From 50mT to 7T: *Pulseq* Live
Across Hardware Platforms and Field Strengths

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Pulseq

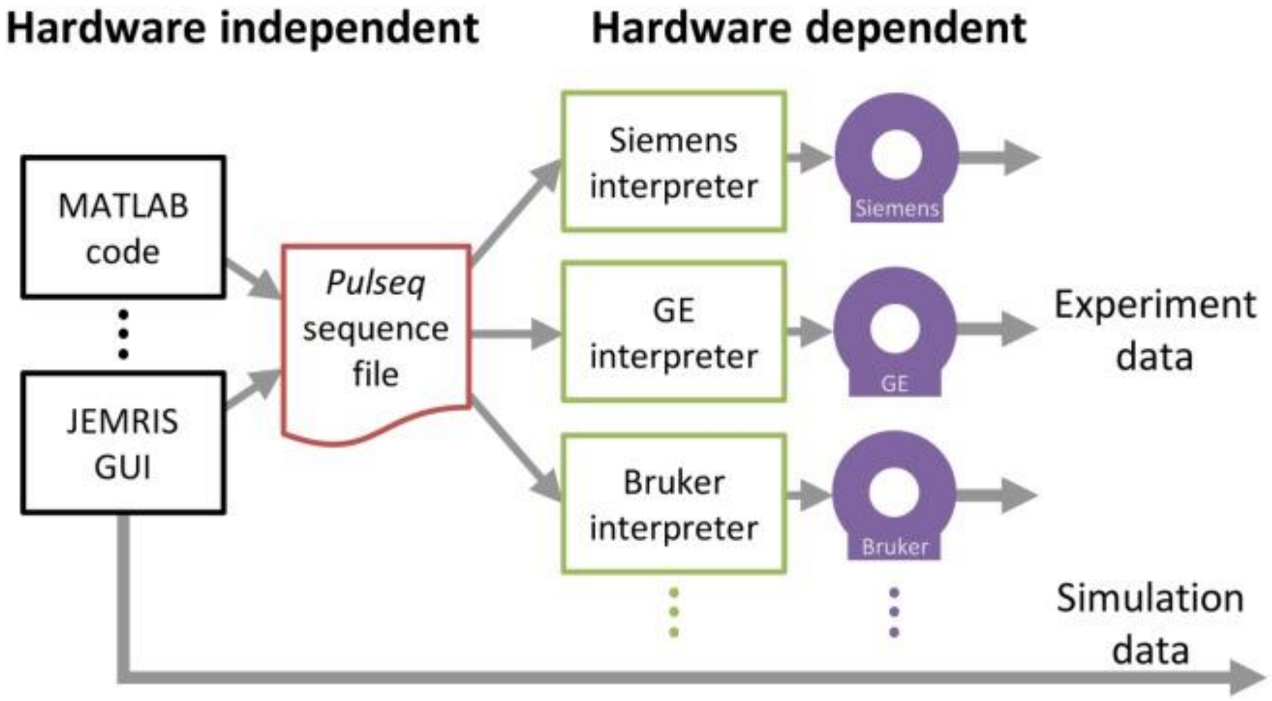
http://pulseq.github.io

Outline

- ***Pulseq*** sequence definition and programming language overview
- Using ***Pulseq*** on different types of scanners:
  - Siemens, GE, and tabletop scanners using OCRA
- Live demo of ***Pulseq*** across sites
  1. Basic pulse-acquire scans: Free Induction Decay (FID), Spin-Echo (SE)
  2. Cartesian spin-echo imaging
  3. Radial imaging (spin-echo and gradient echo)
  4. Advanced topics (gradient delays and correction, etc…)

Pulseq sequence programming

- Cross-platform pulse programming framework for MRI
- Low level: *Pulseq* file
- High level: MATLAB[1] or Python[2] toolboxes



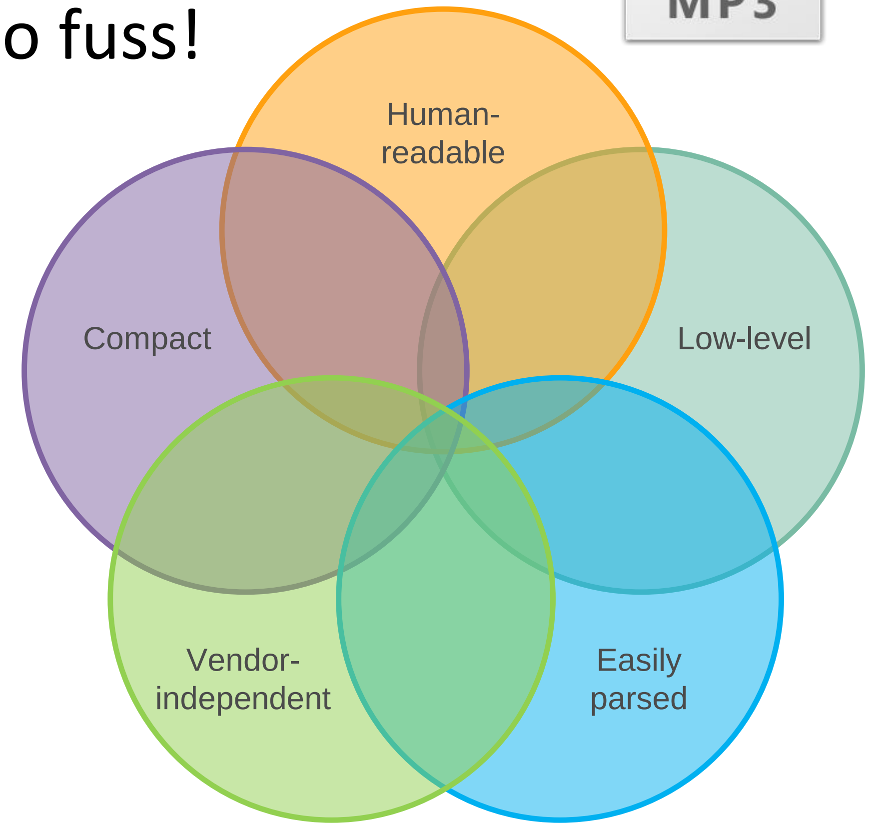
Source: Layton, et al., "Pulseq: A rapid and hardware-independent pulse sequence prototyping framework", MRM 2017

1. http://pulseq.github.io
2. http://github.com/imr-framework/pypulseq

Pulseq file

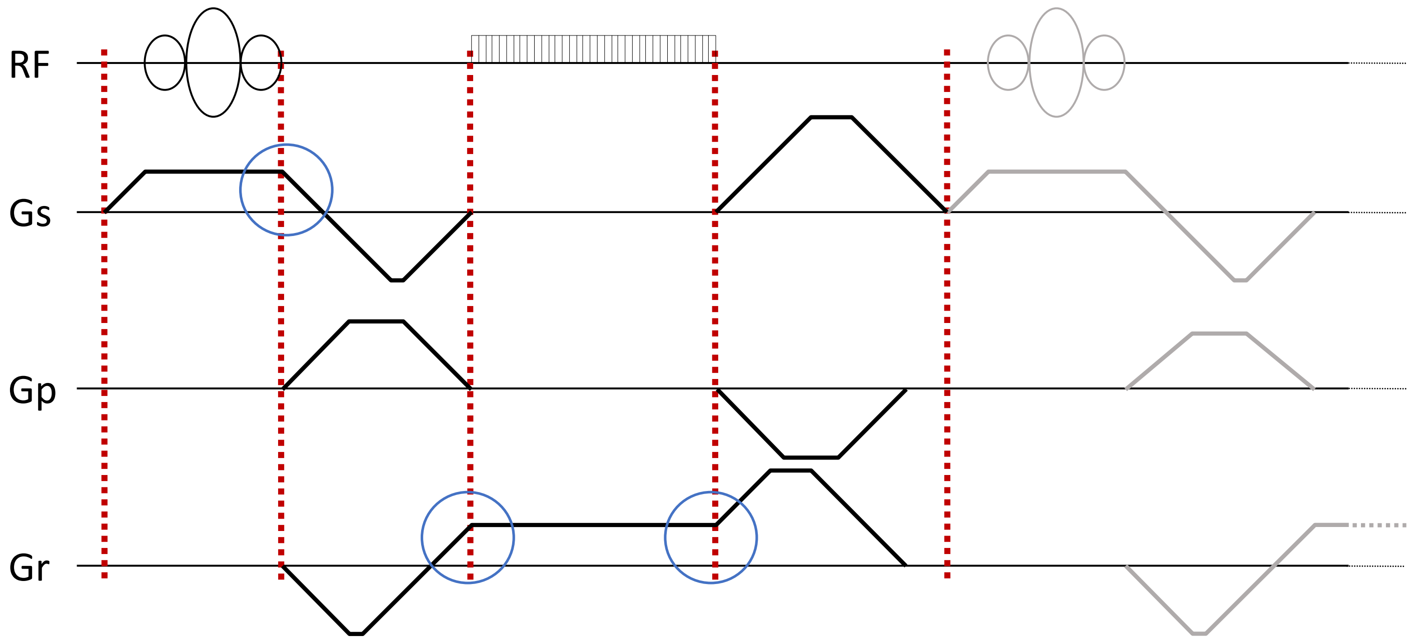
- Explicit (low level) specification of the pulse sequence
  - Think of an MP3 file (or more precisely lossless FLAC)
- No loops, no parameters, no dependencies, no fuss!

- 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



Pulse sequence definition

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 (advanced feature available on some hardware platforms)

High-level programming environments

- Matlab *Pulseq* toolbox
- Python *pypulseq* toolbox

- Further options
  - Pulseq-GPI – a graphical sequence programming environment
  - 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
  - …

Pulseq

Matlab Pulseq workflow

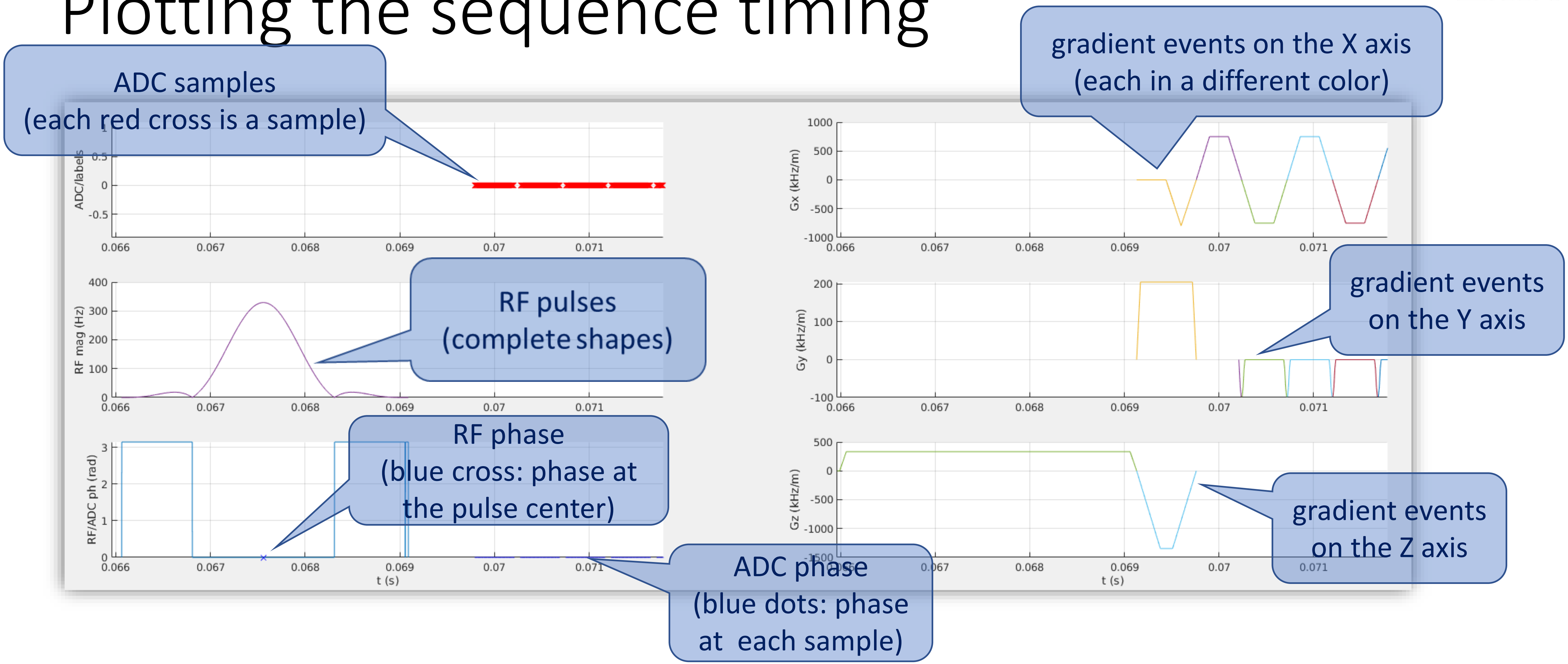
- Define the system properties
- Define high-level parameters (convenience)
- Define pulses used in the sequence
- Calculate the delays and reordering tables
- Loop and define sequence blocks
  - Duration of each block is defined by the duration of the longest event
- Copy ‘gre.seq’ to the scanner and run it!
- *Screenshot shows an entire runnable gradient echo sequence code (similar to Siemens’ example miniFlash)*

```matlab
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')
```

