

Basics of Pulseq

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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

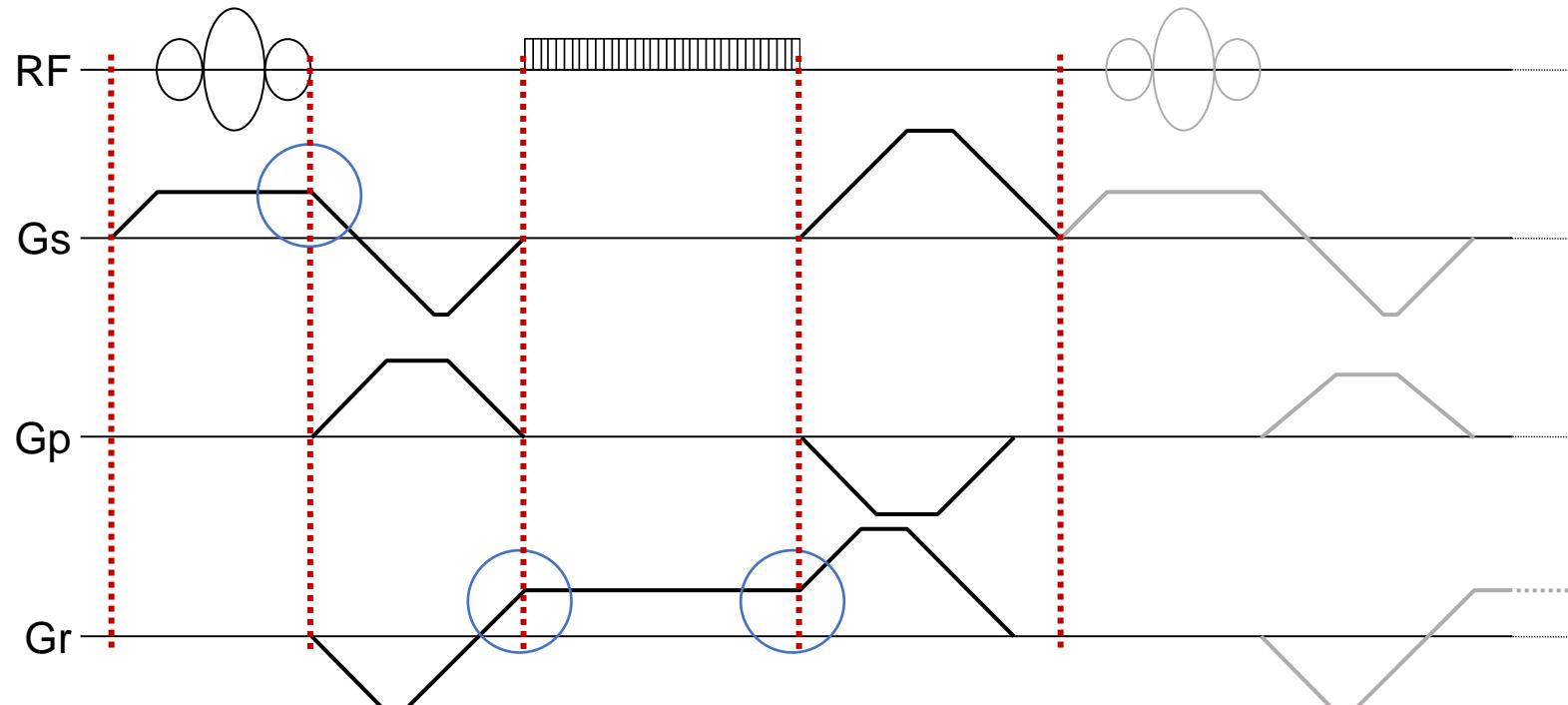
Pulseq ecosystem includes sequences, software to generate them and software and hardware to consume them

Pulseq Philosophy

- Minimize effort for implementation and support on hardware
 - Lean sequence-to-hardware interface
- Remove the initial threshold in sequence programming
 - Turn simple things really simple
- Make researcher-oriented features easily accessible
 - Arbitrary gradients, arbitrary RF, flexible reordering, 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!**



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



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...



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 (Jon-Fredrik Nielsen will talk about it today)
 - 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);

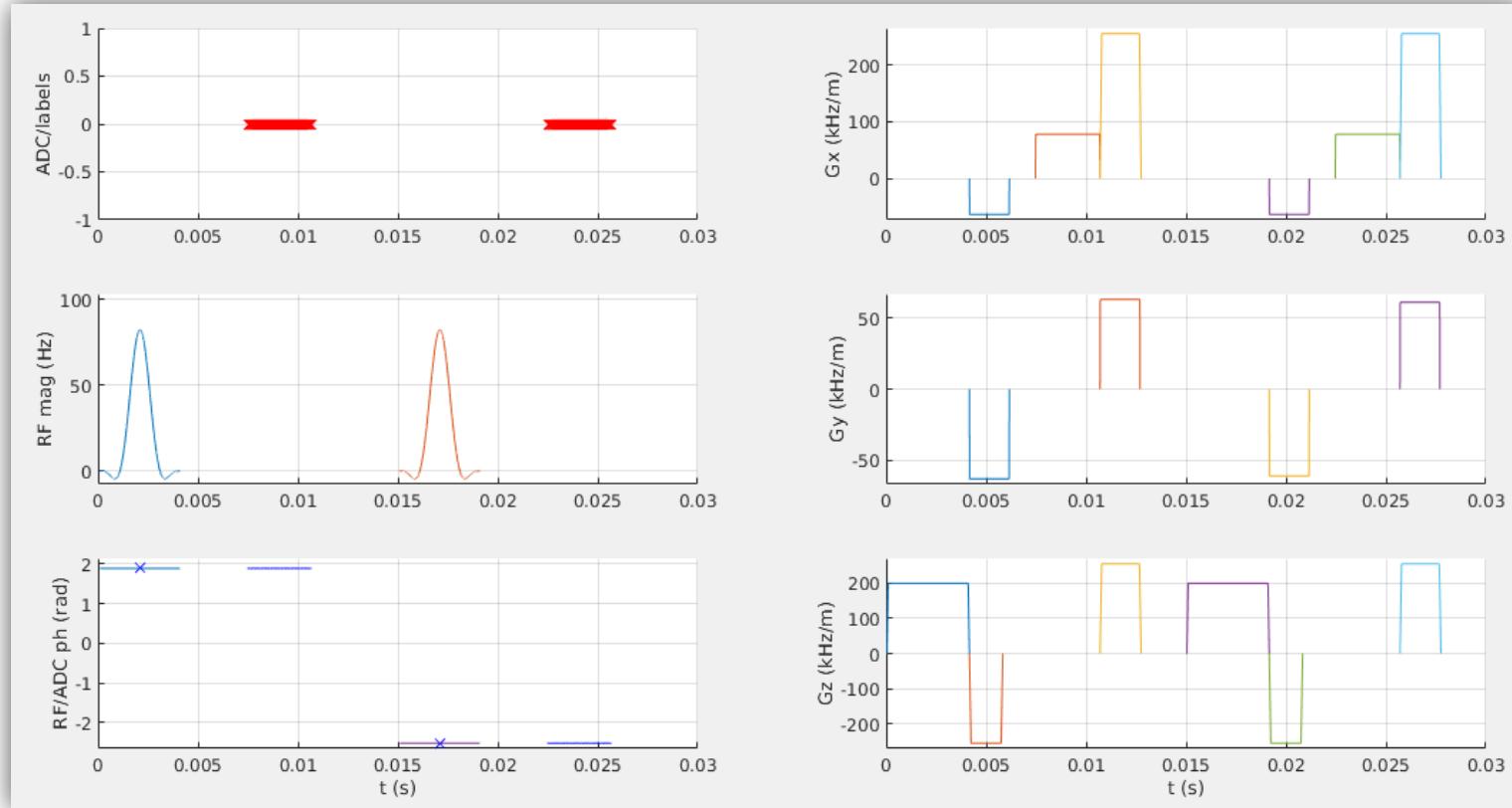
for i=1:Ny
    seq.addBlock(rf,gz);
    gyPre = mr.makeTrapezoid('y',system,'Area',phaseAreas(i),...
        'Duration',2e-3);
    seq.addBlock(gxPre,gyPre,gzReph);
    seq.addBlock(delay1);
    seq.addBlock(gx,adc);
    seq.addBlock(delay2)
end

