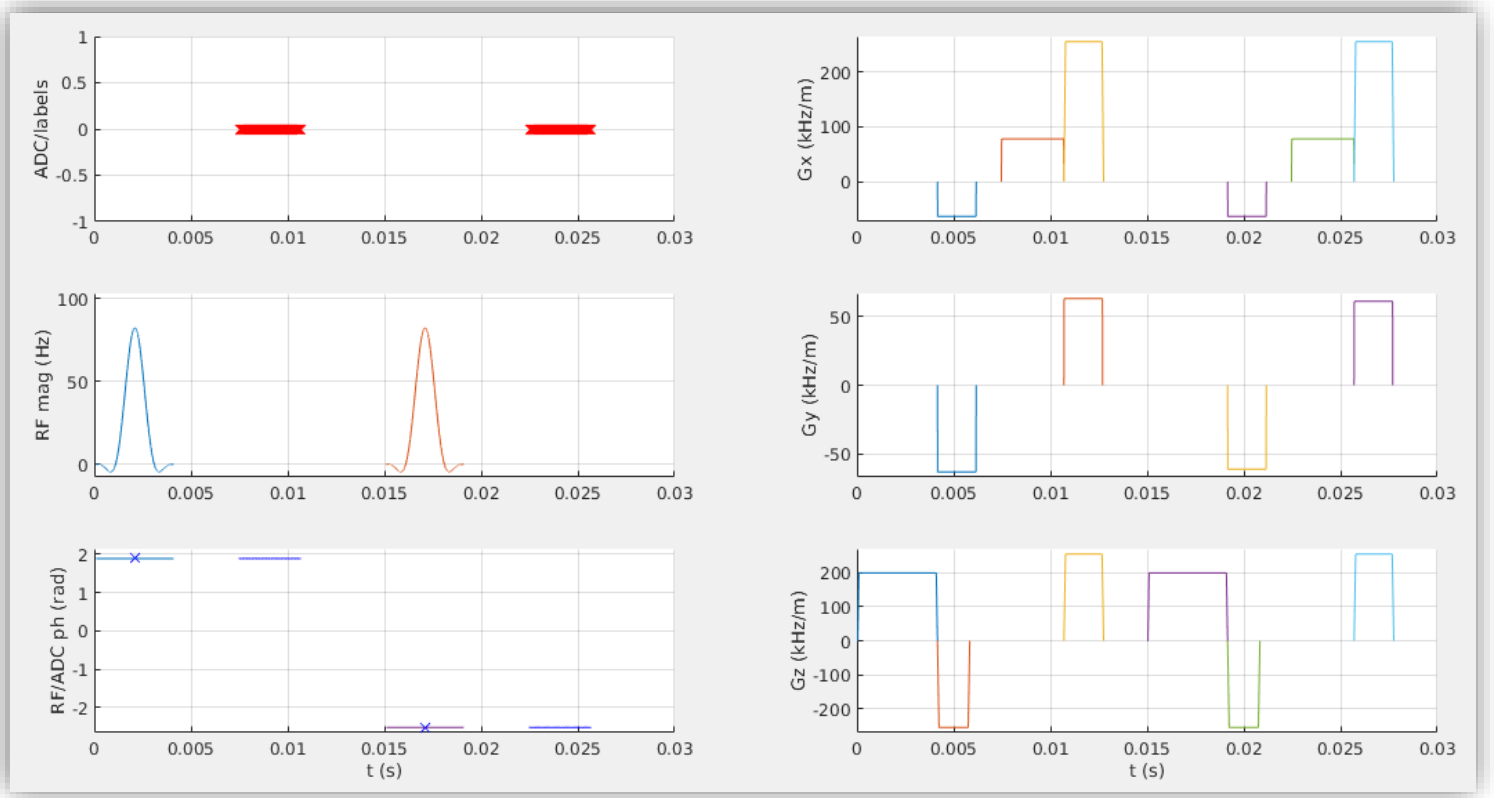
Sequence examples

Example 1: simple gradient echo



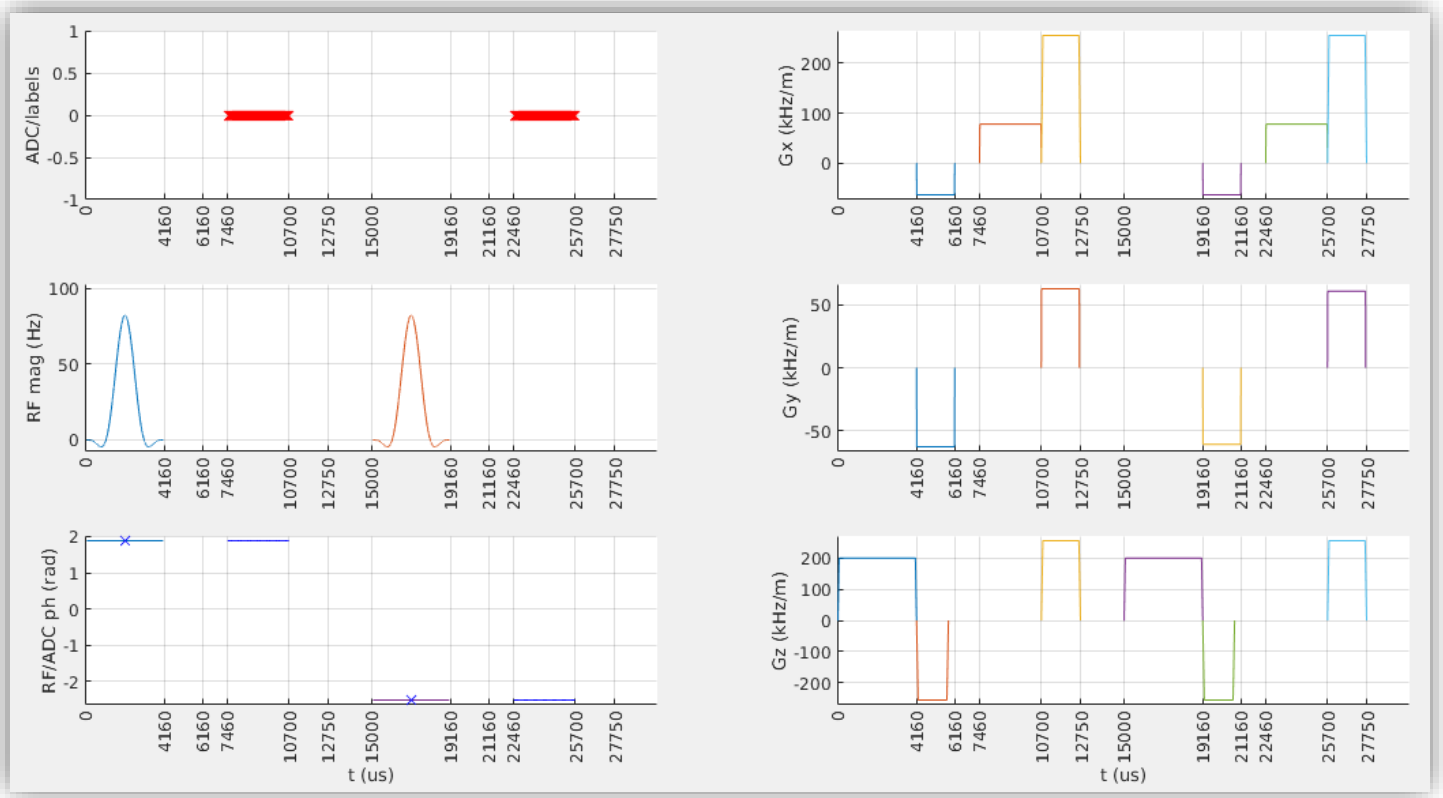
- No overlapping gradient ramps on different axes
- Events are clearly separated