Development and debugging

- Visualize sequences with seq.plot()
- Verify raster alignment and system delays with seq.checkTiming()
- Check echo conditions and visualize k-spaces with seq.calculateKspace() and calculateKspacePP()
- Check details of gradient waveforms with seq.gradient_waveforms()
- Evaluate further details (TE,TR, slew rate, etc…) with seq.testReport()
- Listen to seq.sound()

Plotting the sequence timing

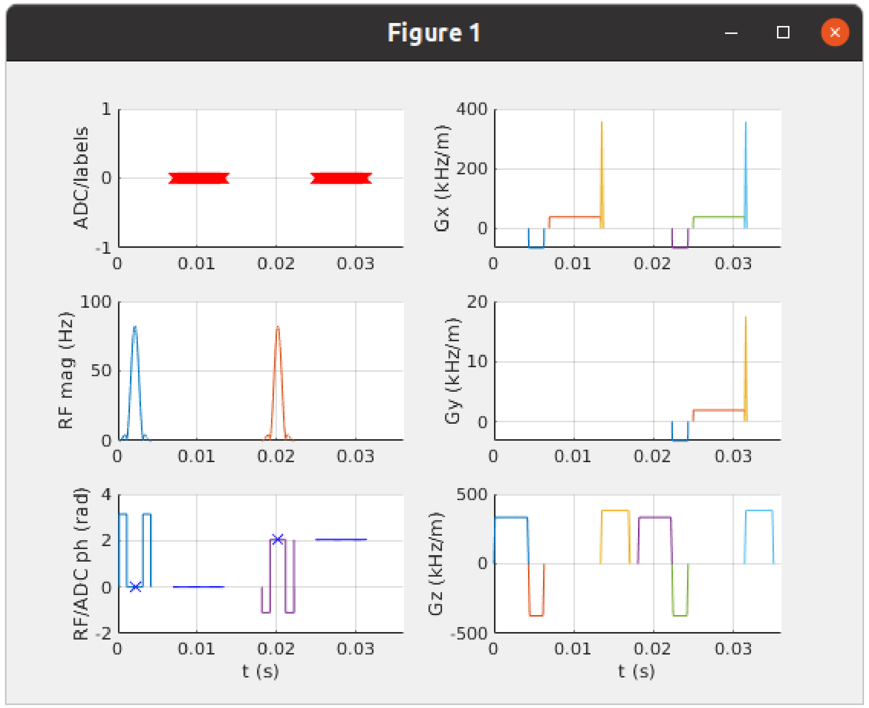


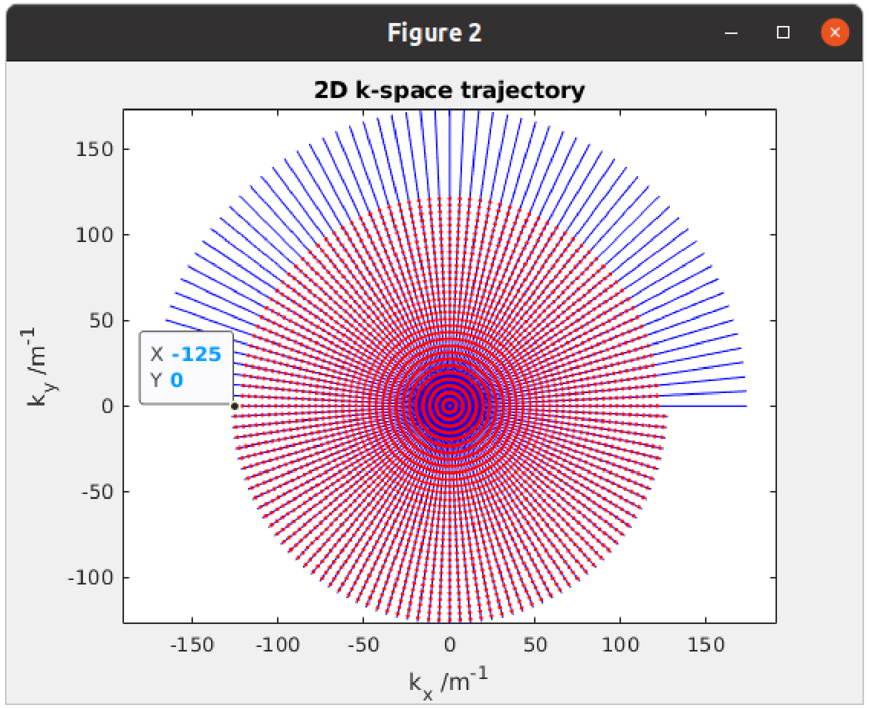
- Further plot options: 'timeRange', 'TimeDisp', 'showBlocks', 'Label'

Pulseq unit conventions

- Default to SI units where possible
- Default gradient unit is **Hz/m**
  - Other units possible
- K-space unit is **1/m**
- FOV calculations are trivial

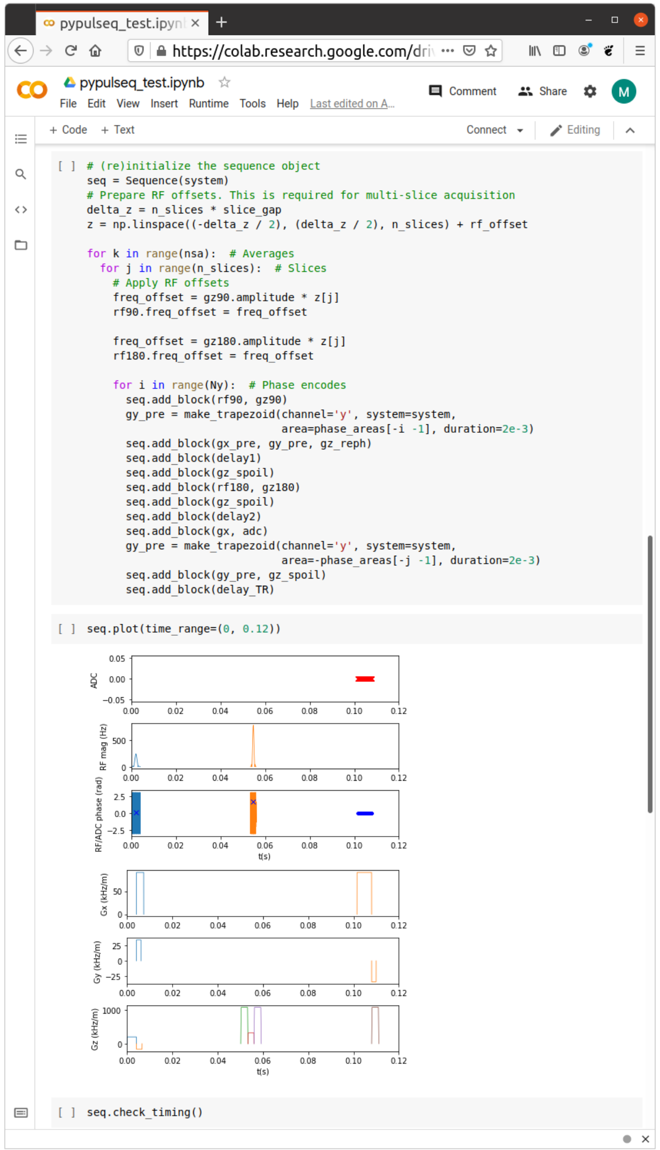
  $k_{max}=1/\Delta x \quad \Delta k=1/FOV$
  - No γ required!
  - No 2π required!
- K-space analysis is trivial
  - Spatial resolution of the sequence in Fig. 2 is 1m/125=4mm





PyPulseq : a 100% free *Pulseq*

- *PyPulseq* is a close replica of the original Pulseq toolbox that does not require a MATLAB license
- Runs in many of established Python environments, e.g. in Jupyter notebook (http://jupyter.org/)
- *PyPulseq* may now run in your browser via the Google Colaboratory
- To learn more about *PyPulseq* check out ISMRM 2021 e-poster #3760 on Thursday or visit http://github.com/imr-framework/pypulseq



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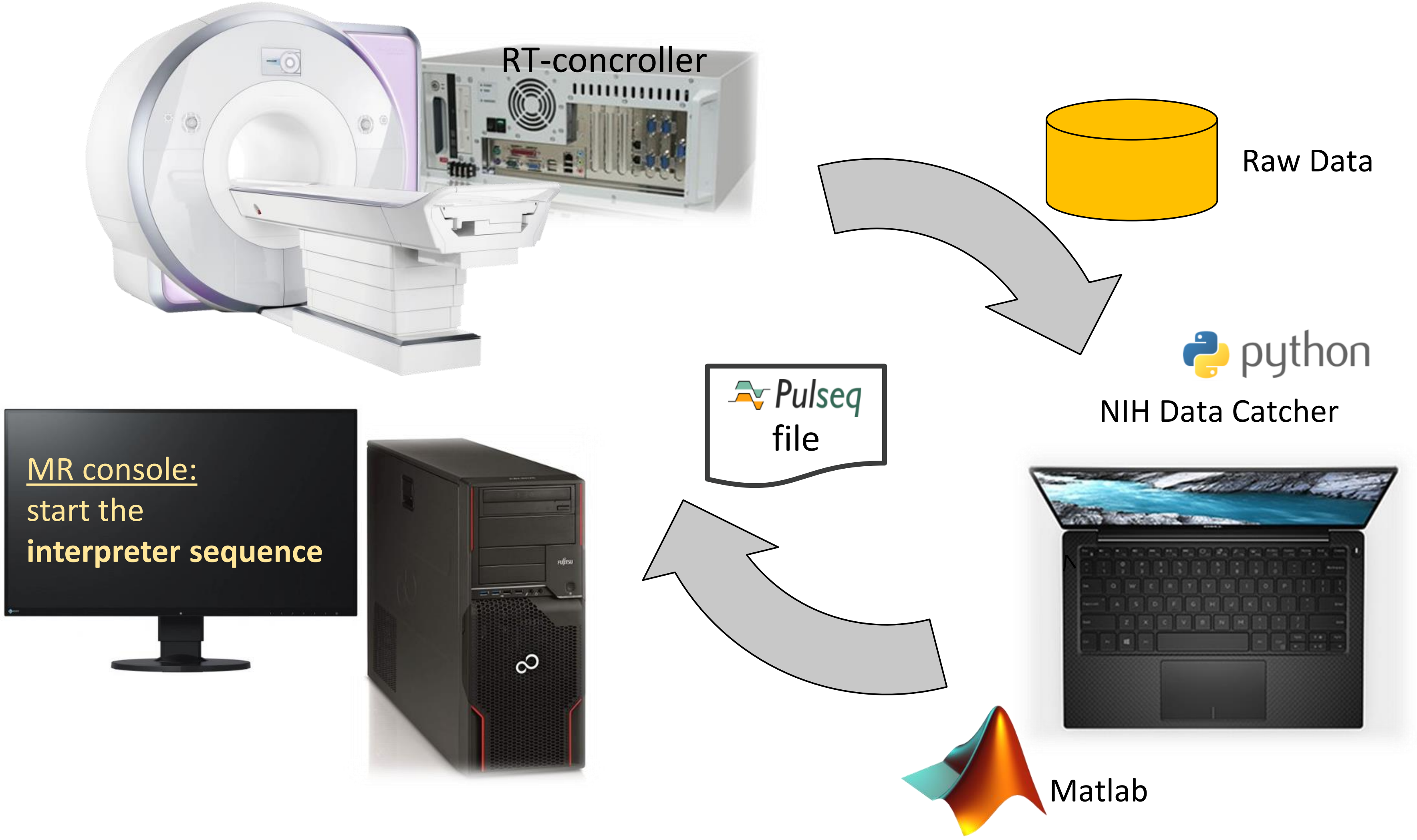
Pulseq on Siemens scanners