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

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

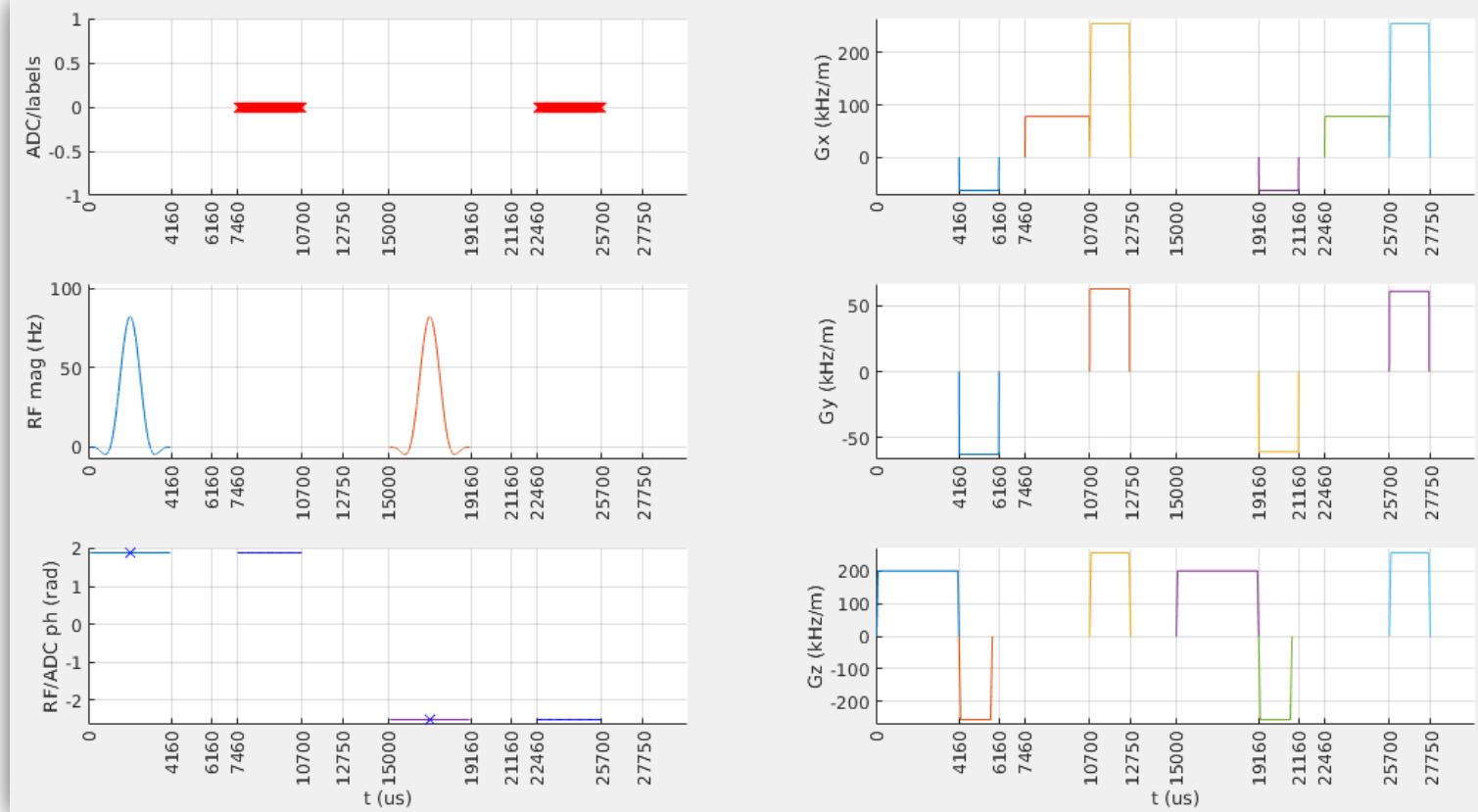
- Define the system properties
- Define high-level parameters (convenience)
- Define pulses and ADC objects used in the sequence
- Calculate the delays and reordering tables
- Loop and define sequence blocks
 - Duration of each block is defined by the duration of the longest event
 - *Copy ‘*.seq’ to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

Basic sequence display options



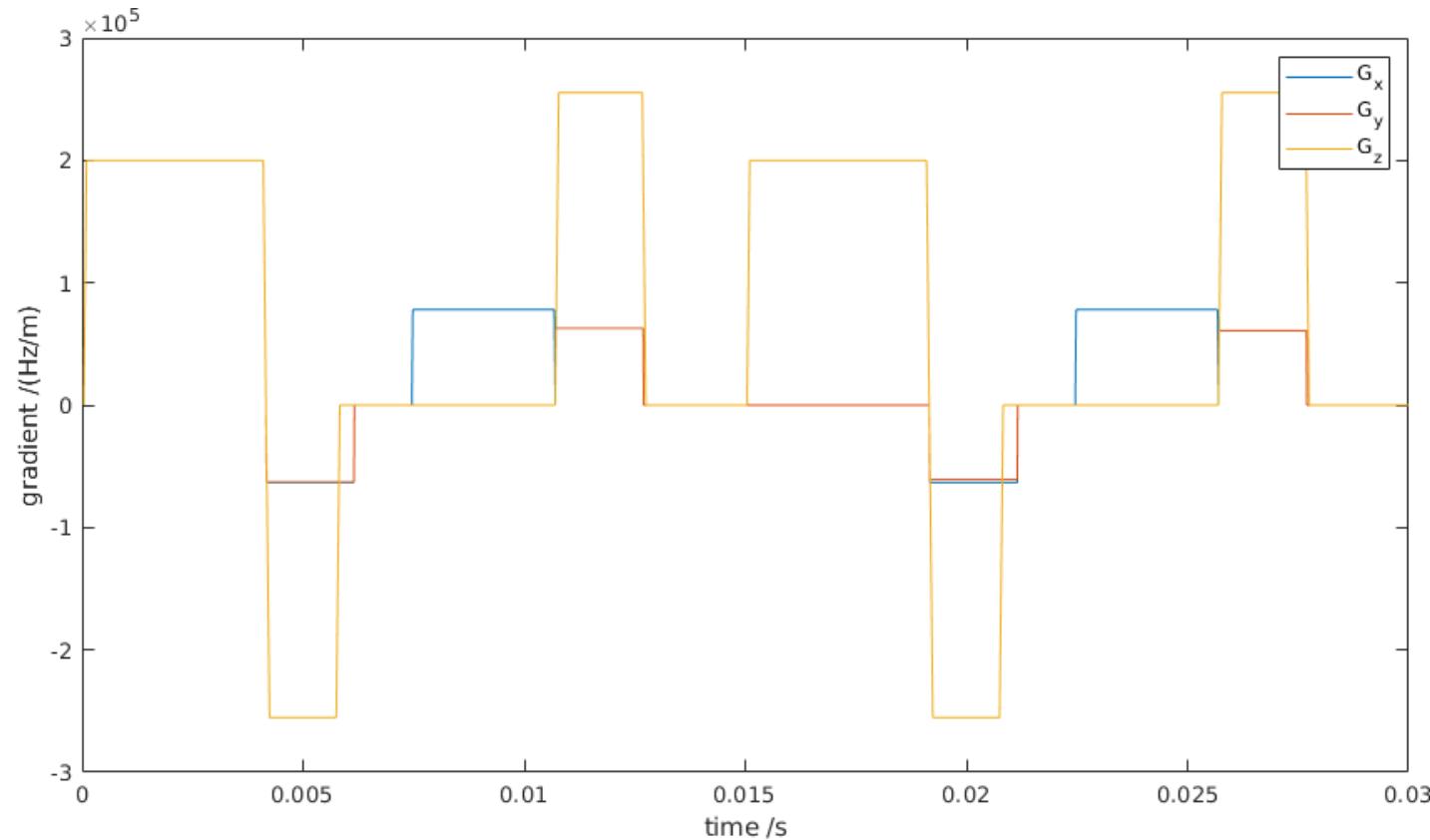
- Pulseq 6-panel plot: seq.plot()
 - ADC, RF magnitude, RF phase, Gx, Gy, Gz
 - Each event plotted in its own color