Example 1: basic sequence display options



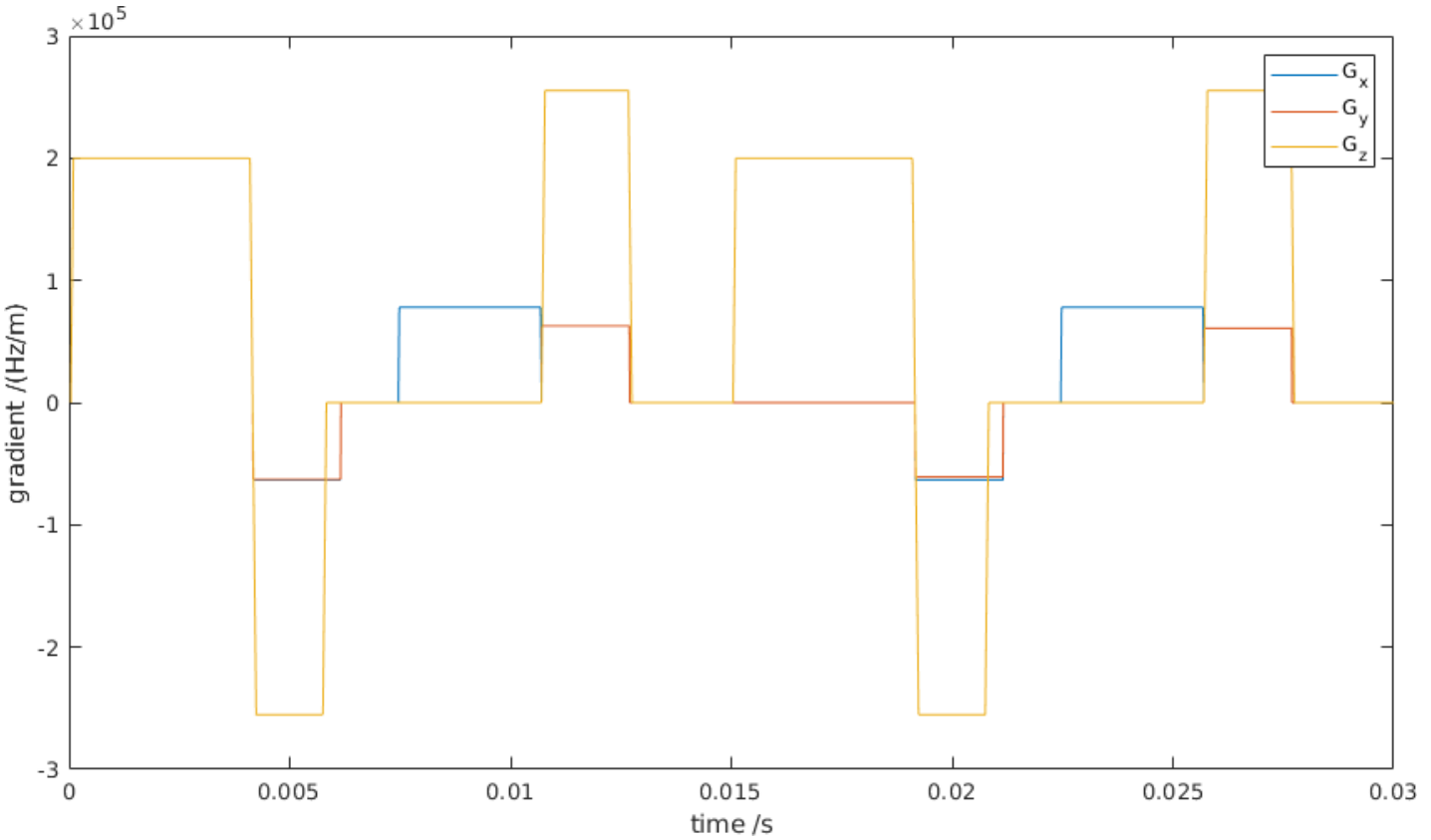
- Pulseq 6-panel plot: seq.plot()
  - ADC, RF magnitude, RF phase, Gx, Gy, Gz
  - Each event plotted in its own color

Example 1: display block structure



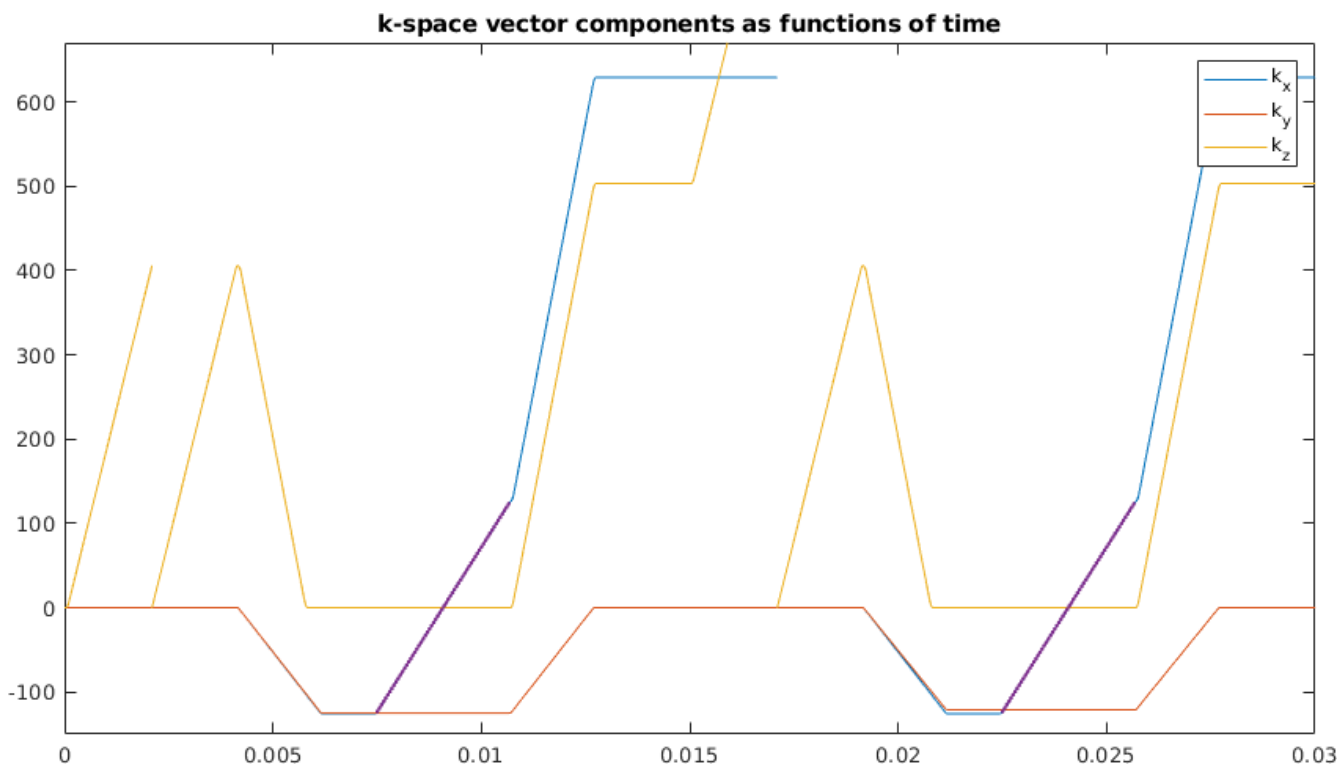
- Advantageous to separate PE & PR gradients into different blocks
- To visualize block structure:
  - seq.plot('showBlocks',true,'timeDisp','us');