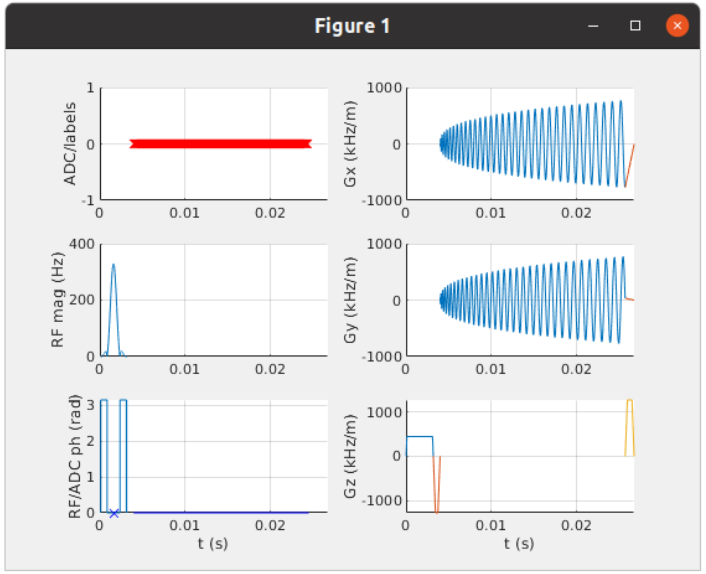
- *Optional step: connect an additional PC to the scanner*
- Save the .seq file on the scanner as external.seq
- Run the interpreter_sequence on the scanner
- *Optional step: stream raw data to your PC with NIH_DataCatcher*
- or export raw data manually

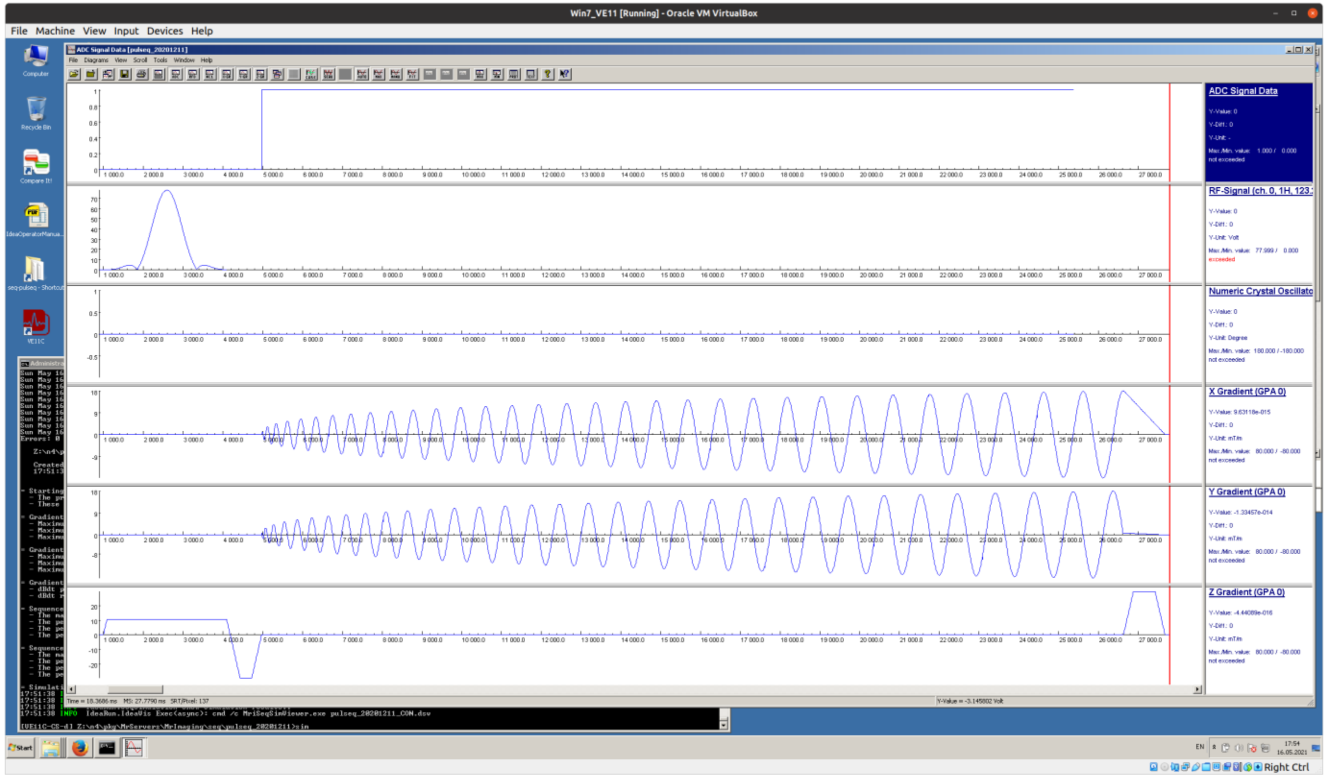


IDEA simulation with *Pulseq*

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**





To acquire the Pulseq interpreter sequence contact pulseq.mr@uniklinik-freiburg.de

Pulseq on GE scanners

Step 1: Download the 'PulseqGEq' and 'TOPPE' Matlab toolboxes

```
$ git clone git@github.com:toppeMRI/PulseGEq.git
$ git clone git@github.com:toppeMRI/toppe.git
```

Step 2: Set system hardware parameters (max gradient, slew, etc)

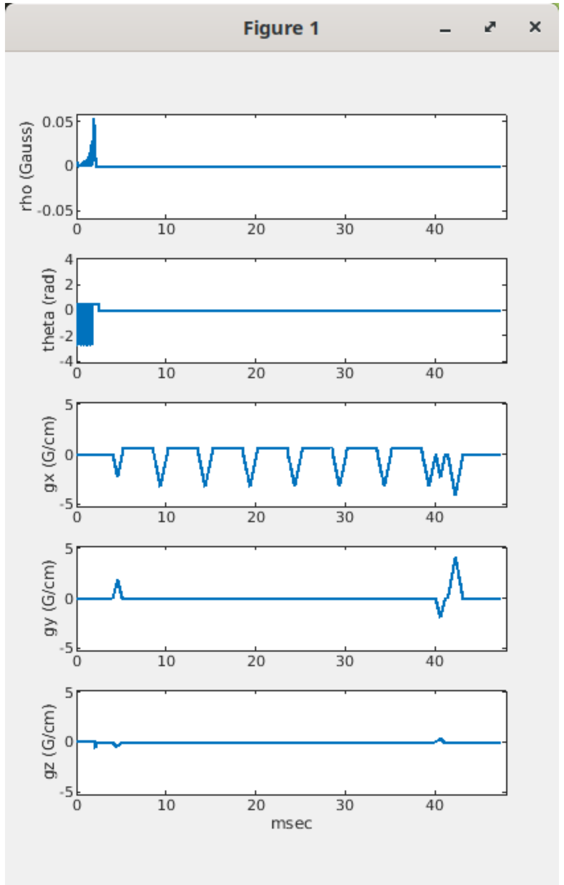
```
>> sys = toppe.systemspecs('maxGrad',5,'gradUnit','G/cm');
```

Step 3: Convert the .seq file to the TOPPE file format

```
>> pulsegeq.seq2ge('se_radial.seq','system',sys);
```

Step 4: Preview the sequence in movie/loop mode

```
>> toppe.playseq(3);
```

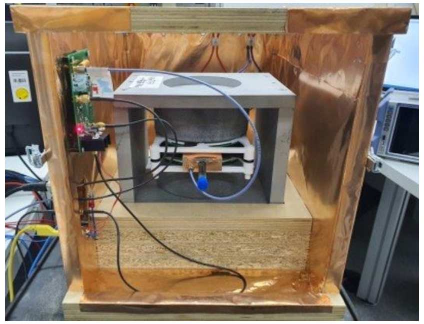


Step 5: Copy 'toppeScanFiles.tar' to the scanner, untar, and run the TOPPE interpreter sequence

Pulseq on tabletop scanners using OCRA/FLOCRA

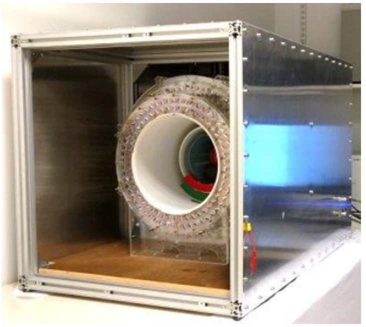
OCRA/FLOCRA: Open source consoles compatible with tabletop and custom scanners

- Runs on Red Pitaya 122 (FLOCRA/OCRA) and 125 (OCRA) boards
- Open source Python code runs MR experiments using ***Pulseq*** .seq files

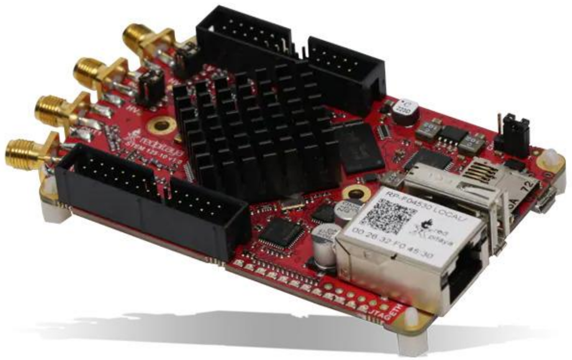


0.48T Tabletop
Dortmund, Germany

0.35T Tabletop
Boston, MA, USA



50mT Halbach
Leiden, Netherlands



Red Pitaya 122 board

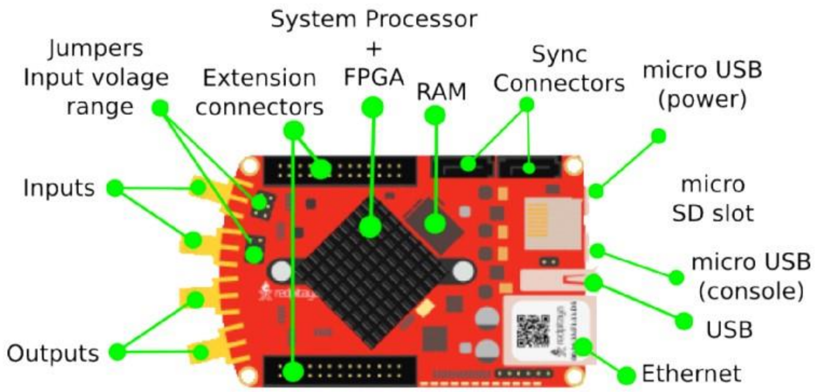
FLOCRA: `$ git clone https://github.com/lcbMGH/flocra-pulseq.git`

OCRA: `$ git clone --recurse-submodules https://github.com/OpenMRI/ocra-pack.git`

Pulseq on tabletop scanners using OCRA/FLOCRA

RP-122/125 Board Hardware:

- Two RF inputs, two RF outputs, capable of 300 kHz to 100 MHz signals.
- 16 digital pins for extensions – used for gradient SPI bus and TR-switch control
- 125 (RP-125), 122.88 (RP122) MS/s sample rate
- Compatible with OCRA1 and GPA-FHDO gradient DAC boards
- Ethernet connection for control



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     are only covered in the live portion of the tutorial

Pulseq – seq01

- Example 1:
  free induction decay sequence
- After line 25
  the sequence is ready (in Matlab's memory)
- Further lines: display, sanity checks, export to disk