Display block structure



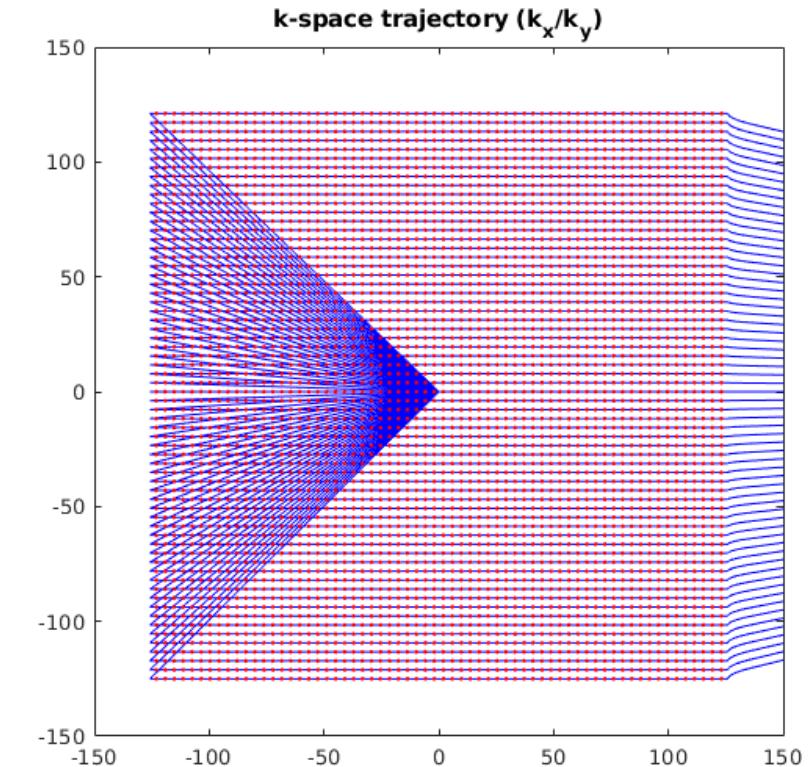
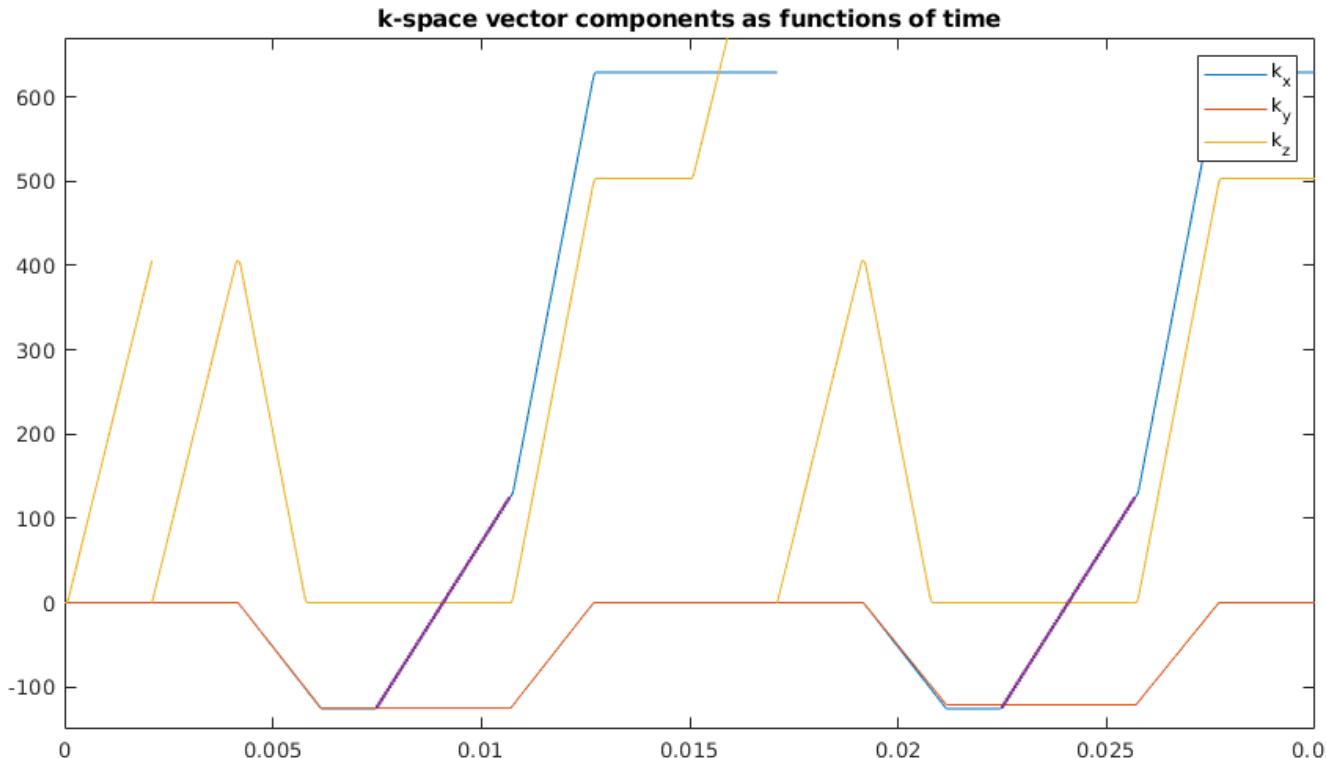
- To visualize block structure:
 - `seq.plot('showBlocks',true,'timeDisp','us');`

Plot gradient waveforms



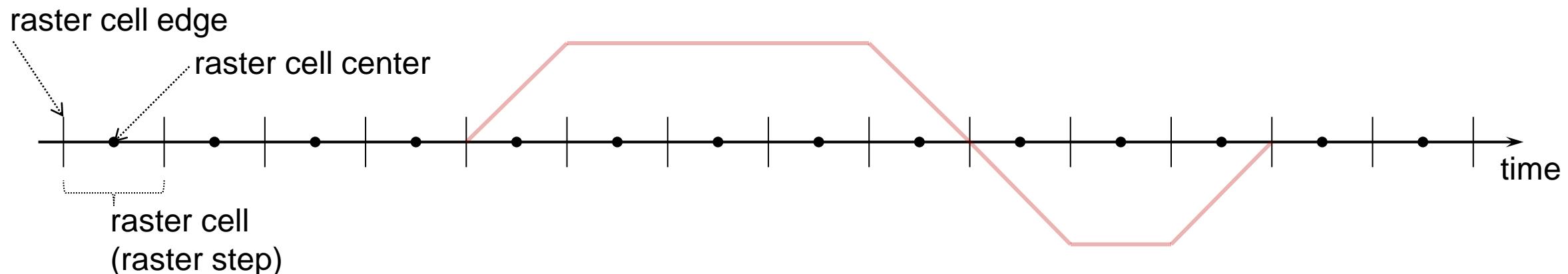
- Plot entire waveforms for all axes
 - Native gradient unit in *Pulseq*: Hz/m