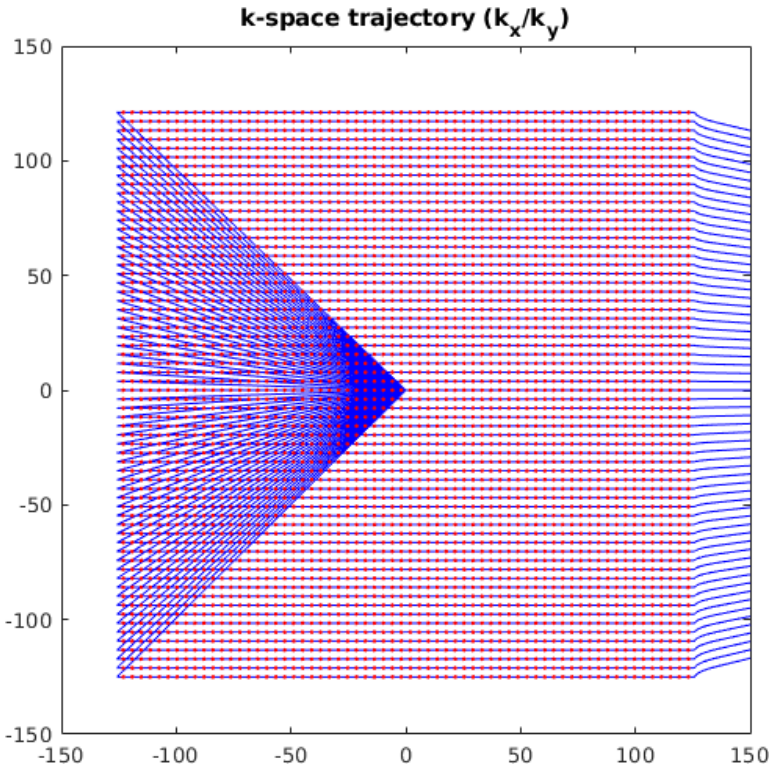
Plot gradient waveforms



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

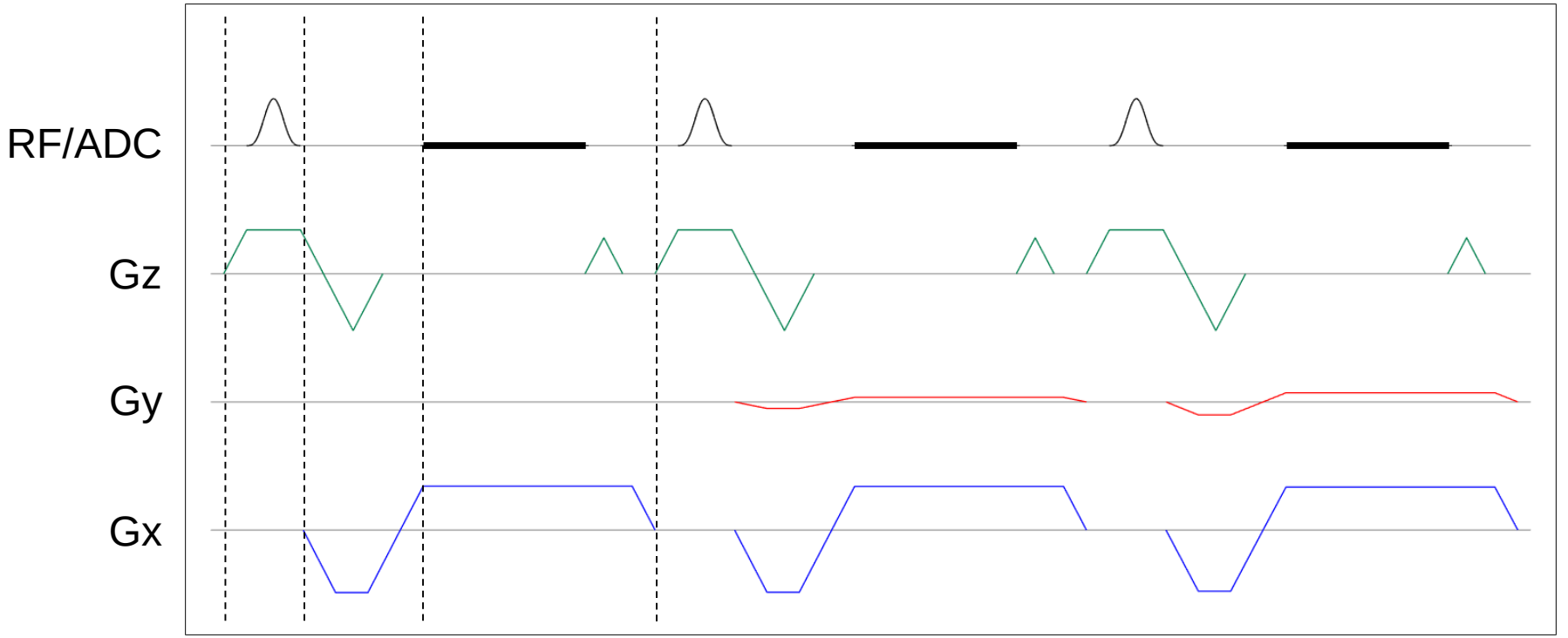
Basic sequence display options: k-space





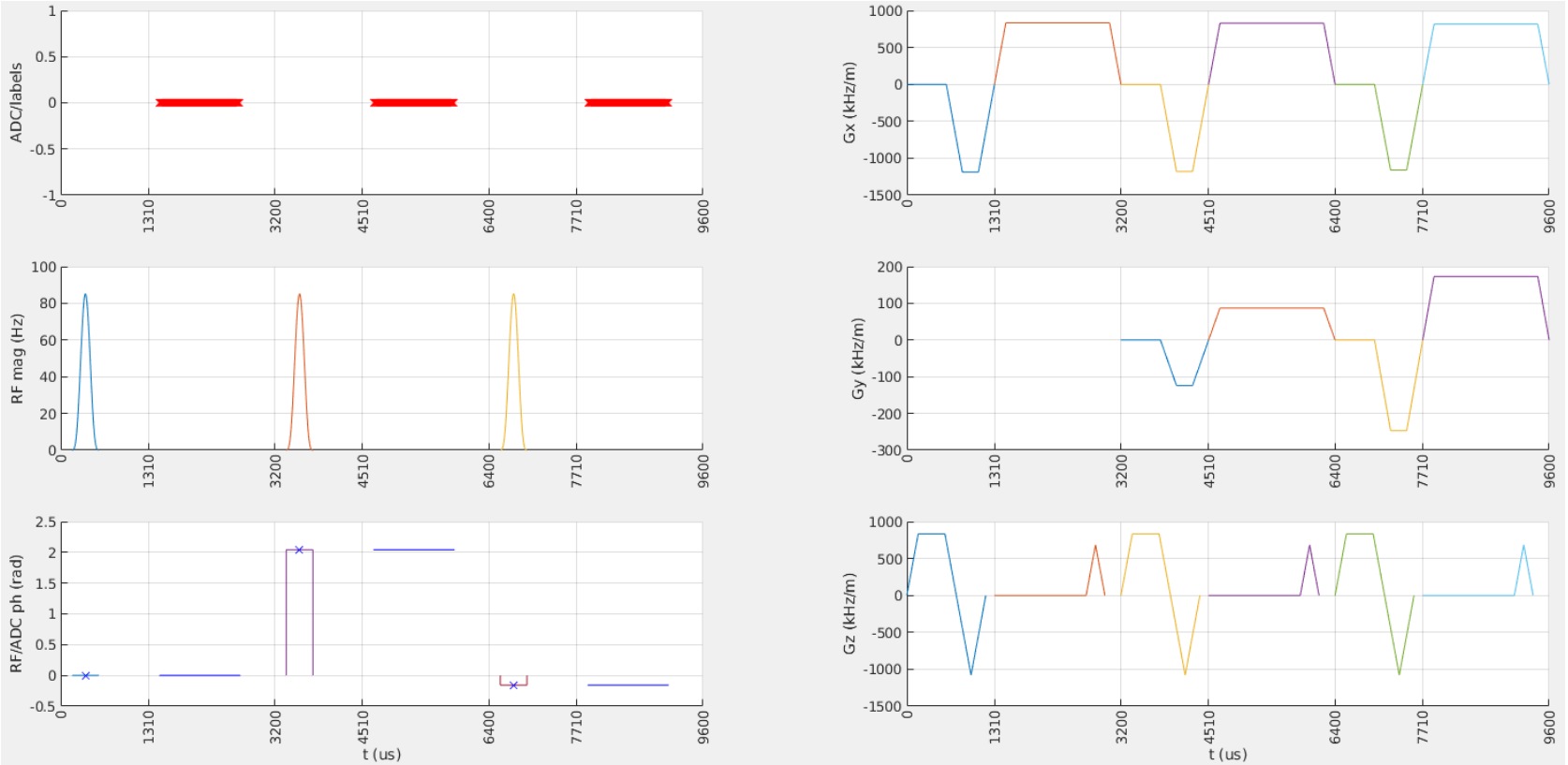
- Plot k-space time evolution or 2D (or even 3D) trajectories
  - Native k-space unit in *Pulseq*: m^{-1}