RF pulse

ADC

/home/zaitsev/pulseq_home/pulseq_public/matlab/ismrmTutorial/seq/seq01_Fid.m

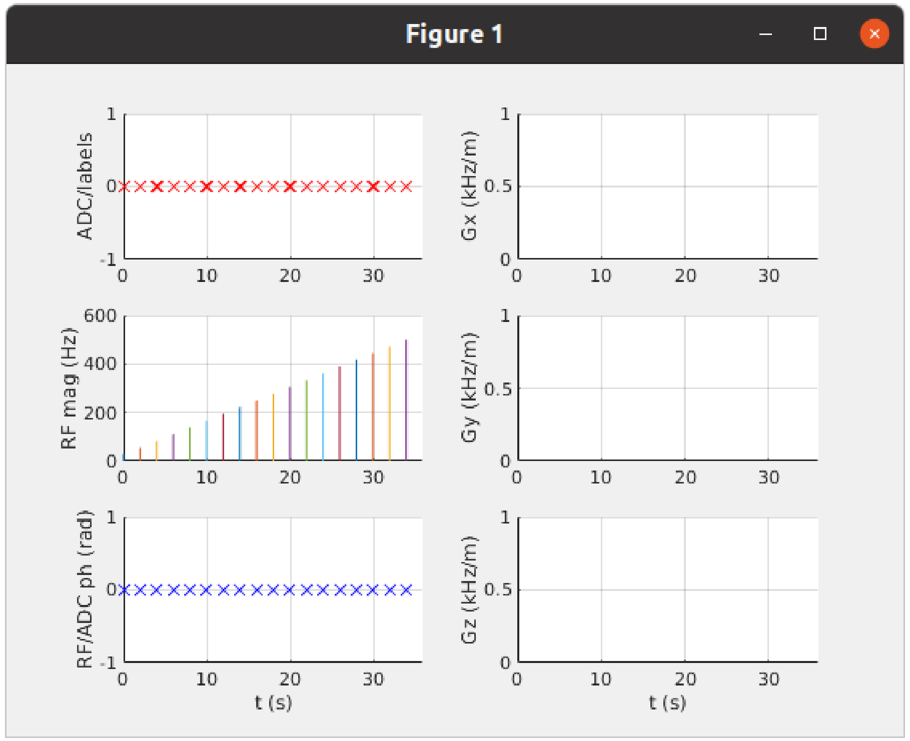
```matlab
1  system = mr.opts('rfRingdownTime', 20e-6, 'rfDeadTime', 100e-6, ...
2                   'adcDeadTime', 20e-6);
3  
4  seq=mr.Sequence(system);              % Create a new sequence object
5  Nx=4096;
6  Nrep=1;
7  adcDur=51.2e-3;
8  rfDur=500e-6;
9  TR=5000e-3;
10 TE=10e-3;
11 
12 % Create non-selective pulse
13 rf = mr.makeBlockPulse(pi/2,'Duration',rfDur, 'system', system);
14 
15 % Define delays and ADC events
16 adc = mr.makeAdc(Nx,'Duration',adcDur, 'system', system, 'delay', TE-rfDur/2-system.rfRingdownTime);
17 
18 delayTR=TR-mr.calcDuration(rf);
19 assert(delayTR>=0);
20 
21 % Loop over repetitions and define sequence blocks
22 for i=1:Nrep
23     seq.addBlock(rf);
24     seq.addBlock(adc,mr.makeDelay(delayTR));
25 end
26 
27 % show the "interesting part" of the sequence
28 seq.plot('timeRange',[0 TE+rfDur+adcDur+1e-3]);
29 
30 % check whether the timing of the sequence is compatible with the scanner
31 [ok, error_report]=seq.checkTiming;
32 
33 if (ok)
34     fprintf('Timing check passed successfully\n');
35 else
36     fprintf('Timing check failed! Error listing follows:\n');
37     fprintf([error_report{:}]);
38     fprintf('\n');
39 end
40 
41 seq.write('fid.seq')       % Write to pulseq file
42 %seq.install('siemens');    % copy to scanner
```

basic parameters

create blocks

Pulseq – seq02

- Example 2:
  FID sequence with
  flip angle variation



/home/zaitsev/pulseq_home/pulseq_public/matlab/ismrmTutorial/seq/seq02_Fid_multipleFAs.m

```matlab
system = mr.opts('rfRingdownTime', 20e-6, 'rfDeadTime', 100e-6, ...
                 'adcDeadTime', 20e-6);

seq=mr.Sequence(system);              % Create a new sequence object
Nx=4096;
Nrep=1;
adcDur=51.2e-3;
rfDur=1000e-6; % increased to 1ms
TR=2000e-3;    % may increase to ~5s avoid T1 saturation
TE=10e-3;
flip_angles=18;

% Define delays and ADC events
adc = mr.makeAdc(Nx,'Duration',adcDur, 'system', system, 'delay', TE-rfDur/2-system.rfRingdown

delayTR=TR-mr.calcDuration(rf);
assert(delayTR>=0);

% Loop over repetitions and define sequence blocks
for f=1:flip_angles
    % Create non-selective pulse
    rf = mr.makeBlockPulse(pi/flip_angles*f,'Duration',rfDur, 'system', system);
    % Loop over repetitions and define sequence blocks
    for i=1:Nrep
        seq.addBlock(rf);
        seq.addBlock(adc,mr.makeDelay(delayTR));
    end
end

% show the entire sequence
seq.plot();

% check whether the timing of the sequence is compatible with the scanner
[ok, error_report]=seq.checkTiming;

if (ok)
    fprintf('Timing check passed successfully\n');
else
    fprintf('Timing check failed! Error listing follows:\n');
    fprintf([error_report{:}]);
    fprintf('\n');
end

seq.write('fid.seq')       % Write to pulseq file
%seq.install('siemens');   % copy to scanner
```

RF pulse now here

Pulseq – seq03

- Example 3:
  naive spin-echo
- The sequence is ready after line 34
- We (ab)use k-space calculation routines for their ability to deliver timestamps

two RF pulses

more delays to calculate

check TE calculation

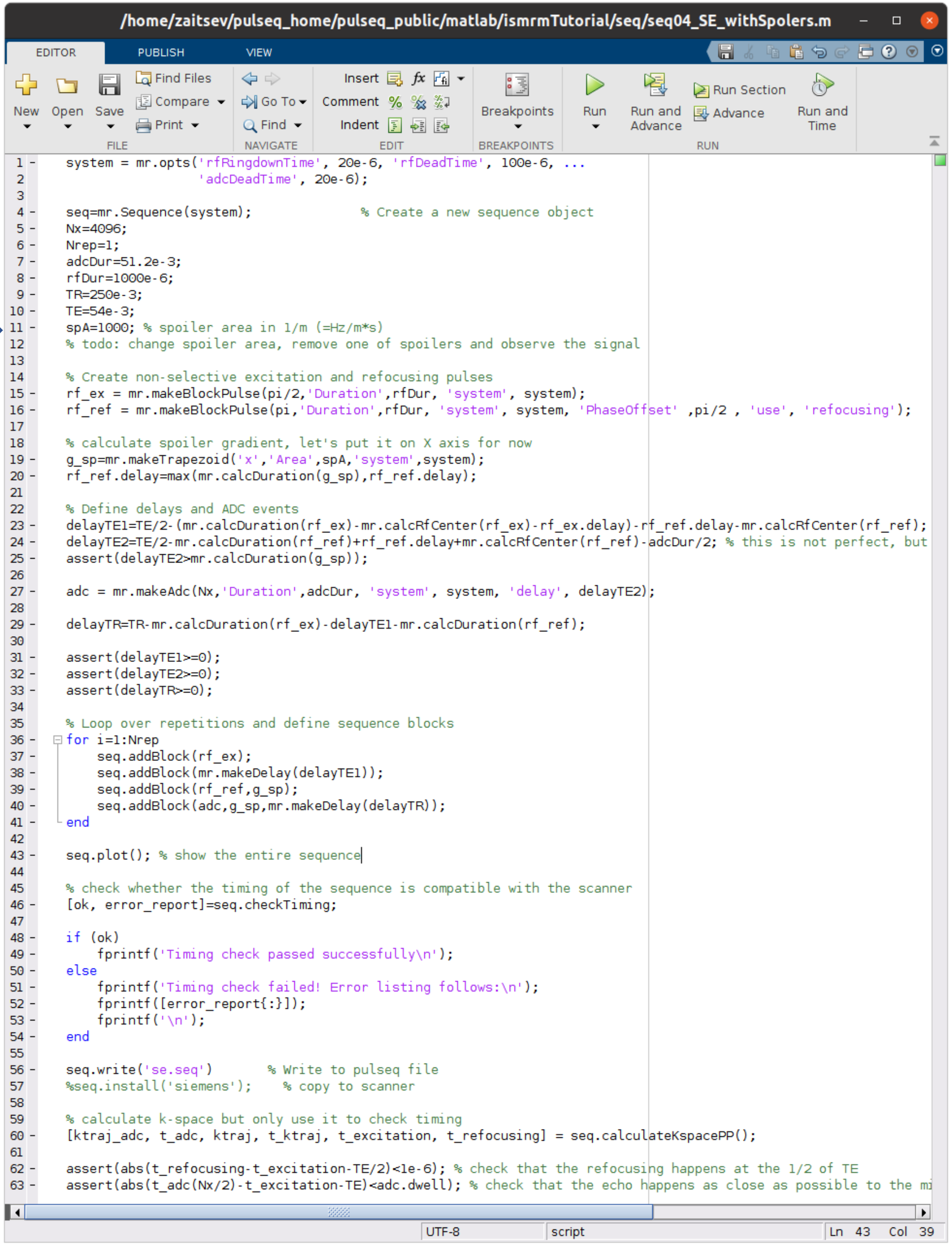
/home/zaitsev/pulseq_home/pulseq_public/matlab/ismrmTutorial/seq/seq03_SE.m

```
1  system = mr.opts('rfRingdownTime', 20e-6, 'rfDeadTime', 100e-6, ...
2                   'adcDeadTime', 20e-6);
3
4  seq=mr.Sequence(system);              % Create a new sequence object
5  Nx=4096;
6  Nrep=1;
7  adcDur=51.2e-3;
8  rfDur=1000e-6;
9  TR=100e-3;
10 TE=54e-3;
11
12 % Create non-selective excitation and refocusing pulses
13 rf_ex = mr.makeBlockPulse(pi/2,'Duration',rfDur, 'system', system);
14 rf_ref = mr.makeBlockPulse(pi,'Duration',rfDur, 'system', system, 'PhaseOffset' ,pi/2 , 'use', 'refocusing');
15
16 % Define delays and ADC events
17 delayTE1=TE/2-mr.calcDuration(rf_ex)/2-mr.calcDuration(rf_ref)/2;
18 delayTE2=TE/2-mr.calcDuration(rf_ref)+rf_ref.delay+mr.calcRfCenter(rf_ref)-adcDur/2; % this is not perfect, bu
19
20 adc = mr.makeAdc(Nx,'Duration',adcDur, 'system', system, 'delay', delayTE2);
21
22 delayTR=TR-mr.calcDuration(rf_ex)-delayTE1-mr.calcDuration(rf_ref);
23
24 assert(delayTE1>=0);
25 assert(delayTE2>=0);
26 assert(delayTR>=0);
27
28 % Loop over repetitions and define sequence blocks
29 for i=1:Nrep
30     seq.addBlock(rf_ex);
31     seq.addBlock(mr.makeDelay(delayTE1));
32     seq.addBlock(rf_ref);
33     seq.addBlock(adc,mr.makeDelay(delayTR));
34 end
35
36 % show the entire sequence showing the block structure
37 seq.plot('showBlocks',1,'timeDisp','ms');
38
39 % check whether the timing of the sequence is compatible with the scanner
40 [ok, error_report]=seq.checkTiming;
41
42 if (ok)
43     fprintf('Timing check passed successfully\n');
44 else
45     fprintf('Timing check failed! Error listing follows:\n');
46     fprintf([error_report{:}]);
47     fprintf('\n');
48 end
49
50 seq.write('se.seq')       % Write to pulseq file
51 %seq.install('siemens');    % copy to scanner
52
53 % calculate k-space but only use it to check the TE calculation
54 [ktraj_adc, t_adc, ktraj, t_ktraj, t_excitation, t_refocusing] = seq.calculateKspacePP();
55
56 assert(abs(t_refocusing-t_excitation-TE/2)<1e-6); % check that the refocusing happens at the 1/2 of TE
57 assert(abs(t_adc(Nx/2)-t_excitation-TE)<adc.dwell); % check that the echo happens as close as possible to the
```