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}

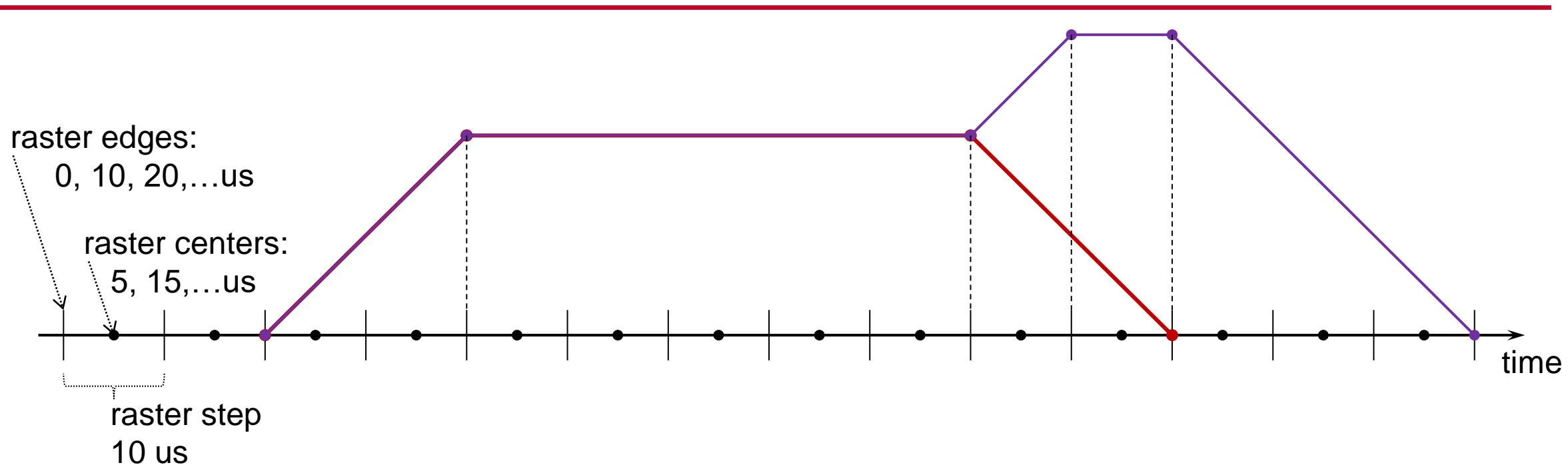
Shapes and Raster Times *Pulseq*



- 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

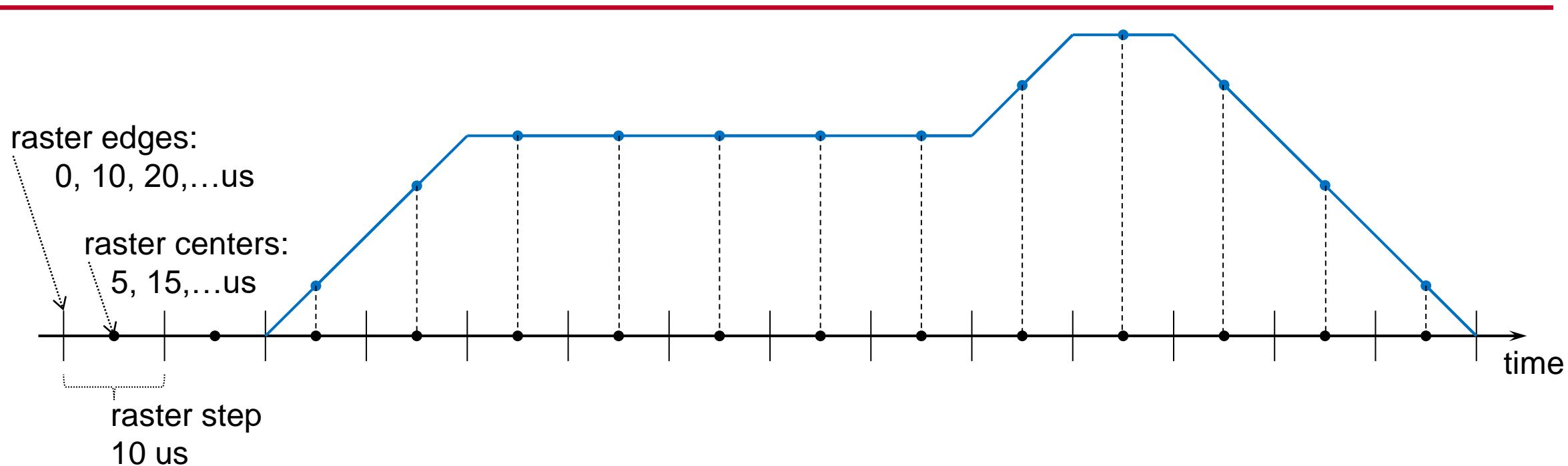


Gradient Raster and Shapes



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

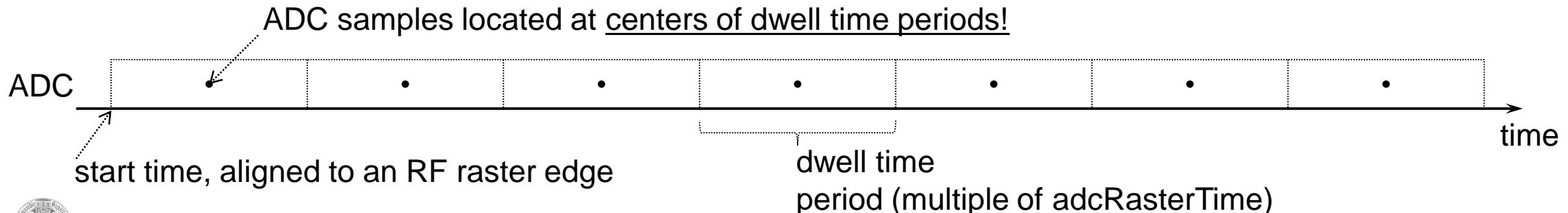
Gradient Raster and Shapes



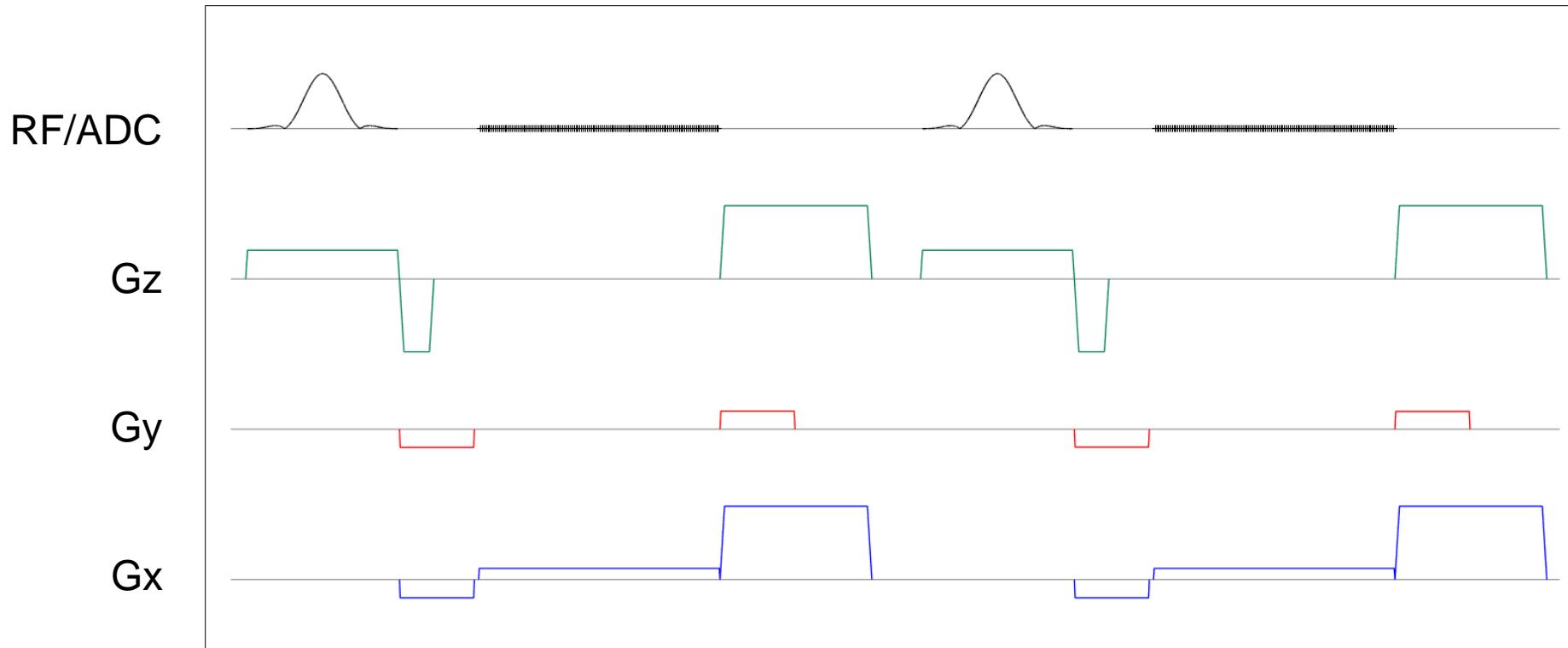
- Gradient raster (10 us on Siemens)
 - Trapezoid and extended trapezoids: nodes on raster edges
 - Sampled (arbitrary) gradients: samples on raster centers

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)