Example 2: fast radial gradient echo



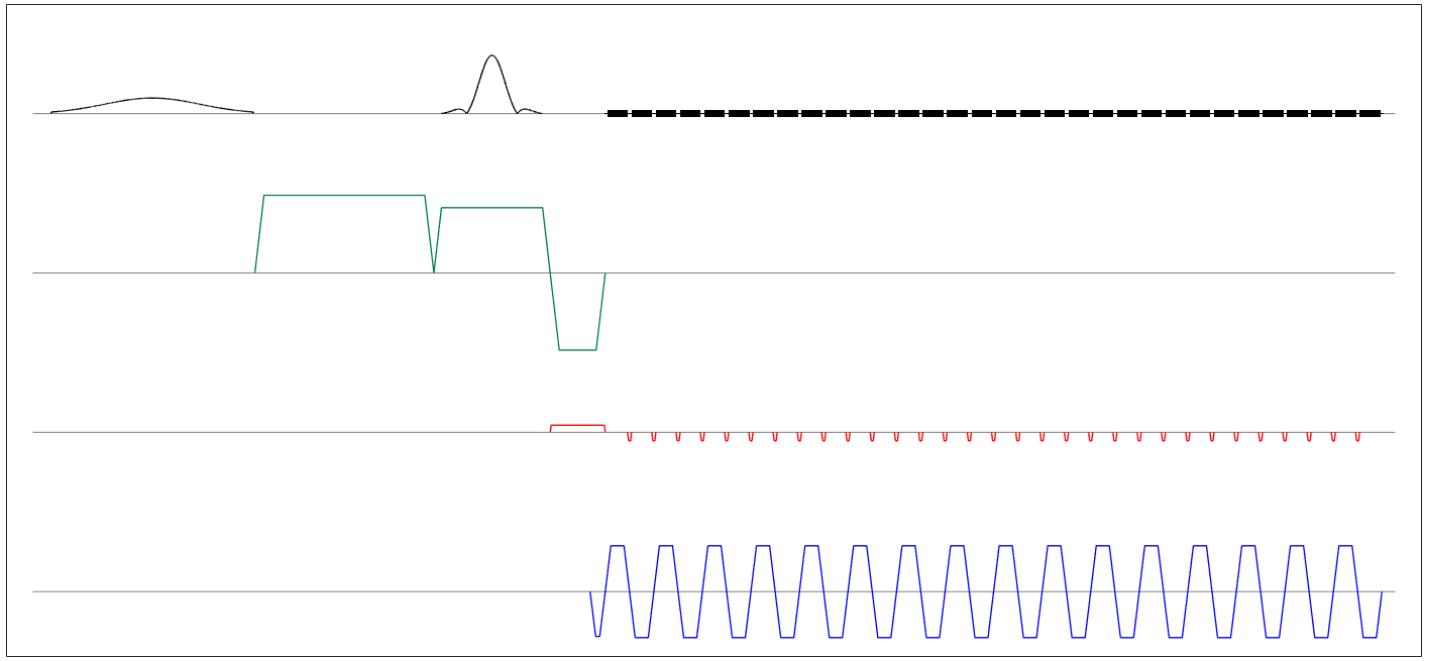
- Block separation is less obvious
  - Merging all into one block is possible, but this would make Z spoiler a part of a shaped gradient….

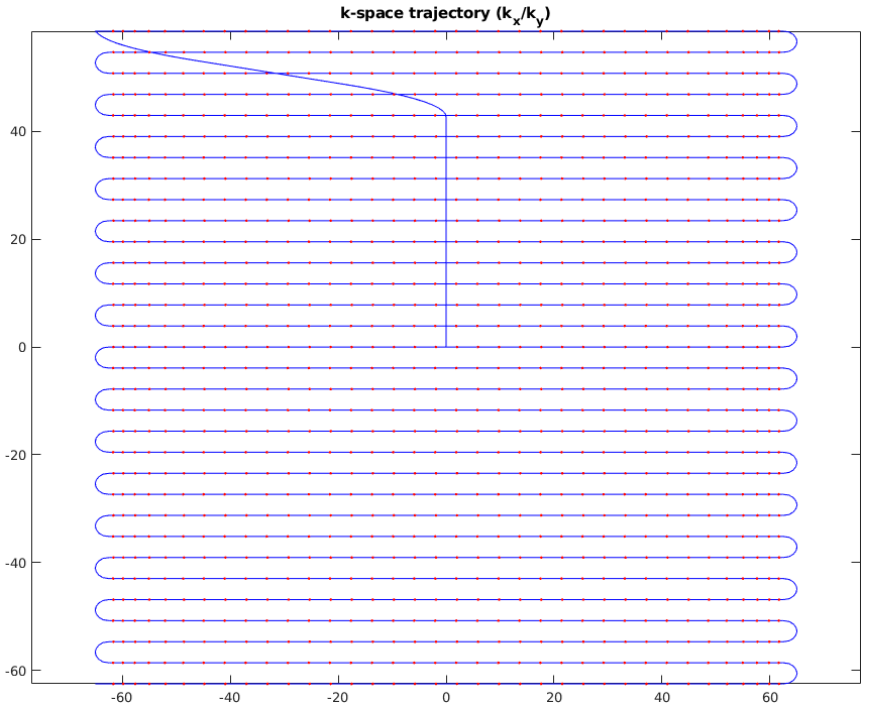
Fast radial gradient echo block structure



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

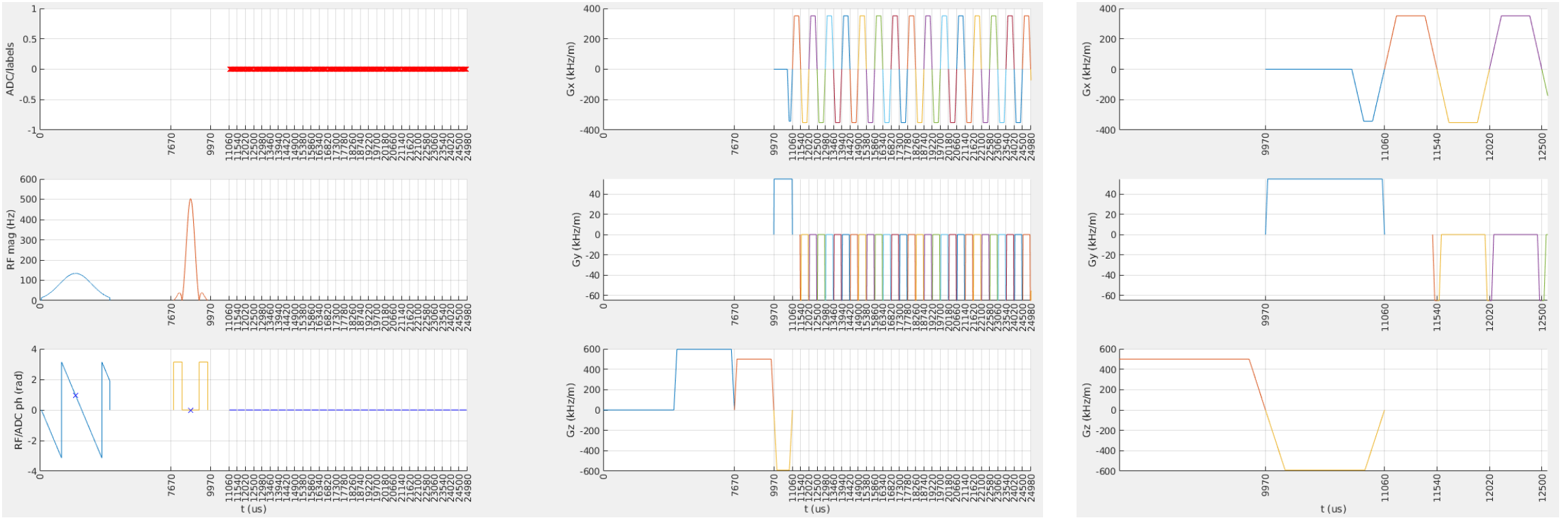
Example 3: echo planar imaging (EPI)