Pulseq – seq04

spoiling
area

- Example 4:
  spin-echo with
  spoilers around
  the refocusing pulse
- Create spoiling gradient
- Use it in the sequence in two different blocks



Pulseq – seq05

- Example 5:
  Cartesian spin-echo imaging sequence
- Use shorter ADC window compared to the spectroscopy sequence
- More gradients to create
- More complex delay calculation
- The sequence is ready at line 67
- *See timing checks in the live portion*

dummy scans

calculate delays

/home/zaitsev/pulseq_home/pulseq_public/matlab/ismrmTutorial/seq/seq05_CartesianSE.m

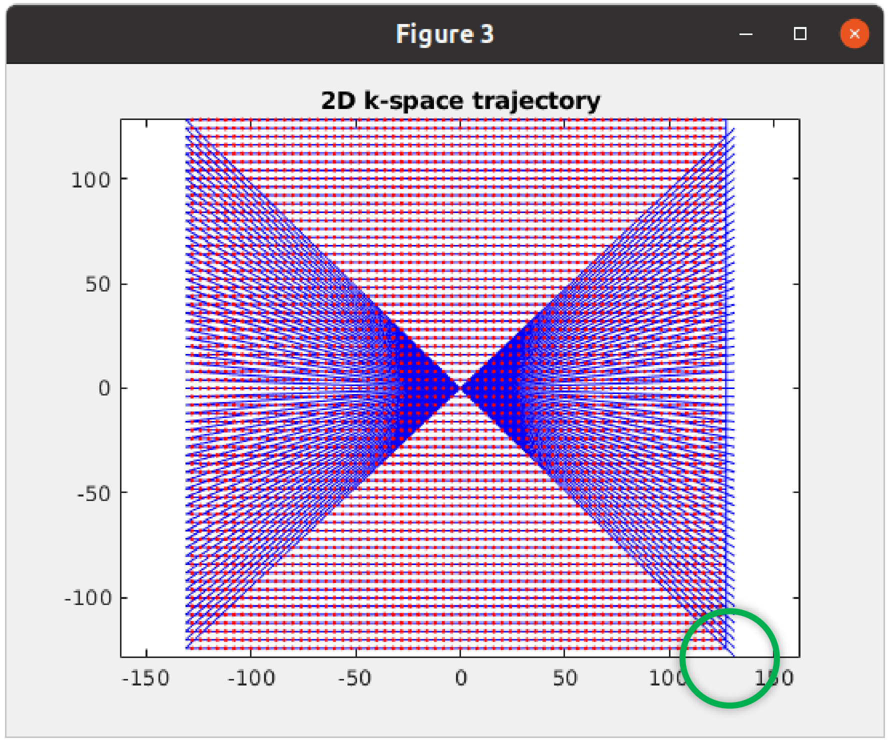
```
1  system = mr.opts('rfRingdownTime', 20e-6, 'rfDeadTime', 100e-6, ...
2                   'adcDeadTime', 20e-6);
3
4  seq=mr.Sequence(system);              % Create a new sequence object
5  adcDur=2.56e-3;
6  rfDur1=3e-3;
7  rfDur2=1e-3;
8  TR=150e-3;
9  TE=54e-3; % 20ms still works with the chosen parameters & sysyem props
10 spA=1000; % spoiler area in 1/m (=Hz/m*s) % MZ: need 5000 for my oi
11
12 sliceThickness=3e-3;             % slice
13 fov=250e-3; Nx=256;              % Define FOV and resolution
14 Ny=Nx;                           % number of radial spokes
15 Ndummy=10;                       % number of dummy scans
16
17 % Create 90 degree slice selection pulse and gradient and even the
18 % refocusing gradient; we will not use the latter however but will subtract
19 % its area from the first (left) spoiler
20 [rf_ex, gs, gsr] = mr.makeSincPulse(pi/2,system,'Duration',3e-3,...
21     'SliceThickness',sliceThickness,'apodization',0.4,'timeBwProduct',4);
22
23 % Create non-selective refocusing pulse
24 rf_ref = mr.makeBlockPulse(pi,'Duration',rfDur2, 'system', system, 'PhaseOffset' ,pi/2 , 'use', 'refocusing'); % need
25
26 % calculate spoiler gradient
27 g_sp1=mr.makeTrapezoid('z','Area',spA+gsr.area,'system',system);
28 rf_ref.delay=max(mr.calcDuration(g_sp1),rf_ref.delay);
29
30 g_sp2=mr.makeTrapezoid('z','Area',spA,'system',system);
31
32 % Define delays and ADC events
33 deltak=1/fov;
34 gr = mr.makeTrapezoid('x',system,'FlatArea',Nx*deltak,'FlatTime',adcDur);
35 adc = mr.makeAdc(Nx,system,'Duration',adcDur,'delay',gr.riseTime);
36
37 grPredur = 5e-3; % use a fixed time to make this gradient visible on the plot
38 grPre = mr.makeTrapezoid('x',system,'Area',gr.area/2+deltak/2,'Duration',grPredur);
39 phaseAreas = ((0:Ny-1)-Ny/2)*deltak;
40
41 delayTE1=TE/2-(mr.calcDuration(gs)-mr.calcRfCenter(rf_ex)-rf_ex.delay)-rf_ref.delay-mr.calcRfCenter(rf_ref)-grPredur;
42 delayTE2=TE/2-mr.calcDuration(rf_ref)+rf_ref.delay+mr.calcRfCenter(rf_ref)-adc.delay-adcDur/2; % this is not perfect,
43 delayTR=TR-mr.calcDuration(gs)-grPredur-delayTE1-mr.calcDuration(rf_ref)-delayTE2-mr.calcDuration(gr);
44
45 assert(delayTE1>=0);
46 assert(delayTE2>mr.calcDuration(g_sp2));
47 assert(delayTR>=0);
48
49 % Loop over repetitions and define sequence blocks
50 for i=(1-Ndummy):Ny
51     seq.addBlock(rf_ex,gs);
52     if (i>0) % semi-negative index -- dummy scans
53         gy = mr.makeTrapezoid('y', 'Area', phaseAreas(i), 'Duration', grPredur);
54     else
55         gy = mr.makeTrapezoid('y', 'Area', 0, 'Duration', grPredur);
56     end
57     seq.addBlock(grPre,gy);
58     seq.addBlock(mr.makeDelay(delayTE1));
59     seq.addBlock(rf_ref,g_sp1);
60     seq.addBlock(g_sp2, mr.makeDelay(delayTE2));
61     if (i>0) % semi-negative index -- dummy scans
62         seq.addBlock(adc,gr);
63     else
64         seq.addBlock(gr);
65     end
66     seq.addBlock(gy,mr.makeDelay(delayTR));
67 end
68
69 % show the first non-dummy TR with the block structure
70 seq.plot('showBlocks',1,'timeRange',TR*(Ndummy+[0 1]),'timeDisp','us');
```

basic parameters

PE steps

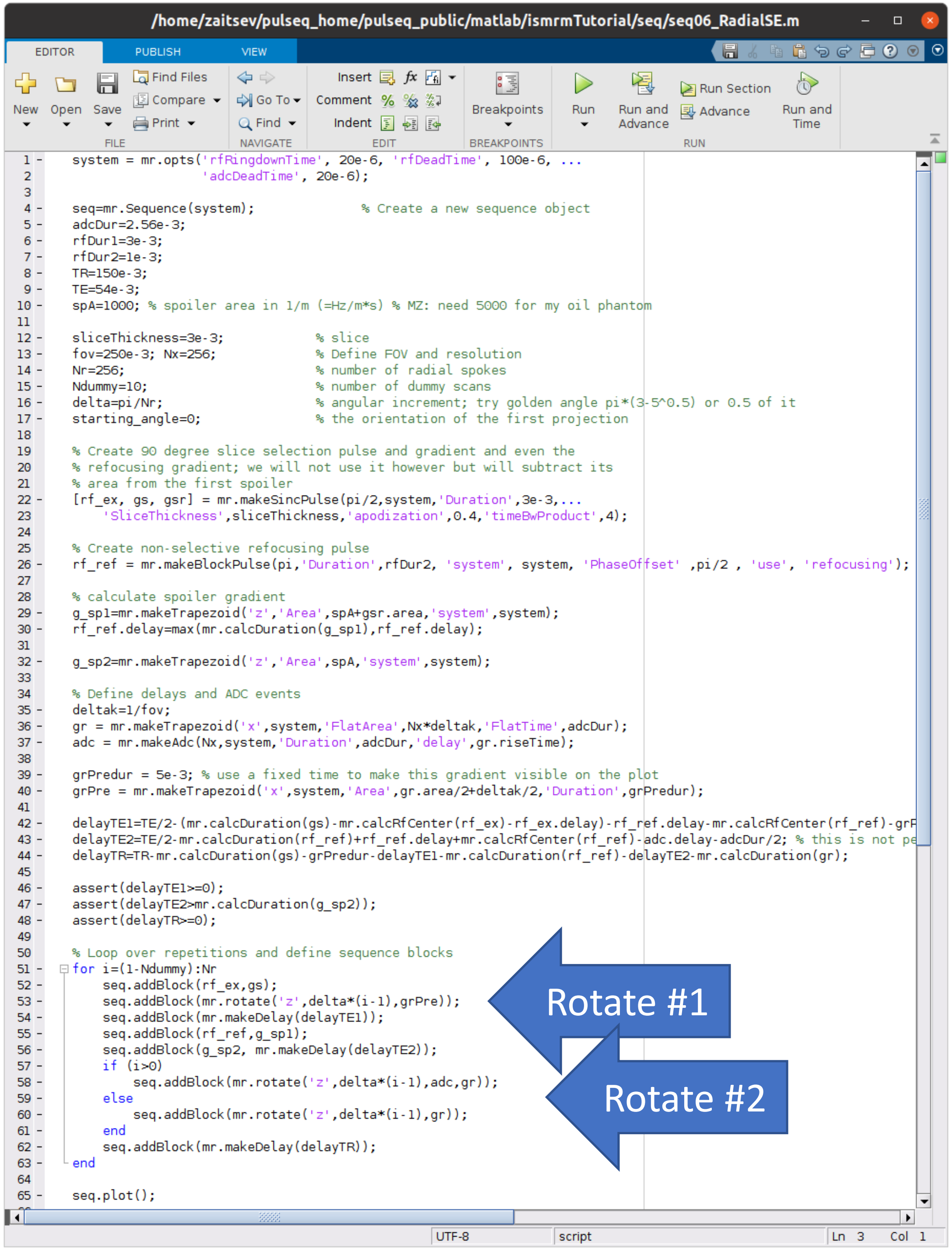
Pulseq – seq05 contd.