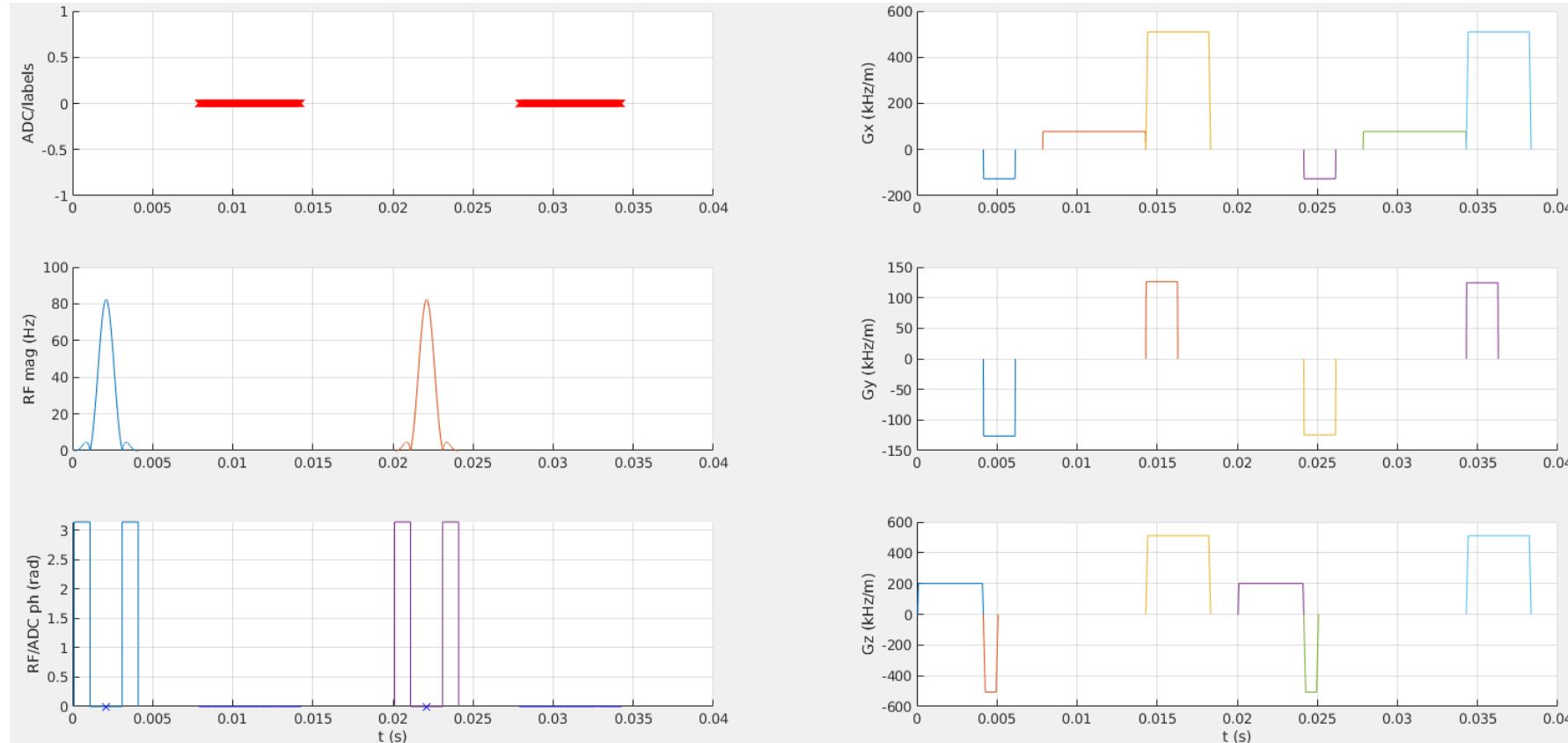
Example 1: simple gradient echo



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

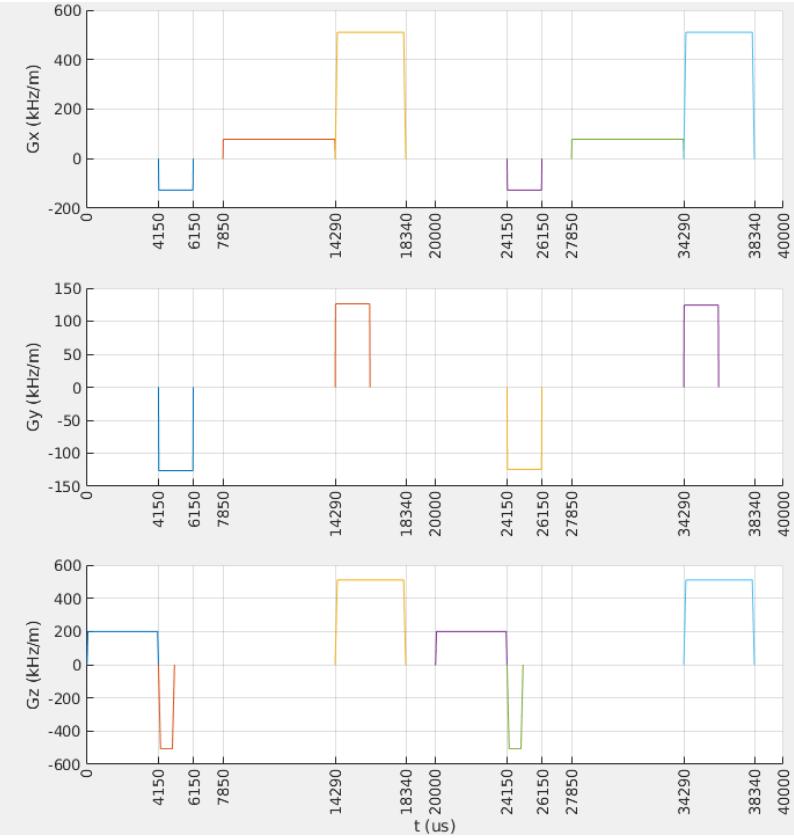
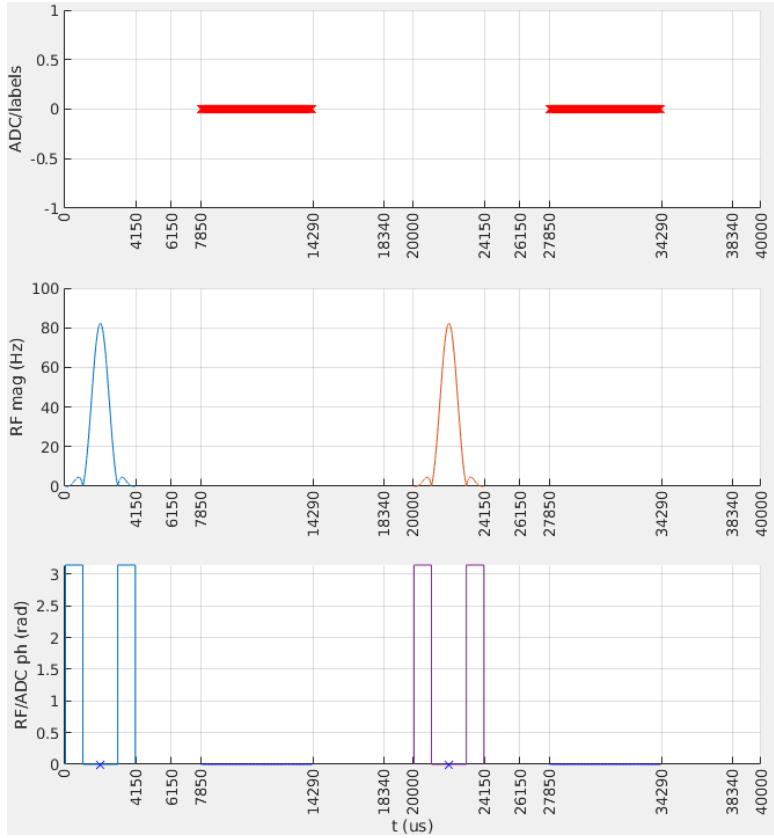