- 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



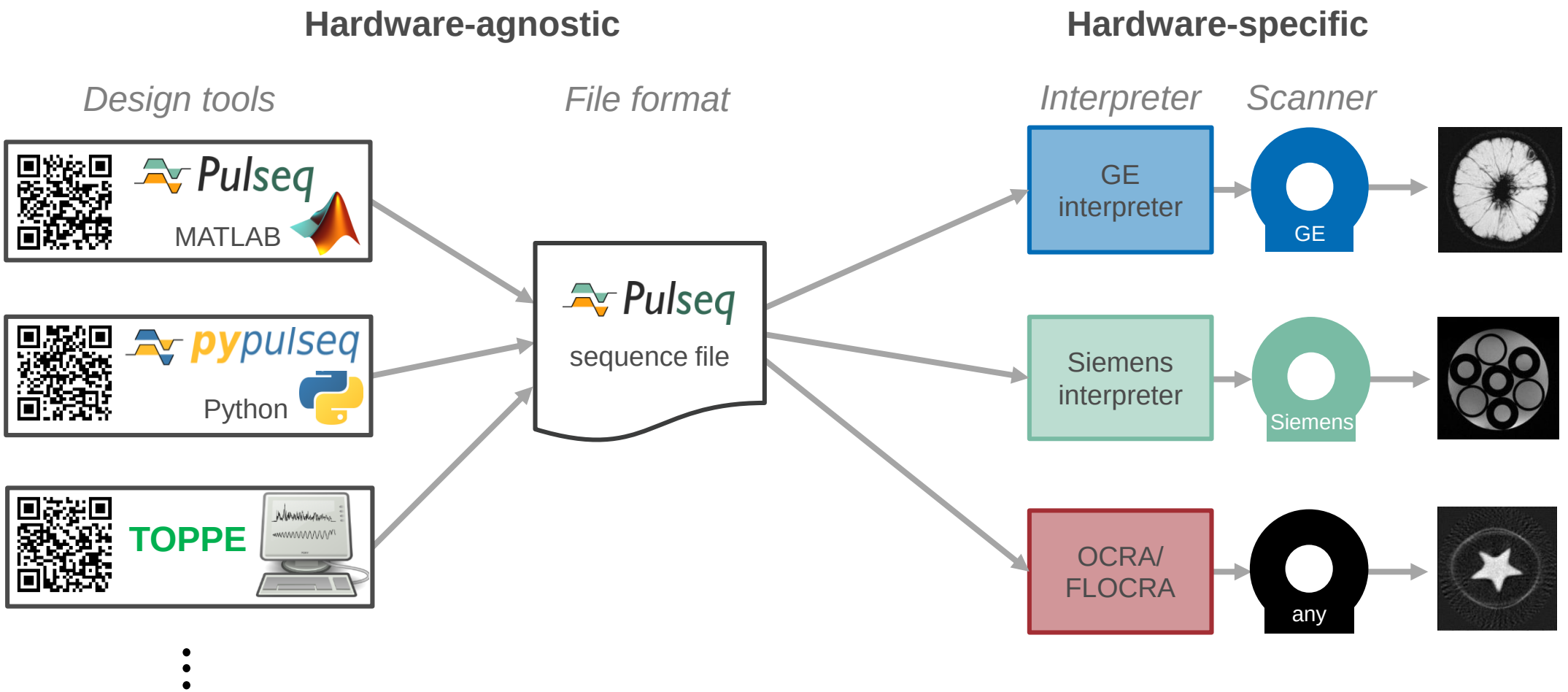
- One possible solution:
  - Keep readout gradient as trapezoid
  - Convert blips to shapes and split them at the center