- Example 5:
  Cartesian spin-echo imaging sequence
- Very useful option in the Pulseq toolbox is the k-space calculation
- See how we travel in the k-space to the bottom right in the last TR to be "teleported" to the upper left corner *(see also k(t) plots in the live session)*



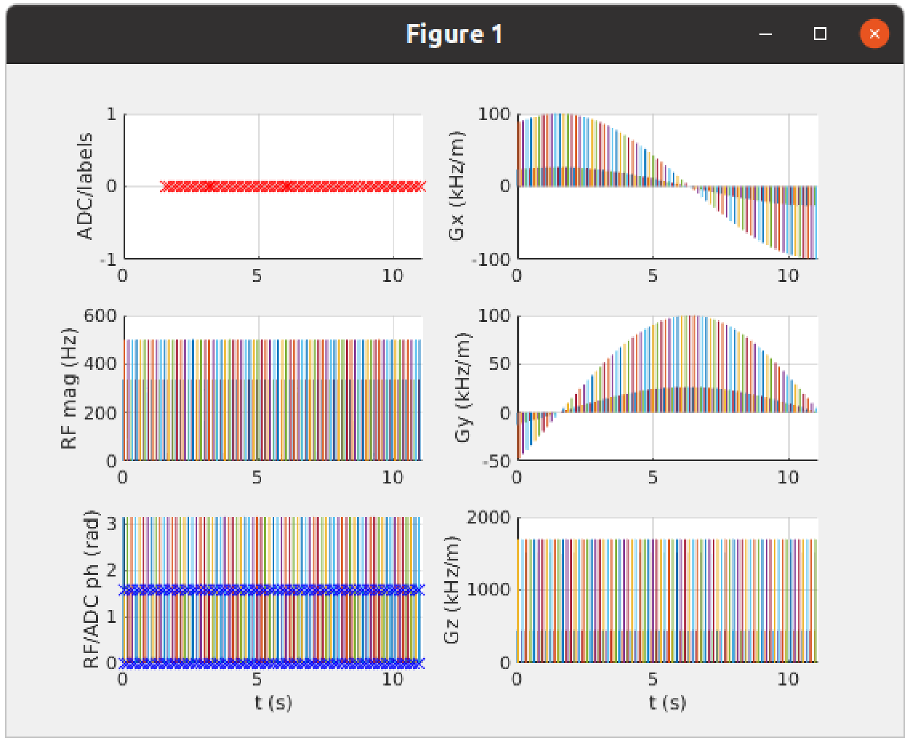
Pulseq – seq06

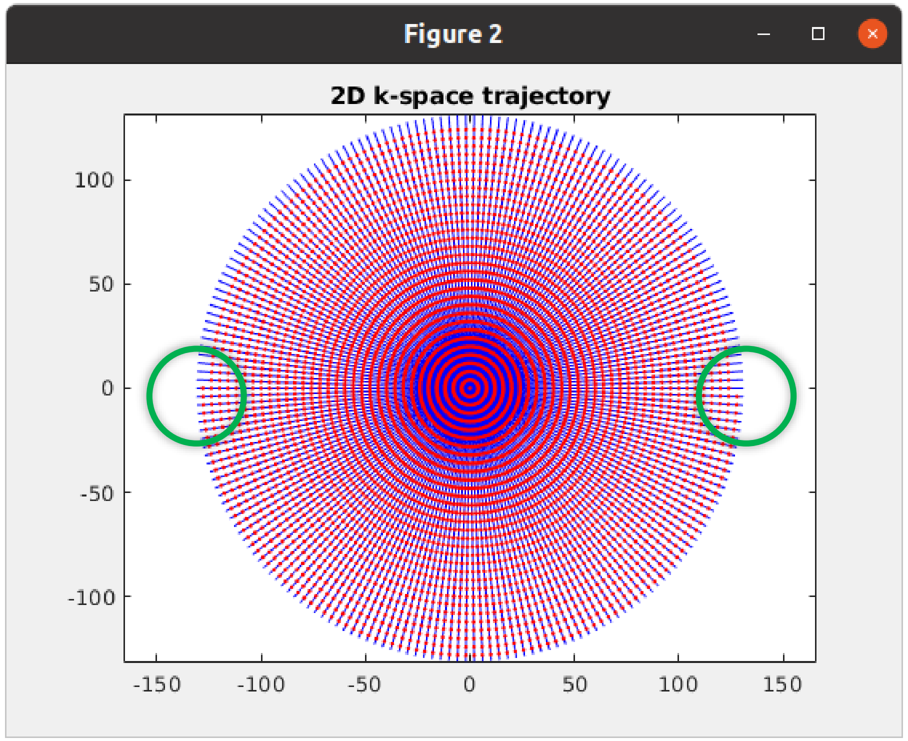
- Example 6:
  2D radial spin-echo imaging sequence
- Remove phase encoding
- Rotate read prephaser and readout gradients
- The sequence is actually simpler
- The sequence is ready at line 63
- *See timing checks in the live portion*



Pulseq – seq06 contd.

- *Time to explore sequence timing and the trajectory*





Pulseq – seq07

- Example 7:
  2D radial gradient echo
- Add RF spoiling
  - Introduce counters
  - Update phase of the RF pulse
  - Remember to update ADC phase
- Add gradient spoiler at the end of the readout gradient
- The sequence is ready at line 63
- *See timing checks in the live portion*

gradient spoiling

RF spoiling

RF spoiling

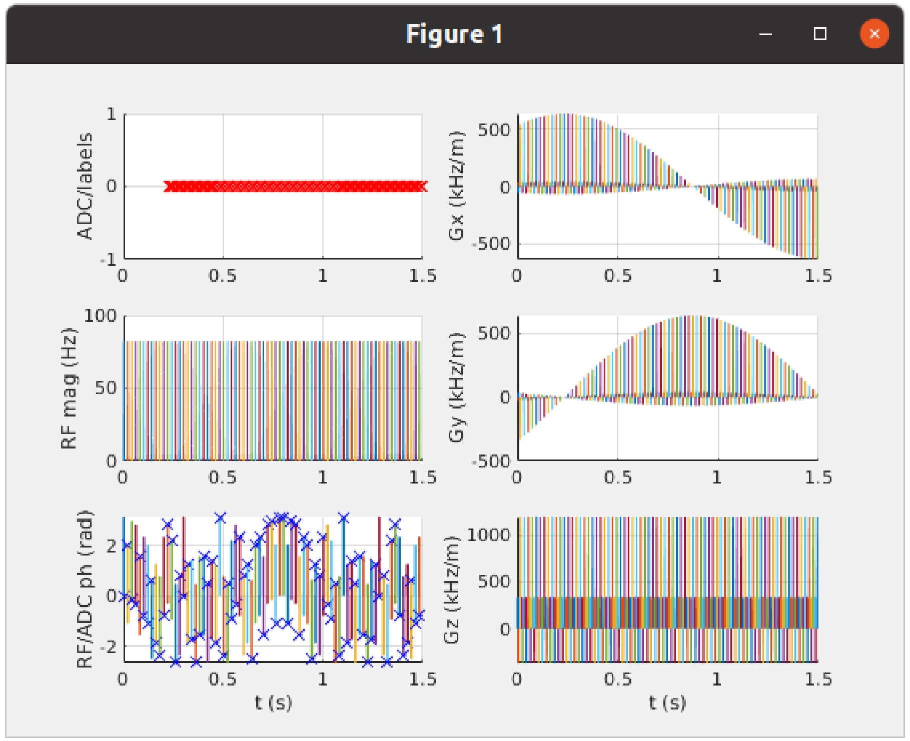
/home/zaitsev/pulseq_home/pulseq_public/matlab/ismrmTutorial/seq/seq07_RadialGradientEcho.m

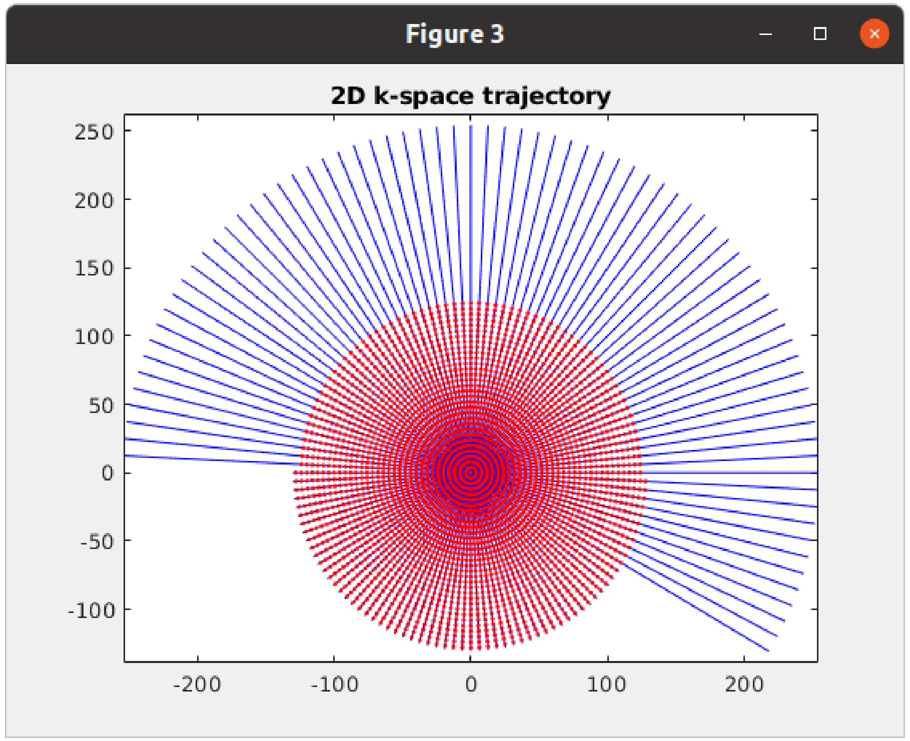
```matlab
1  seq=mr.Sequence();              % Create a new sequence object
2  fov=250e-3; Nx=256;             % Define FOV and resolution
3  alpha=30;                       % flip angle
4  sliceThickness=3e-3;            % slice
5  TE=8e-3;                        % TE; give a vector here to have multiple TEs (e.g. for field mapping)
6  TR=20e-3;                       % only a single value for now
7  Nr=256;                         % number of radial spokes
8  Ndummy=10;                      % number of dummy scans
9  delta=pi/Nr;                    % angular increment; try golden an   pi*(3-5^0.5) or 0.5 of it
10 
11 % more in-depth parameters
12 rfSpoilingInc=117;              % RF spoiling increment
13 
14 % set system limits
15 sys = mr.opts('MaxGrad', 28, 'GradUnit', 'mT/m', ...
16     'MaxSlew', 80, 'SlewUnit', 'T/m/s', 'rfRingdownTime', 20e-6, ...
17     'rfDeadTime', 100e-6, 'adcDeadTime', 10e-6);
18 
19 % Create alpha-degree slice selection pulse and gradient
20 [rf, gz] = mr.makeSincPulse(alpha*pi/180,'Duration',4e-3,...
21     'SliceThickness',sliceThickness,'apodization',0.5,'timeBwProduct',4,'system',sys);
22 
23 % Define other gradients and ADC events
24 deltak=1/fov;
25 gx = mr.makeTrapezoid('x','FlatArea',Nx*deltak,'FlatTime',6.4e-3,'system',sys);
26 adc = mr.makeAdc(Nx,'Duration',gx.flatTime,'Delay',gx.riseTime,'system',sys);
27 gxPre = mr.makeTrapezoid('x','Area',-gx.area/2-deltak/2,'Duration',2e-3,'system',sys); % we need this "d
28 gzReph = mr.makeTrapezoid('z','Area',-gz.area/2,'Duration',2e-3,'system',sys);
29 
30 % gradient spoiling
31 gxSpoil=mr.makeTrapezoid('x','Area',0.5*Nx*deltak,'system',sys);
32 gzSpoil=mr.makeTrapezoid('z','Area',4/sliceThickness,'system',sys);
33 
34 % Calculate timing
35 delayTE=ceil((TE - mr.calcDuration(gxPre) - gz.fallTime - gz.flatTime/2 ...
36     - mr.calcDuration(gx)/2)/seq.gradRasterTime)*seq.gradRasterTime;
37 delayTR=ceil((TR - mr.calcDuration(gxPre) - mr.calcDuration(gz) ...
38     - mr.calcDuration(gx) - delayTE)/seq.gradRasterTime)*seq.gradRasterTime;
39 assert(all(delayTR>=mr.calcDuration(gxSpoil,gzSpoil)));
40 
41 rf_phase=0;
42 rf_inc=0;
43 
44 for i=(-Ndummy):Nr
45     for c=1:length(TE)
46         rf.phaseOffset=rf_phase/180*pi;
47         adc.phaseOffset=rf_phase/180*pi;
48         rf_inc=mod(rf_inc+rfSpoilingInc, 360.0);
49         rf_phase=mod(rf_phase+rf_inc, 360.0);
50         %
51         seq.addBlock(rf,gz);
52         phi=delta*(i-1);
53         seq.addBlock(mr.rotate('z',phi,gxPre,gzReph));
54         seq.addBlock(mr.makeDelay(delayTE(c)));
55         if (i>0)
56             seq.addBlock(mr.rotate('z',phi,gx,adc));
57         else
58             seq.addBlock(mr.rotate('z',phi,gx));
59         end
60         seq.addBlock(mr.rotate('z',phi,gxSpoil,gzSpoil,mr.makeDelay(delayTR)));
61     end
62 end
63 
64 seq.plot();
```

UTF-8 script Ln 10 Col 1

Pulseq – seq07 contd.