Example 1 ctnd.: simple gradient echo



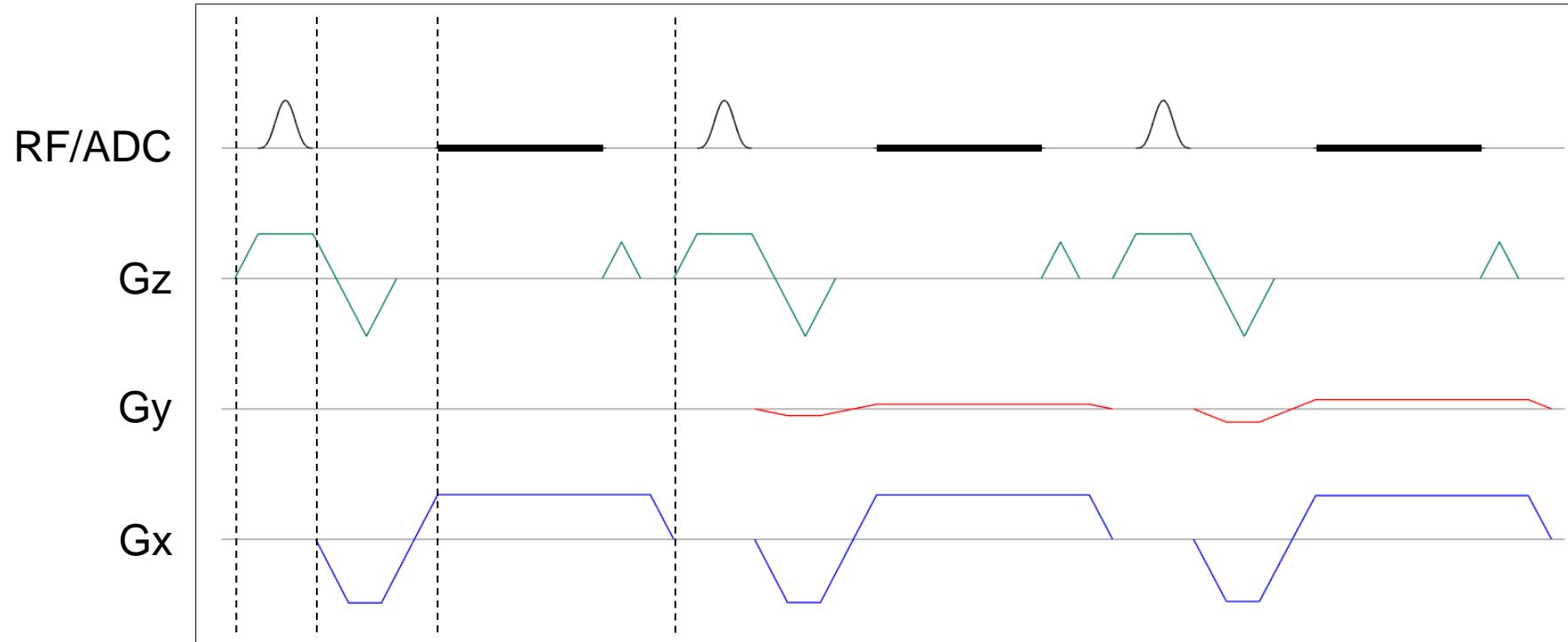
- Advantageous to separate PE & PR gradients into different blocks

Simple gradient echo – block structure



- It is possible to visualize the block structure
 - `seq.plot('showBlocks',true,'timeDisp','us');`

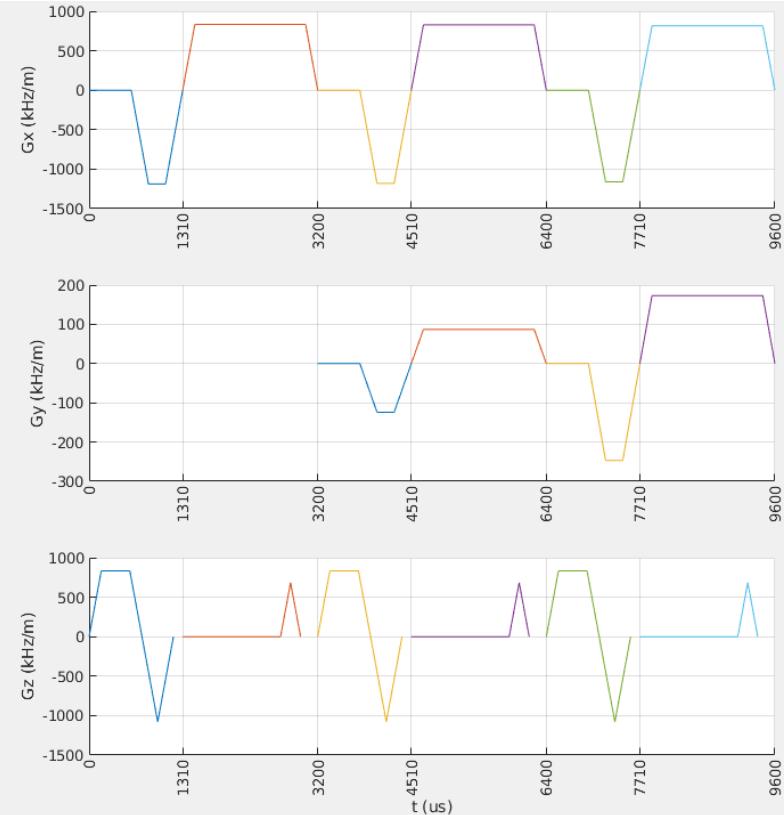
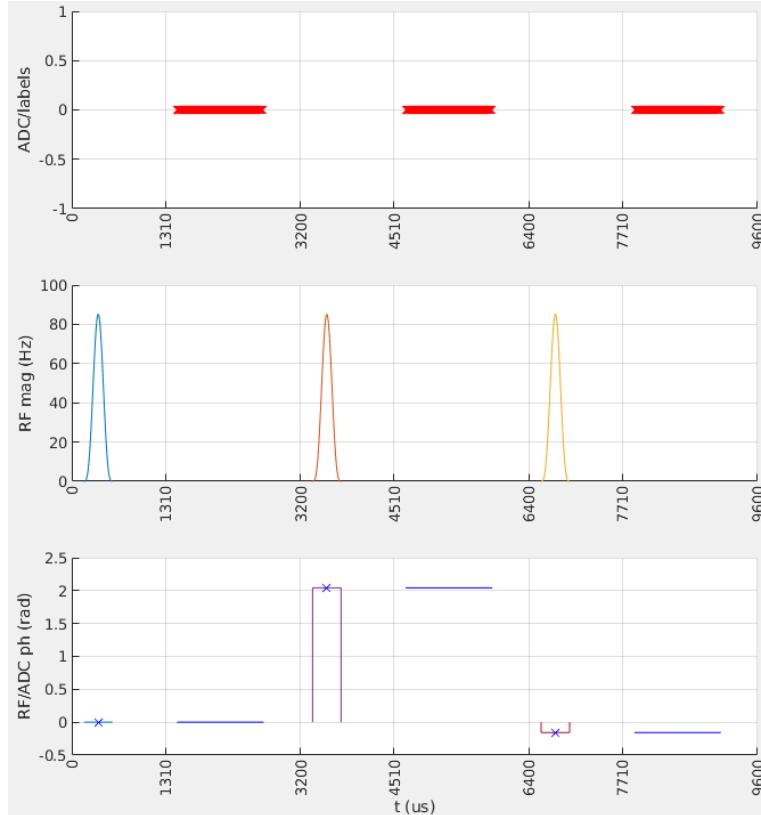
Example 2: fast radial gradient echo