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

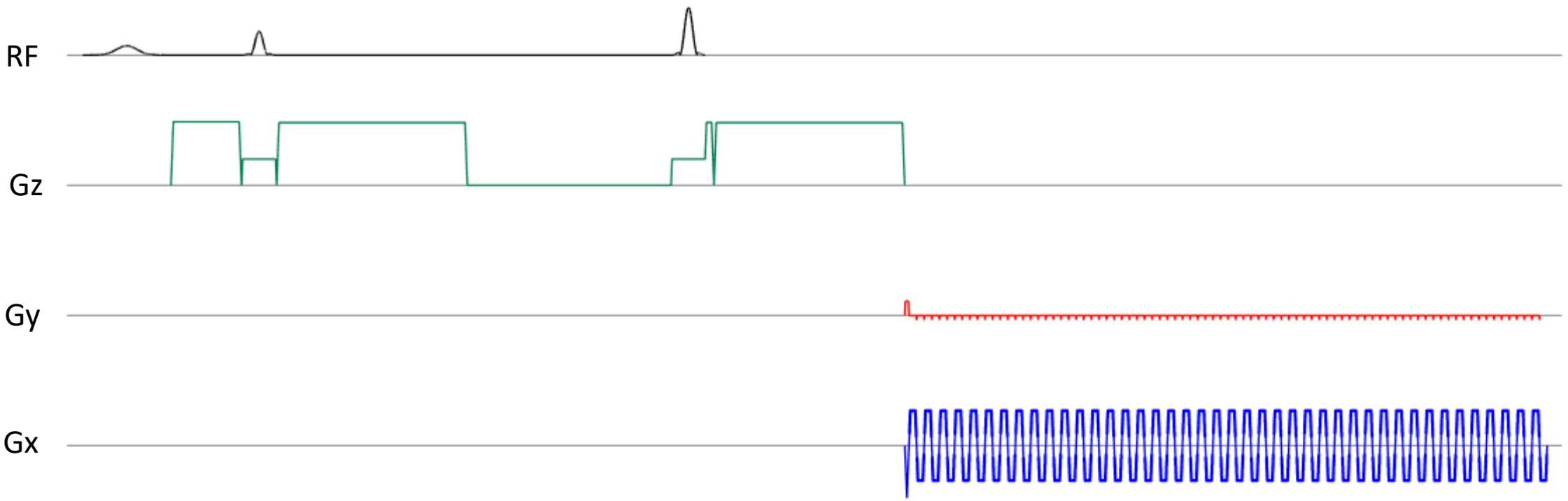
- Direct interface in Matlab-Pulseq

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

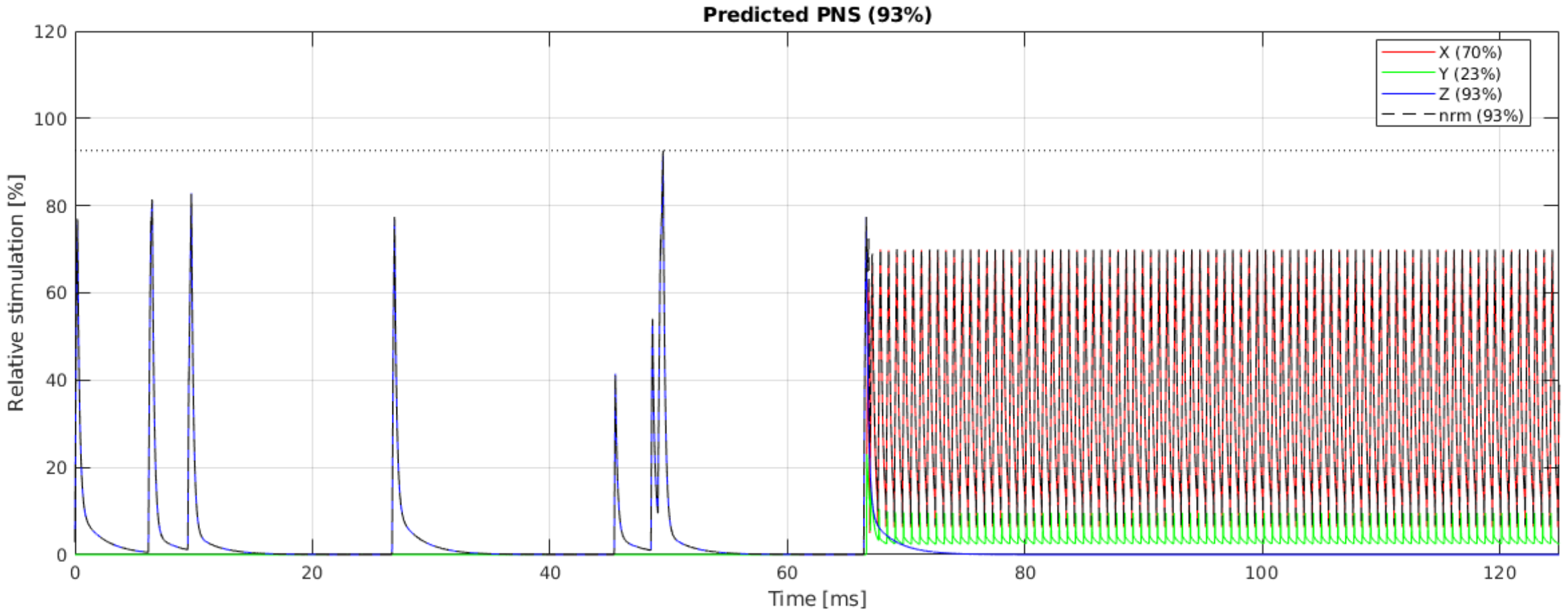
Example: DW-EPI

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



PNS Stimulation: DW-EPI

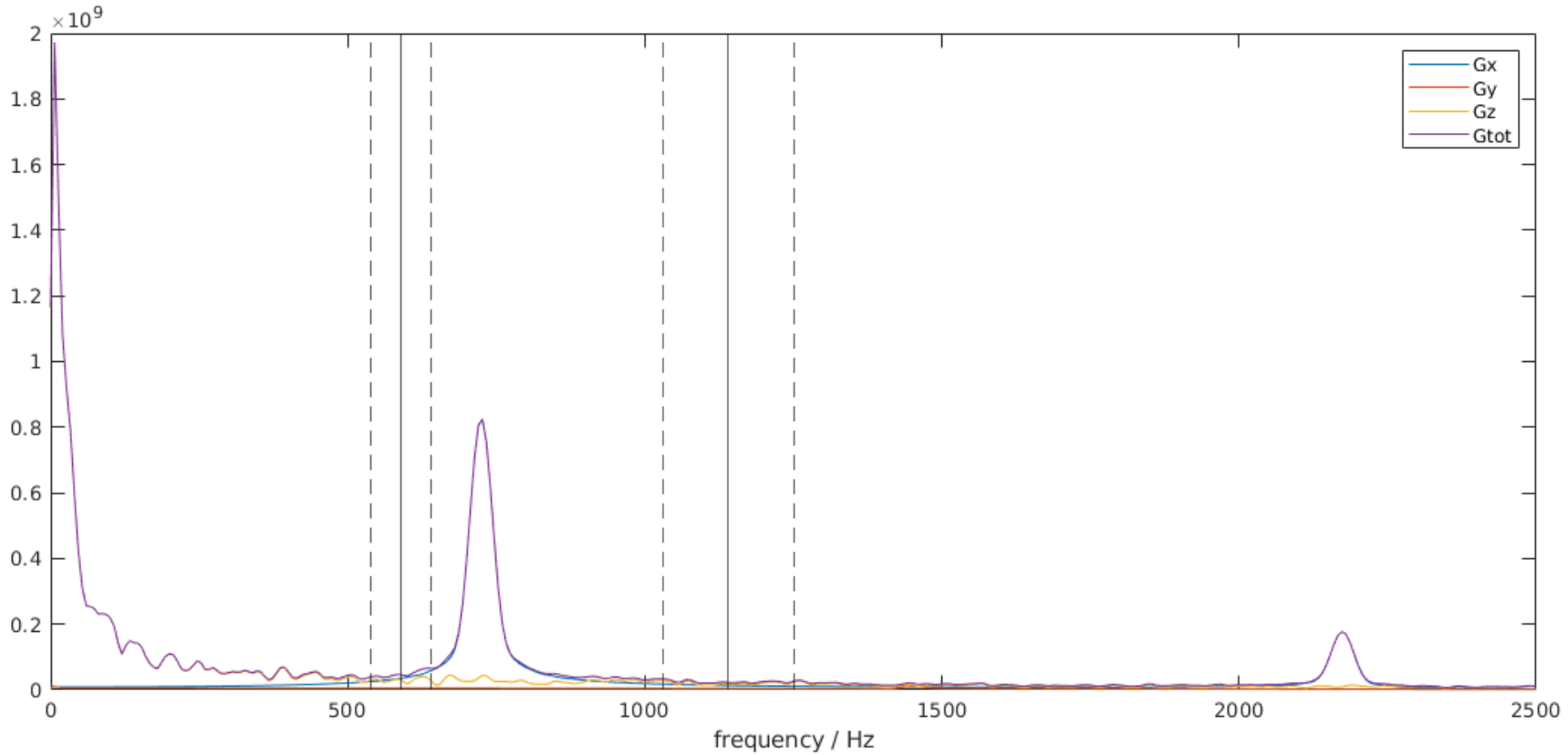
seq.calcPNS('idea/asc/MP_GPA_K2309_2250V_951A_AS82.asc');



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

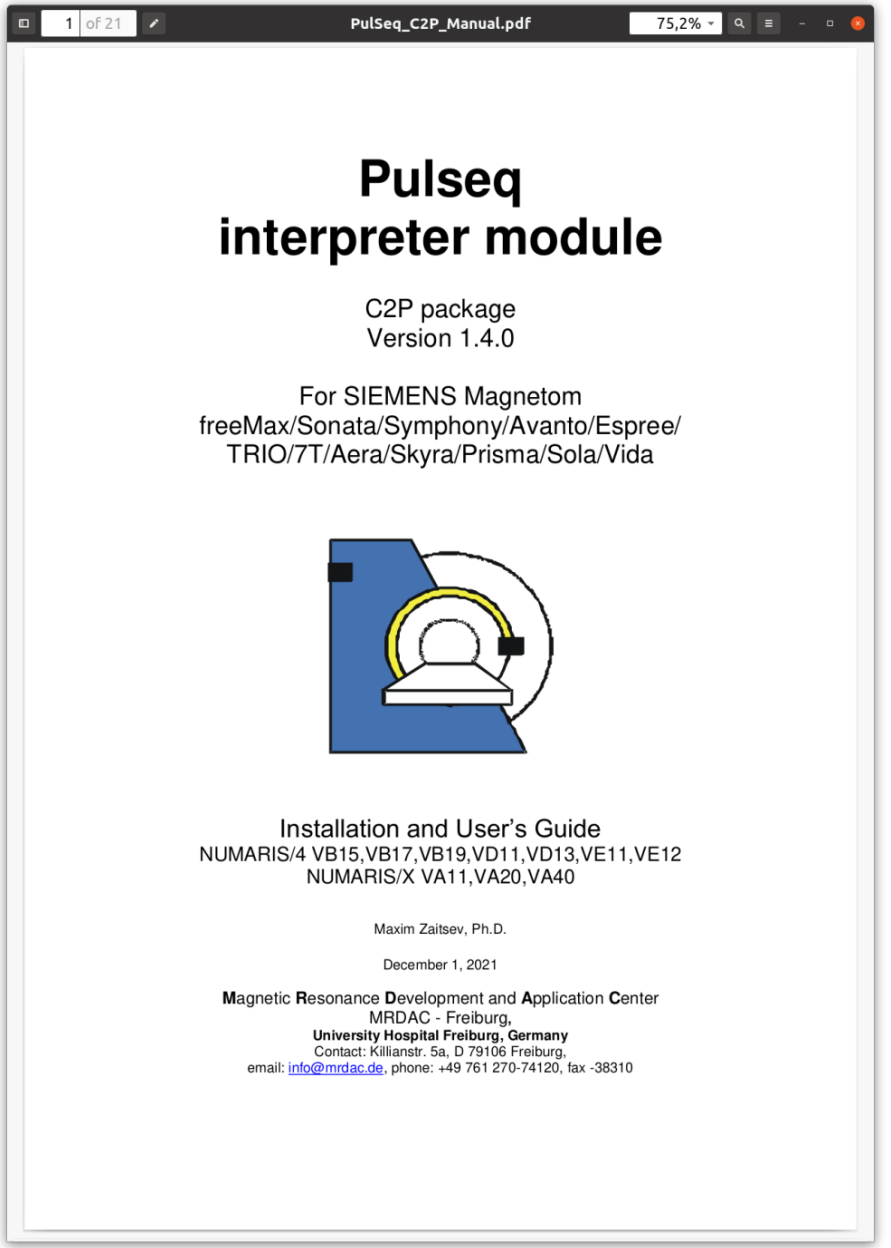


seq.sound(); % another option for acoustic assessment in Matlab ;-)

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

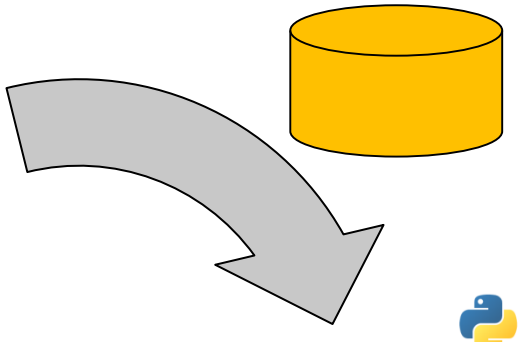
- Over 100 C2P sites
- *Pulseq* works well on:
  - All Numaris4 platforms (tested on vb15…ve12u) and numerous hardware platforms (Symphony, Trio, 7T, 3T Connectom, Skyra, Prisma,…)
  - All released NumarisX versions (xa11, xa20, xa30, xa40, xa5x, xa6x …)