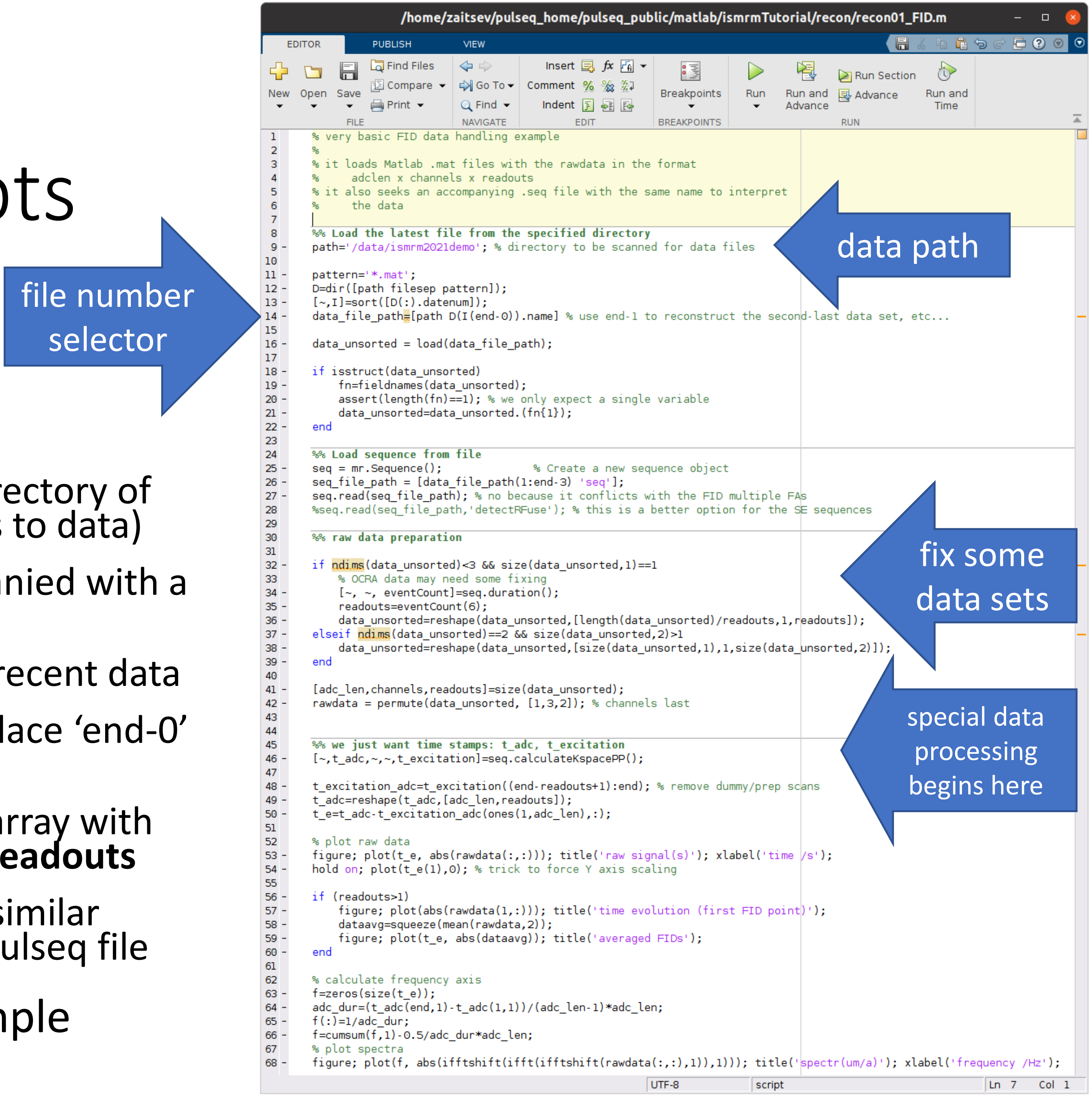
- *Time to explore sequence timing and the trajectory (e.g. RF phase and the gradient spoiling effects on the trajectory)*





Pulseq – recon scripts

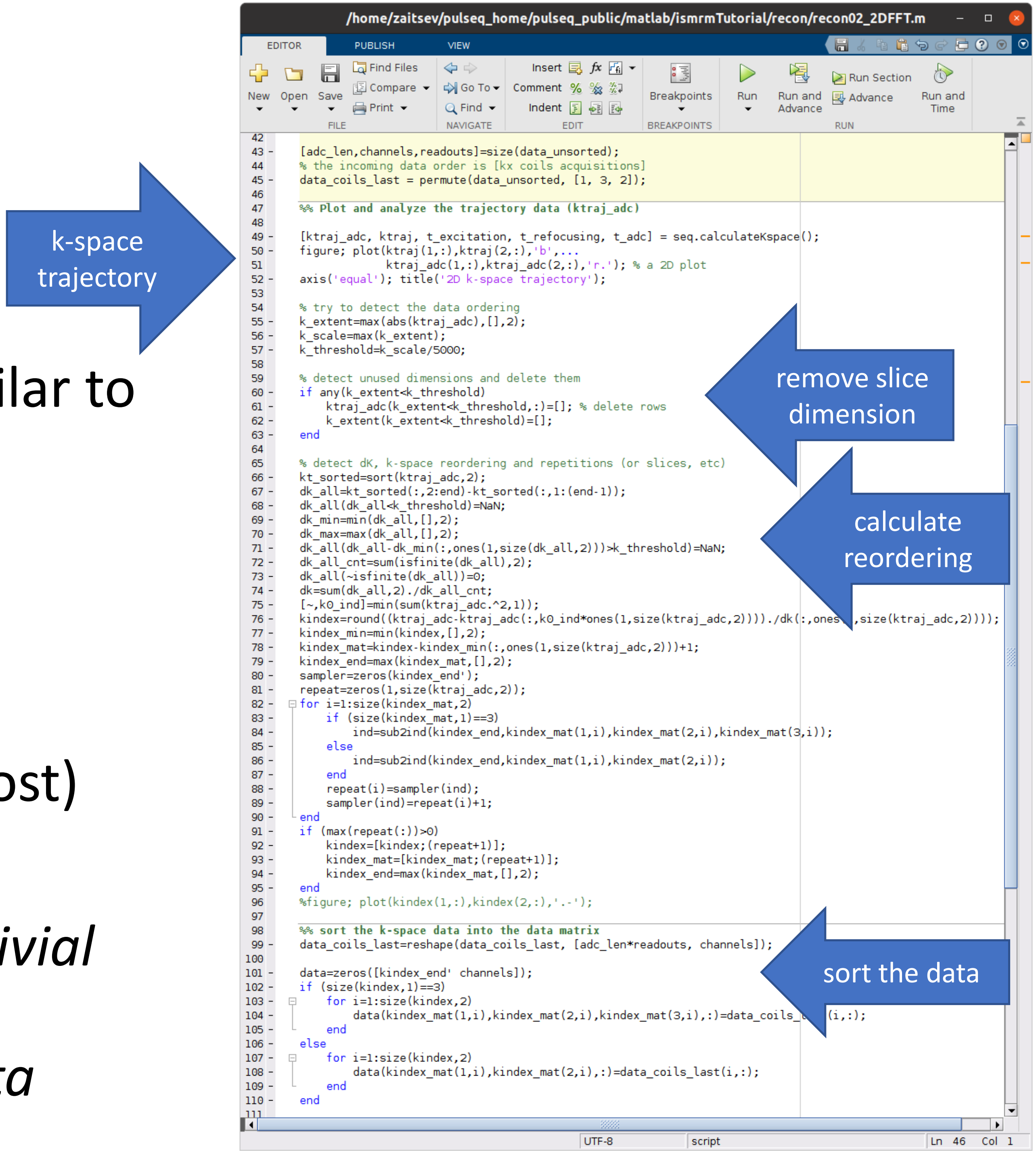
- All recon scripts are similar
- General logic
  - We expect data to be stored in a directory of choice (line 7 in this example points to data)
  - Raw data MUST always be accompanied with a Pulseq file with the identical name
  - By default all scripts load the most recent data
  - To load the second last data set replace ‘end-0’ with ‘end-1’ (line 14)
  - Ideally we expect raw data in a 3D array with dimensions: **samples x channels x readouts**
  - All data counters, data sorting and similar parameters is calculated from the Pulseq file
- Here is the complete FID/SE example




```matlab
1  % very basic FID data handling example
2  %
3  % it loads Matlab .mat files with the rawdata in the format
4  %     adclen x channels x readouts
5  % it also seeks an accompanying .seq file with the same name to interpret
6  %     the data
7  
8  %% Load the latest file from the specified directory
9  path='/data/ismrm2021demo'; % directory to be scanned for data files
10 
11 pattern='*.mat';
12 D=dir([path filesep pattern]);
13 [~,I]=sort([D(:).datenum]);
14 data_file_path=[path D(I(end-0)).name] % use end-1 to reconstruct the second-last data set, etc...
15 
16 data_unsorted = load(data_file_path);
17 
18 if isstruct(data_unsorted)
19     fn=fieldnames(data_unsorted);
20     assert(length(fn)==1); % we only expect a single variable
21     data_unsorted=data_unsorted.(fn{1});
22 end
23 
24 %% Load sequence from file
25 seq = mr.Sequence();              % Create a new sequence object
26 seq_file_path = [data_file_path(1:end-3) 'seq'];
27 seq.read(seq_file_path); % no because it conflicts with the FID multiple FAs
28 %seq.read(seq_file_path,'detectRFuse'); % this is a better option for the SE sequences
29 
30 %% raw data preparation
31 
32 if ndims(data_unsorted)<3 && size(data_unsorted,1)==1
33     % OCRA data may need some fixing
34     [~, ~, eventCount]=seq.duration();
35     readouts=eventCount(6);
36     data_unsorted=reshape(data_unsorted,[length(data_unsorted)/readouts,1,readouts]);
37 elseif ndims(data_unsorted)==2 && size(data_unsorted,2)>1
38     data_unsorted=reshape(data_unsorted,[size(data_unsorted,1),1,size(data_unsorted,2)]);
39 end
40 
41 [adc_len,channels,readouts]=size(data_unsorted);
42 rawdata = permute(data_unsorted, [1,3,2]); % channels last
43 
44 
45 %% we just want time stamps: t_adc, t_excitation
46 [~,t_adc,~,~,t_excitation]=seq.calculateKspacePP();
47 
48 t_excitation_adc=t_excitation((end-readouts+1):end); % remove dummy/prep scans
49 t_adc=reshape(t_adc,[adc_len,readouts]);
50 t_e=t_adc-t_excitation_adc(ones(1,adc_len),:);
51 
52 % plot raw data
53 figure; plot(t_e, abs(rawdata(:,:))); title('raw signal(s)'); xlabel('time /s');
54 hold on; plot(t_e(1),0); % trick to force Y axis scaling
55 
56 if (readouts>1)
57     figure; plot(abs(rawdata(1,:))); title('time evolution (first FID point)');
58     dataavg=squeeze(mean(rawdata,2));
59     figure; plot(t_e, abs(dataavg)); title('averaged FIDs');
60 end
61 
62 % calculate frequency axis
63 f=zeros(size(t_e));
64 adc_dur=(t_adc(end,1)-t_adc(1,1))/(adc_len-1)*adc_len;
65 f(:)=1/adc_dur;
66 f=cumsum(f,1)-0.5/adc_dur*adc_len;
67 % plot spectra
68 figure; plot(f, abs(ifftshift(ifft(ifftshift(rawdata(:,:),1)),1))); title('spectr(um/a)'); xlabel('frequency /Hz');
```