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

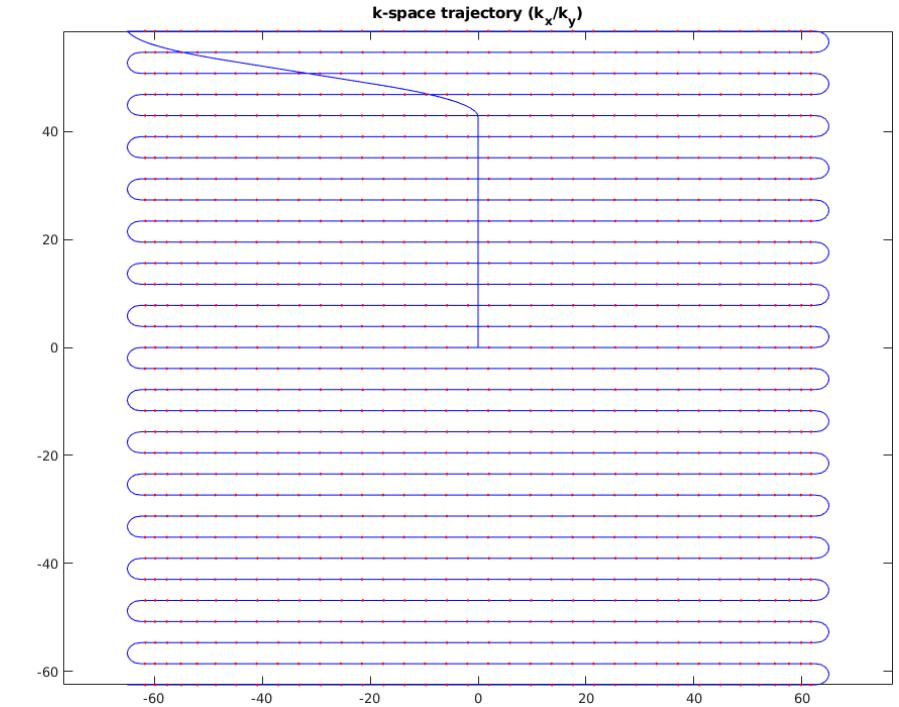
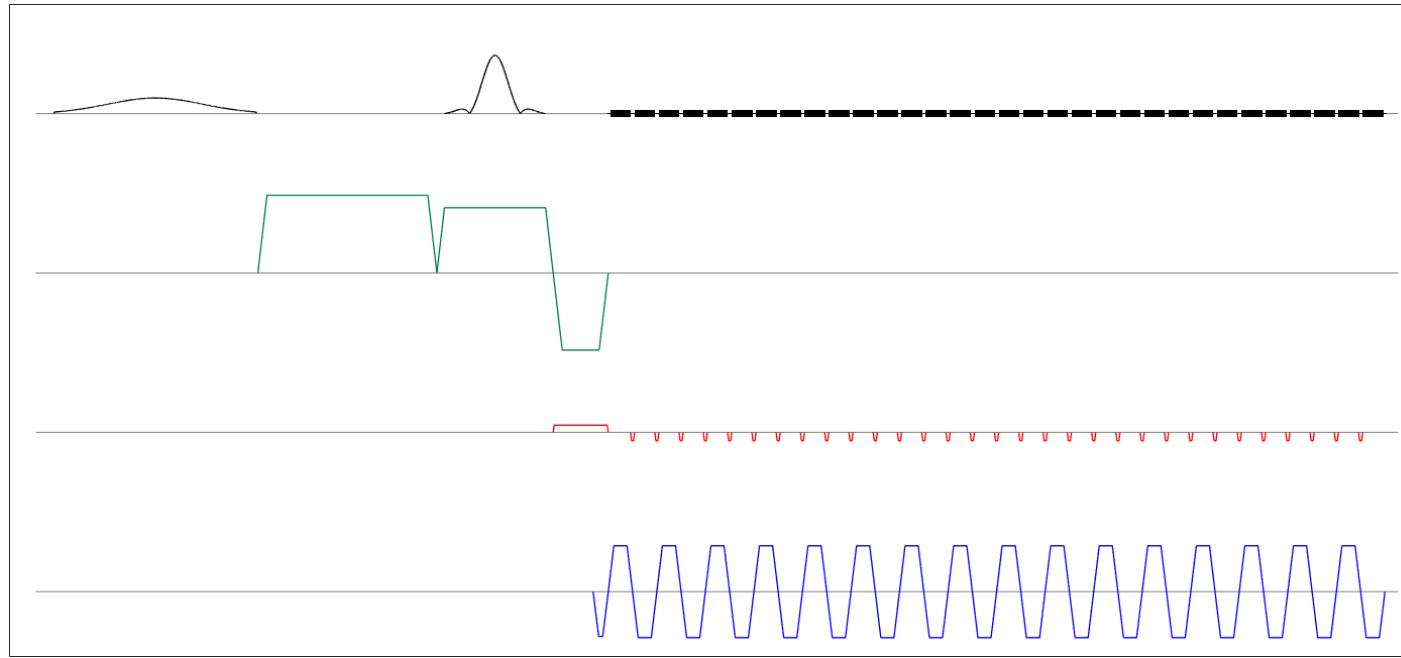


Fast radial gradient echo block structure



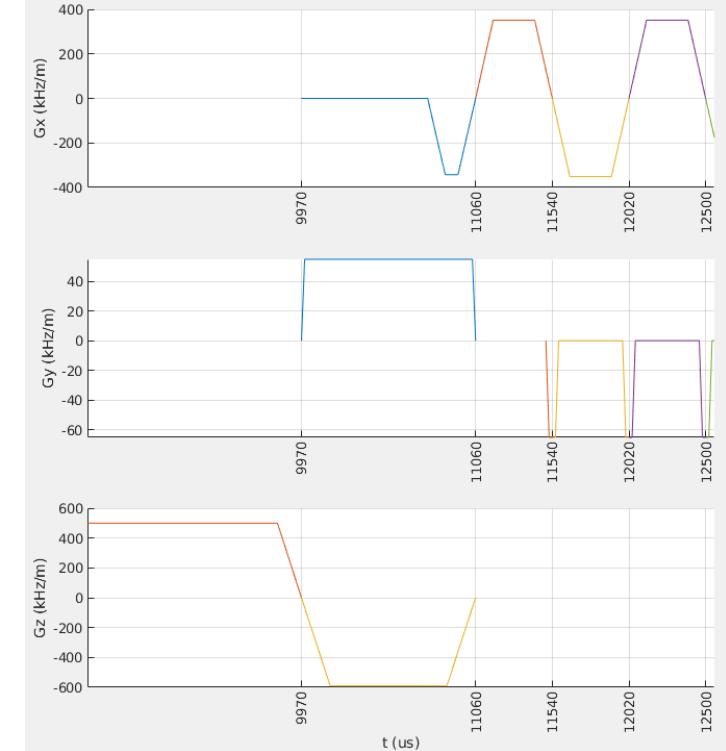
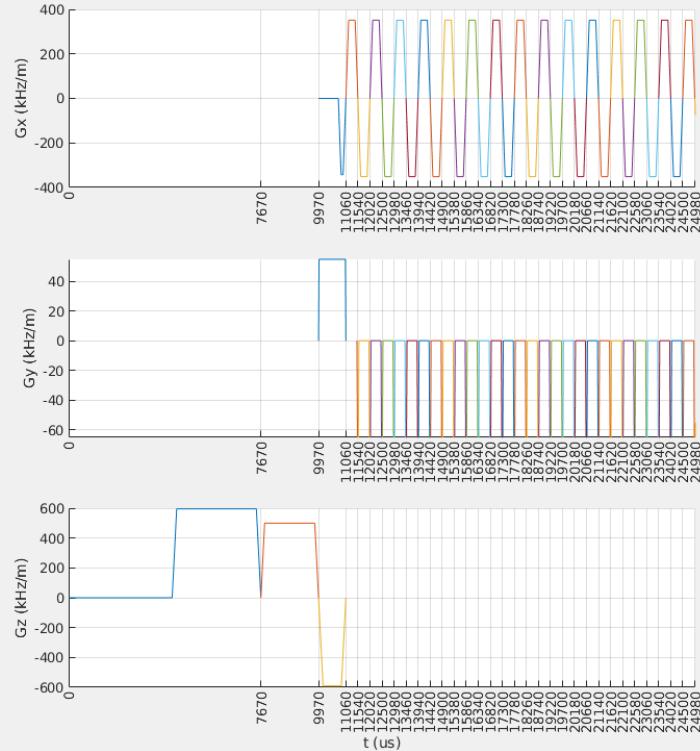
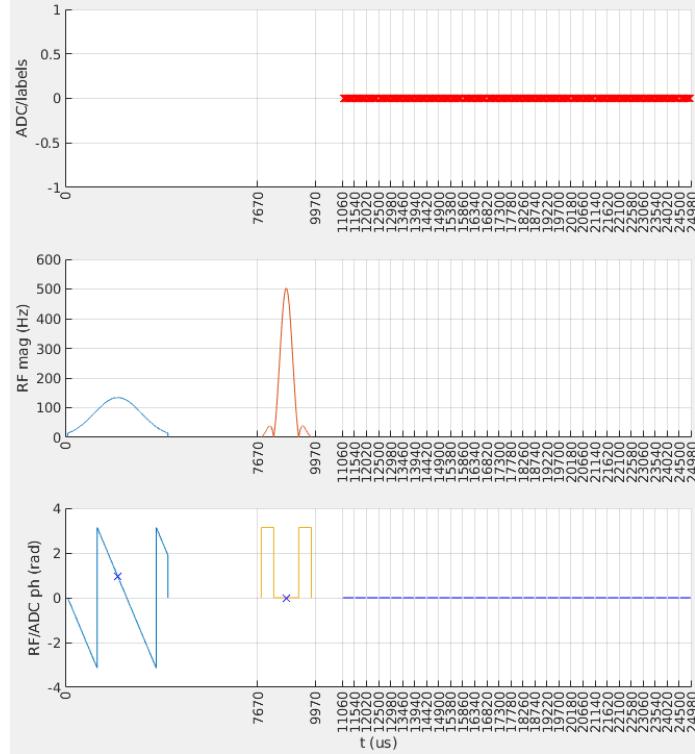
- This is one of many possible solutions
 - Many options work, but your Pulseq file size may vary

Example 3: echo planar imaging (EPI)