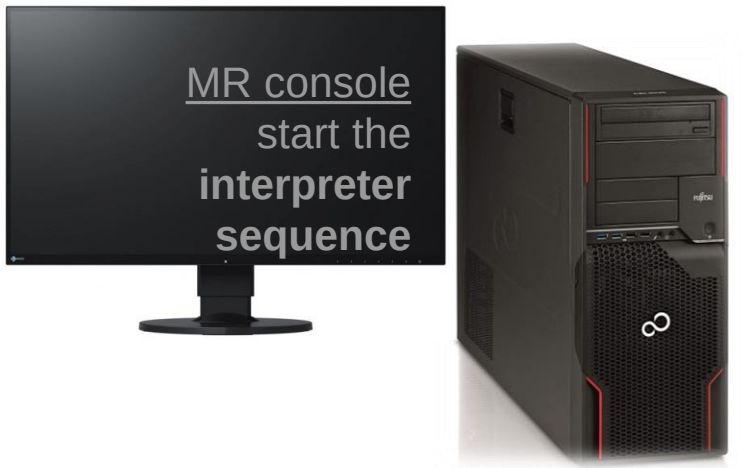


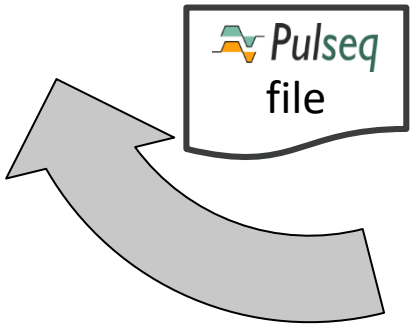
Pulseq on Siemens scanners

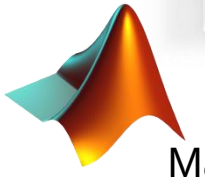
- *Optional initial step: connect your PC to the scanner*
- Save the .seq file on the scanner as external.seq
- Run the interpreter_sequence on the scanner
- *Optional step: stream raw data to your PC with NIH_DataCatcher*
- or export raw data manually