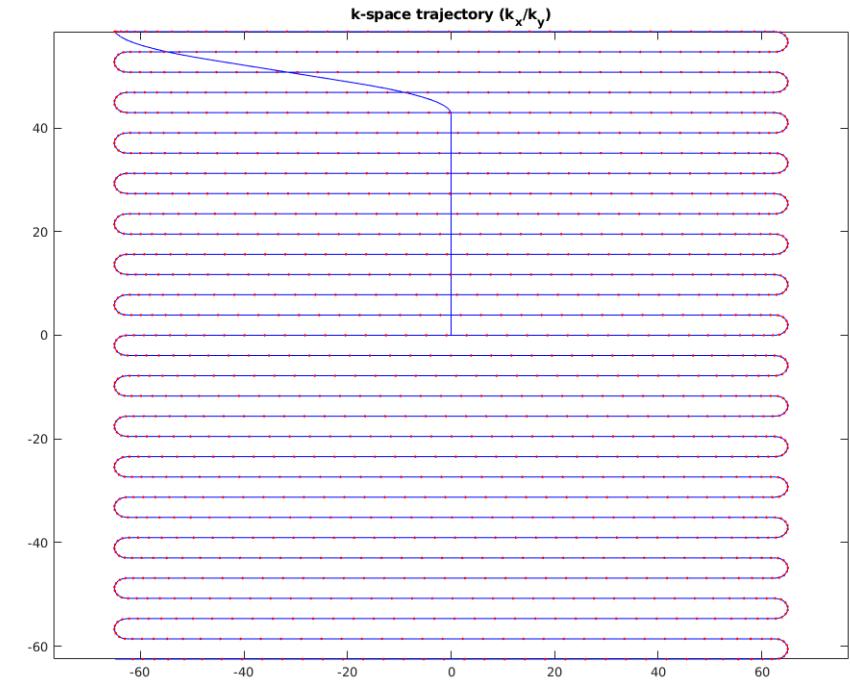
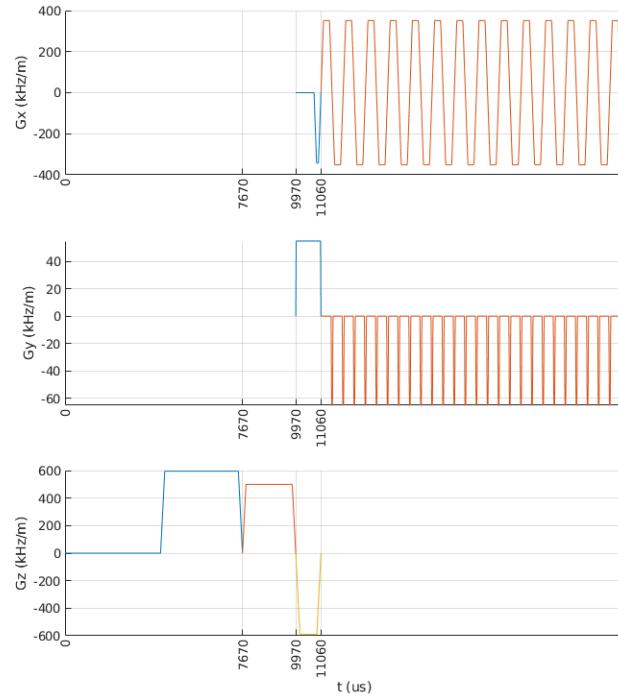
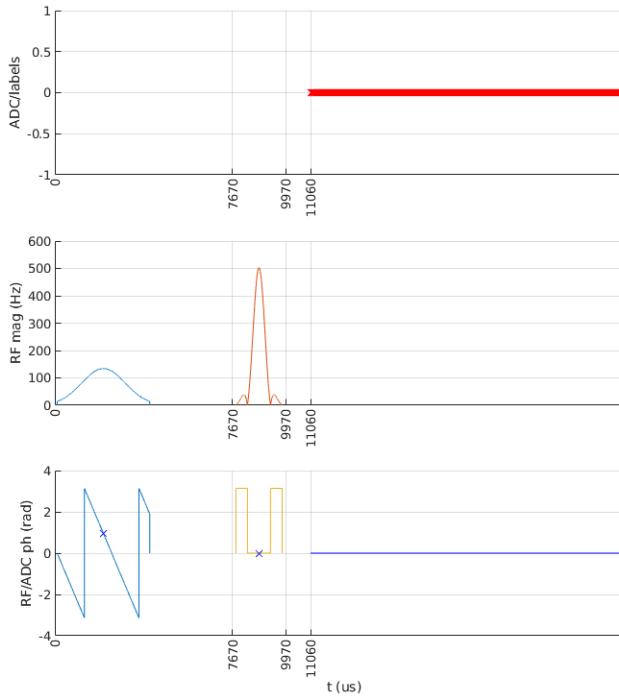
- Two RF pulses need to be in separate blocks
- Each ADC event needs to be in a separate block
 - Challenge with blips, readout ramp and optimal sampling window

EPI block structure



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

Alternative EPI block structure



- Put the entire readout into one block
 - G_x and G_y are now both shaped gradients
 - ADC is sampling continuously (need to crop some points in the recon)

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...
 - You will hear more about this in the next talks
- **Blocks make it easier for the interpreter to play things out**



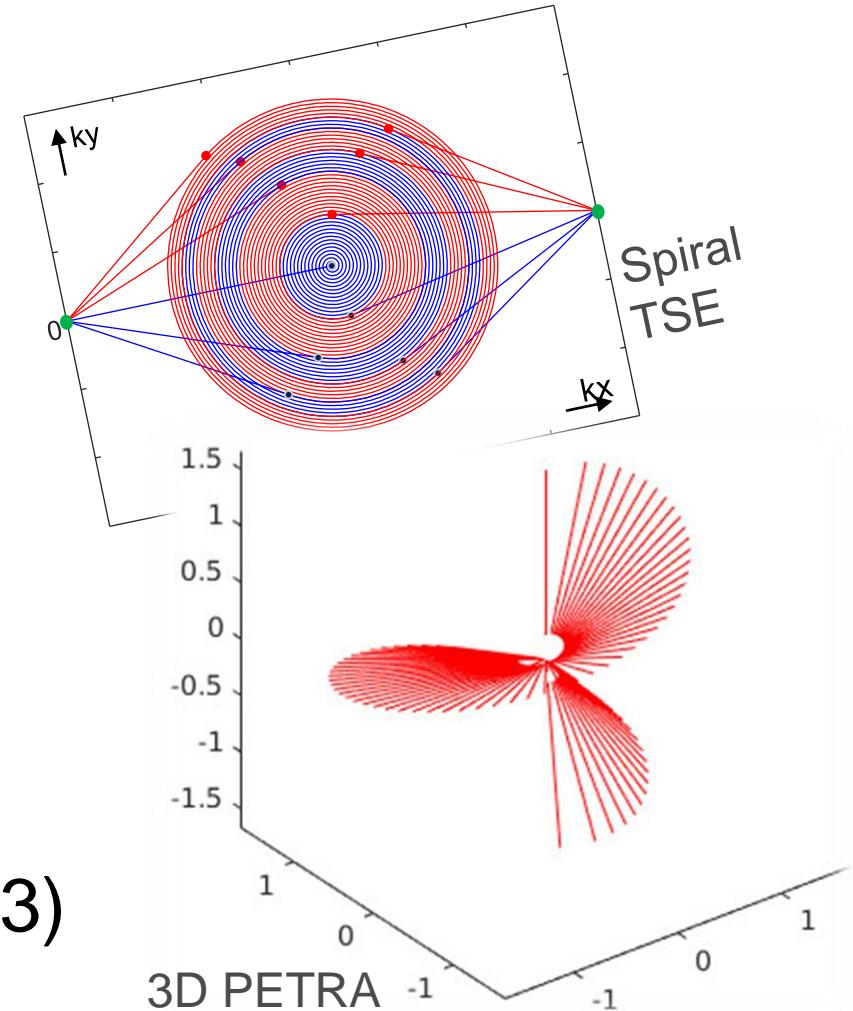
Pulseq objects & blocks

- *Pulseq* objects ‘live’ inside *Pulseq* blocks
 - Gradient & RF pulses
 - ADC objects
 - Delays (dummy objects)
 - Extension objects
 - (data labels, cardiac trigger directives, trigger pulses)
- More in the next presentation by:
Jon-Fredrik Nielsen “Working with Pulseq objects”
- How to assemble sequences from blocks and objects?
Qingping Chen “Tutorials of some basic sequences”



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 : stay with us till Day 3
- Upcoming New release v1.4.2 (Dec 2023)





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