NIH Data Catcher





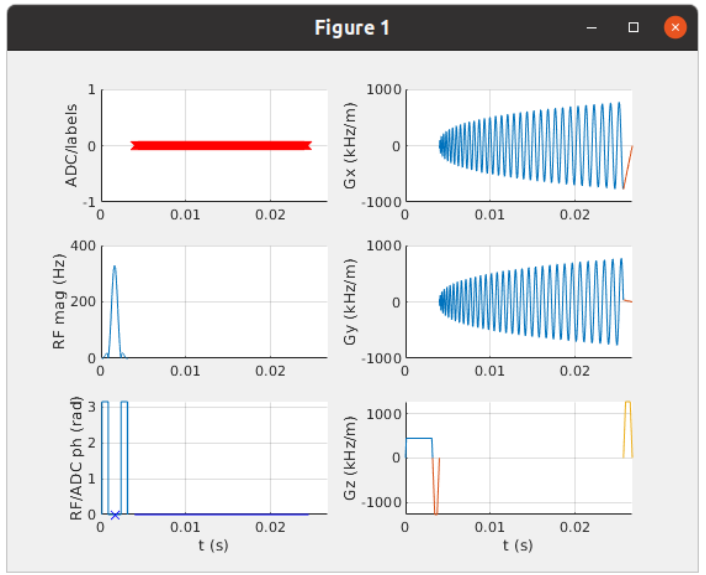


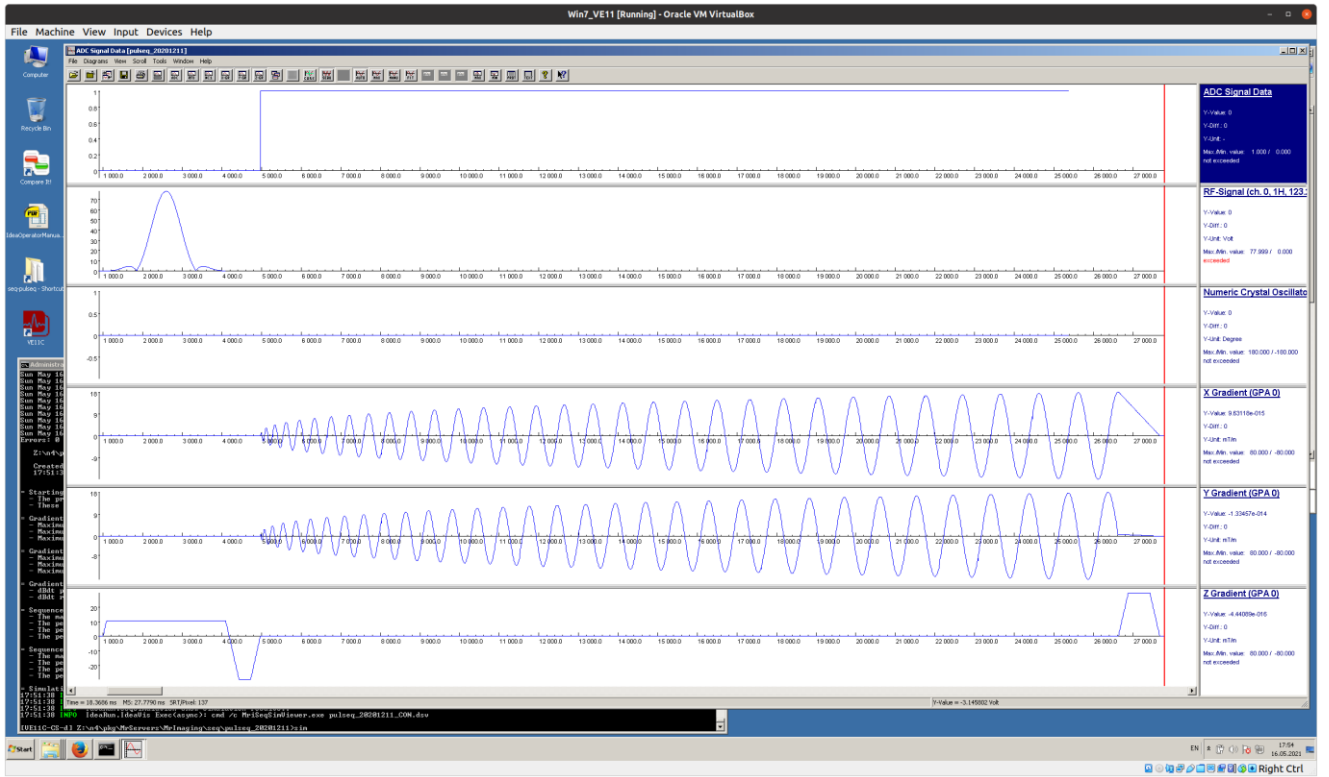
Matlab

IDEA simulation with *Pulseq*

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

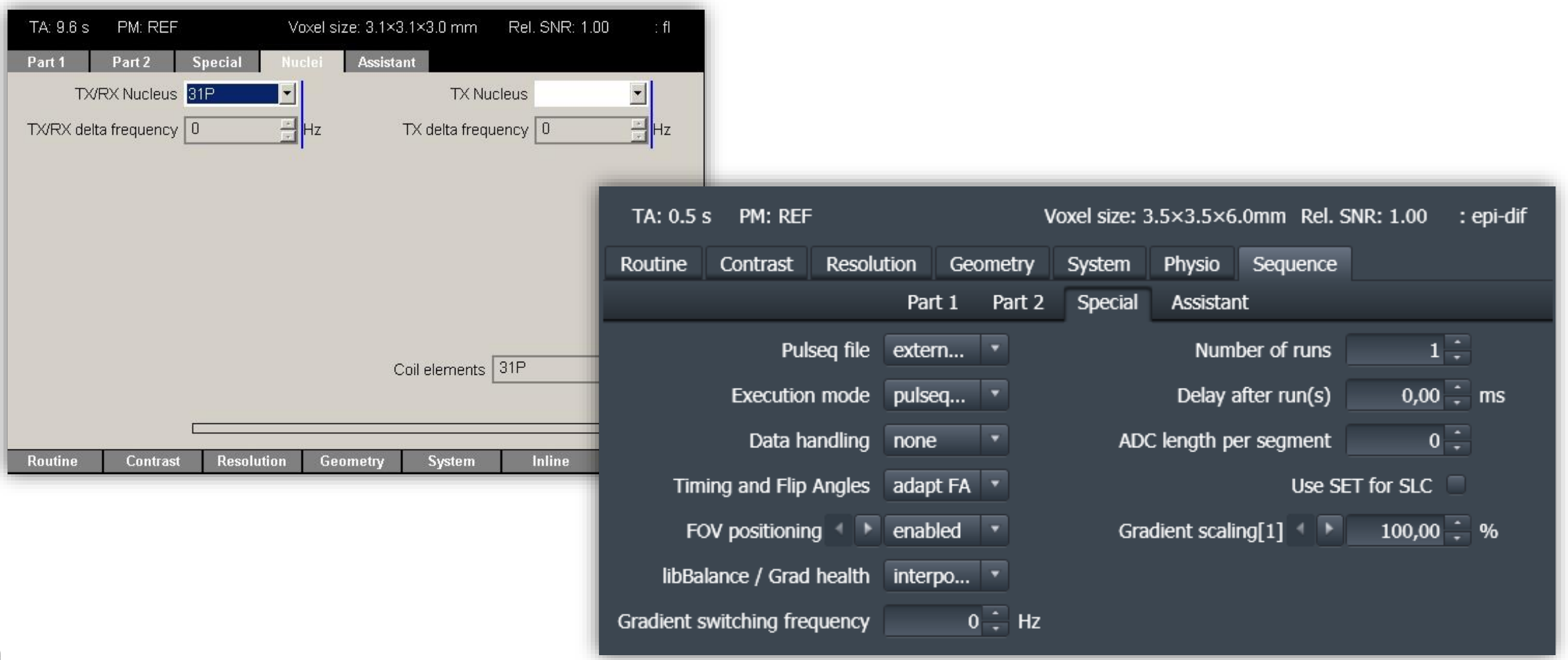
1. Save your .seq file as %CustomerSeq%/Pulseq/external.seq
2. In the IDEA command run **sim**





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

Qingping Chen @ ISMRM

- Offline reconstruction in Matlab & Python
  - Examples for 2D / 3D Cartesian reconstruction
  - Simple gridding reconstruction
  - Example of automated BART reconstuction
- All-in-one FIRE solution : Marten Veldmann et all, MRM 2022, doi:10.1002/mrm.29384

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

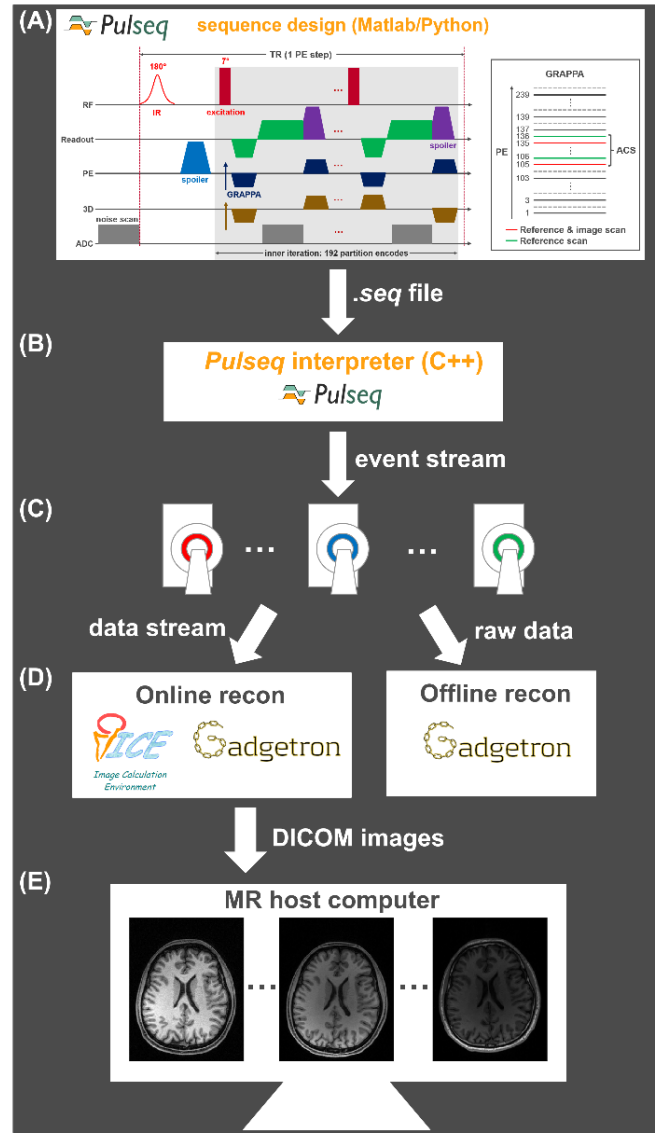
    ```
    mr.makeLabel('SET', 'LIN', 0)
    ```

  - Sequence definitions. E.g. 2D multi-slice mode:

    ```
    seq.setDefinition('SlicePositions', 0) ;
    seq.setDefinition('SliceThickness', sliceThickness) ;
    seq.setDefinition('SliceGap', sliceGap) ;
    ```

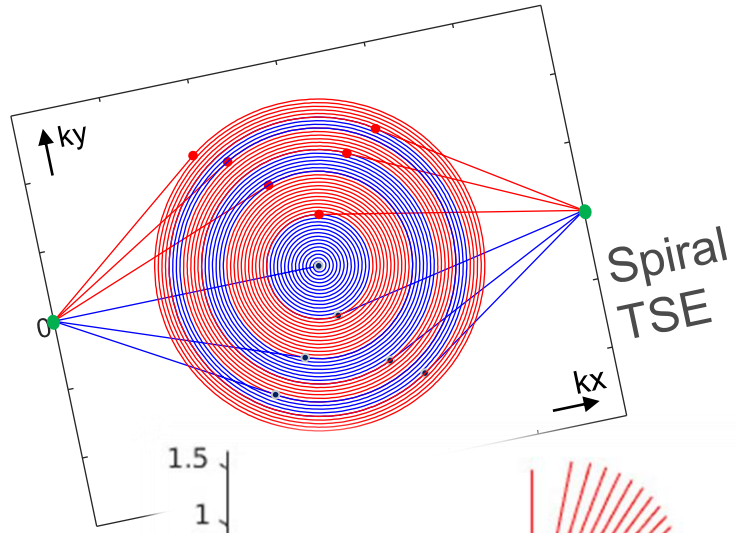
  - Interface setting. E.g:

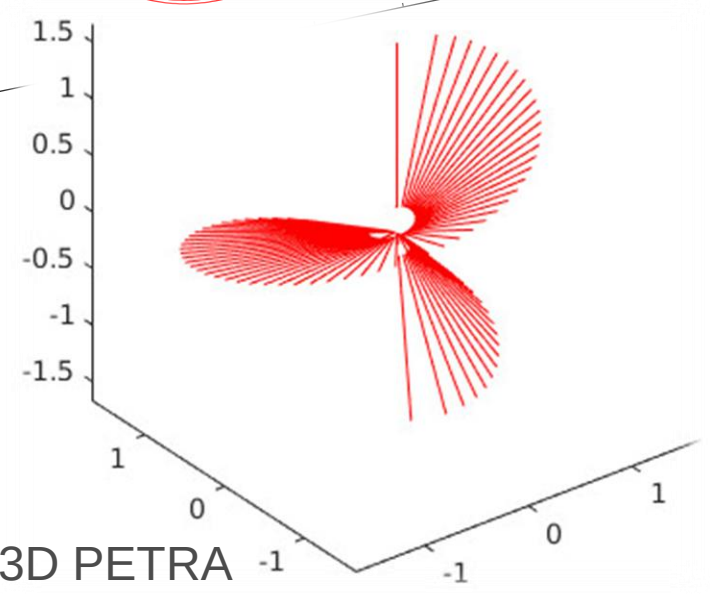
    Sequence->Special Card->Data handling ->ICE 2D



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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Pulseq MATLAB

pypulseq Python

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