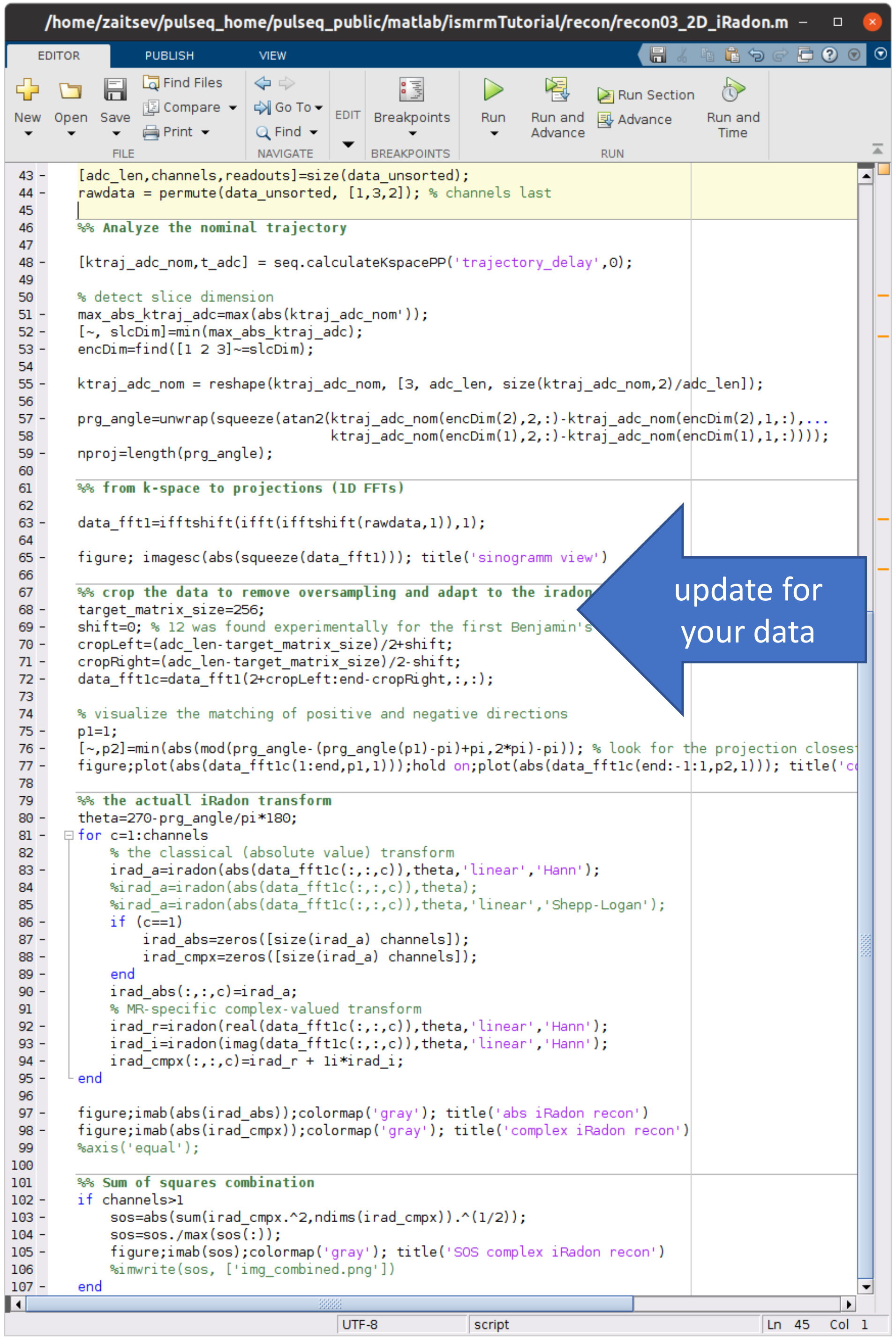
Pulseq – 2D FFT

- The beginning of the script is similar to the FID/SE example
- Screen shot shows automatic counter-free data sorting part
- k-space trajectory automatically updates data reordering for (almost) any 2D Cartesian sequence
- *Following (not shown) part is a trivial 2D FFT and a sum-of-square combination for multichannel data*



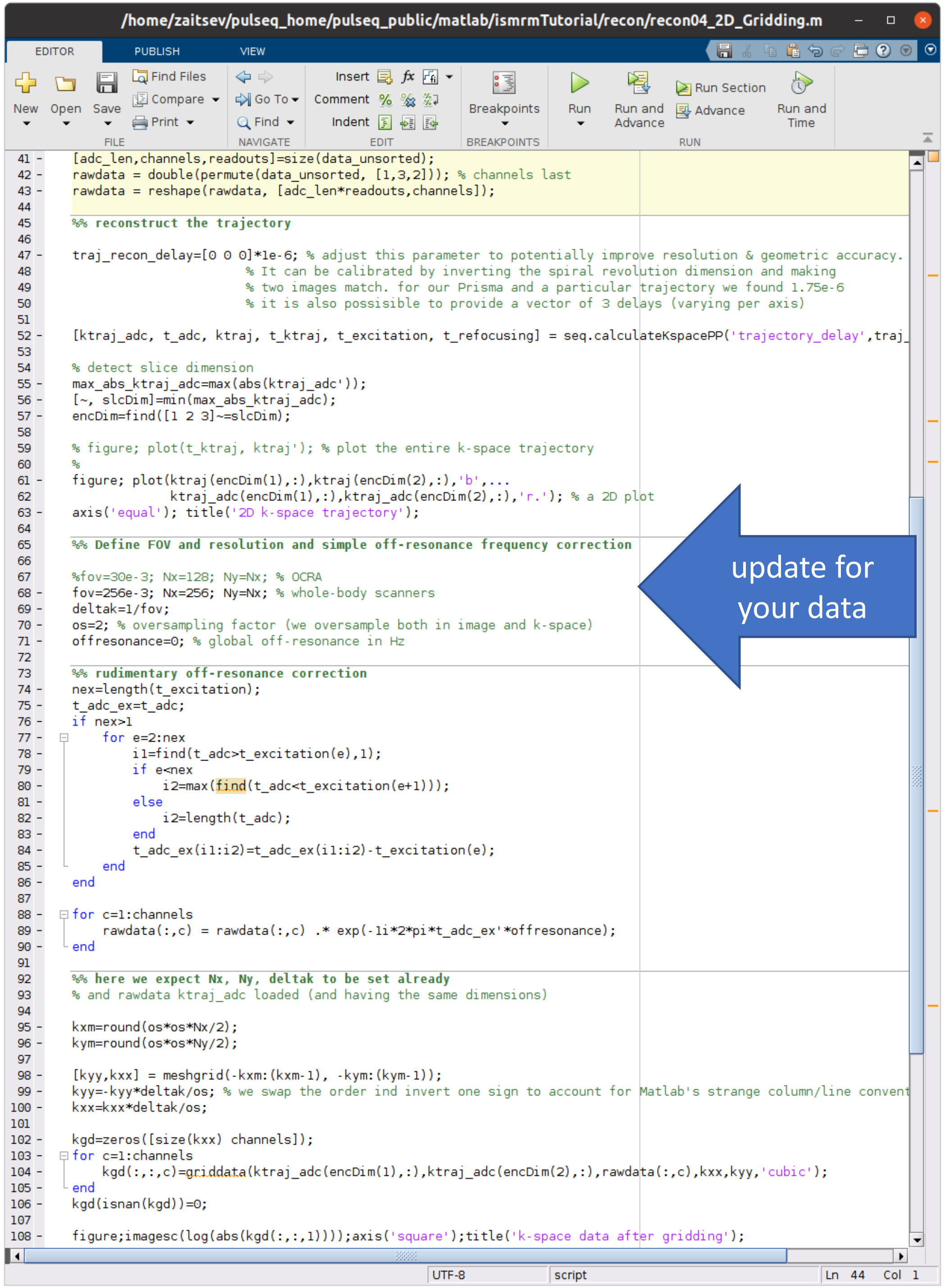
Pulseq – iRadon

- The beginning of the script is similar to the FID/SE/2D FFT examples
- Projection directions are calculated from the Pulseq sequence file
- Matrix size and projection data centering needs to be adjusted manually
- Example also shows a comparison between absolute value and complex inverse Radon transformations
  - Check out the gradient-echo data to notice the difference



Pulseq – 2D Gridding

- The beginning of the script is similar to the FID/SE/2D FFT examples
- Calculate the sampling trajectory from the Pulseq sequence file
  - Any crazy trajectory can be reconstructed
  - *Also 2D Cartesian data are compatible*
- FOW and imaging matrix size may need to be adjusted manually
- The screen shot ends with showing the gridded k-space data
- *Following (not shown) part is a trivial 2D FFT and a sum-of-square combination for multichannel data*



Outline

- ***Pulseq*** sequence definition and programming language overview
- Using ***Pulseq*** on different types of scanners:
  - Siemens, GE, and tabletop scanners using OCRA
- Live demo of ***Pulseq*** across sites
  1. Basic pulse-acquire scans: Free Induction Decay (FID), Spin-Echo (SE)
  2. Cartesian spin-eco imaging
  3. Radial imaging (spin-echo and gradient echo)
  4. *Advanced topics (gradient delays and correction, etc…)*
     are only covered in the live portion of the tutorial

How to reach us

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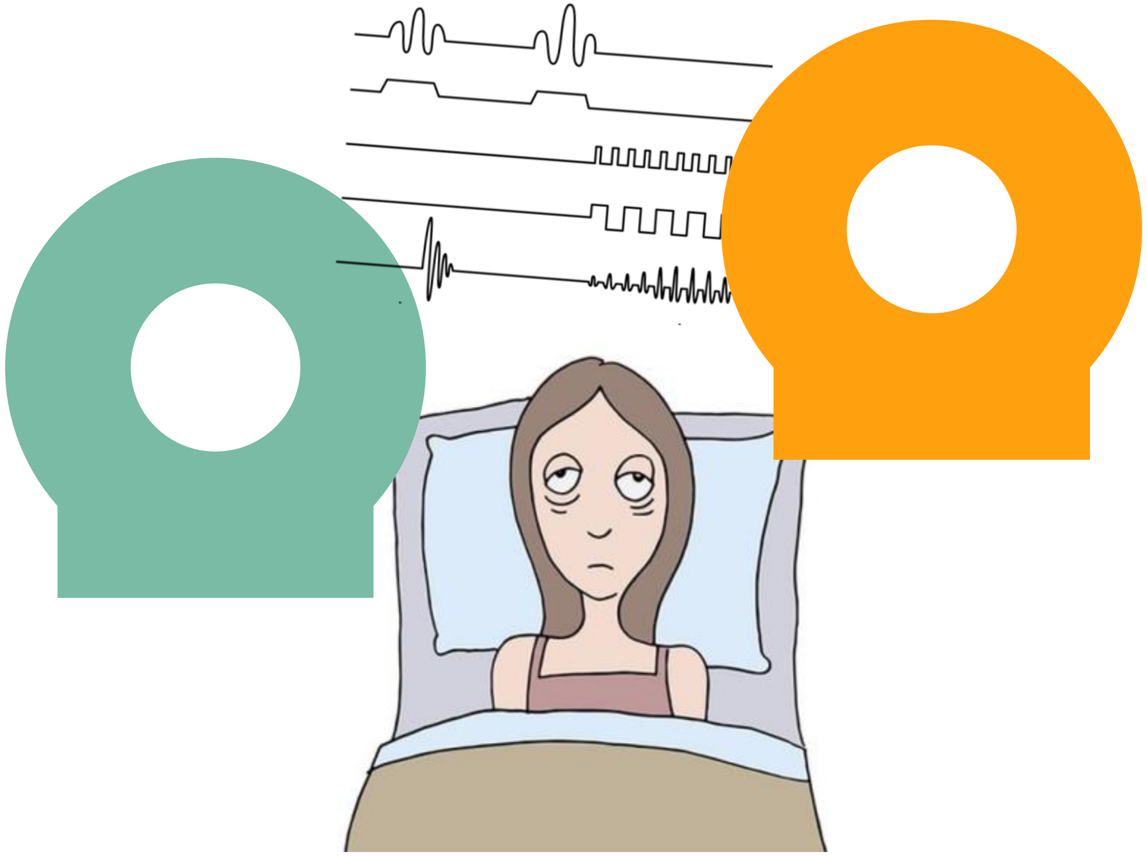
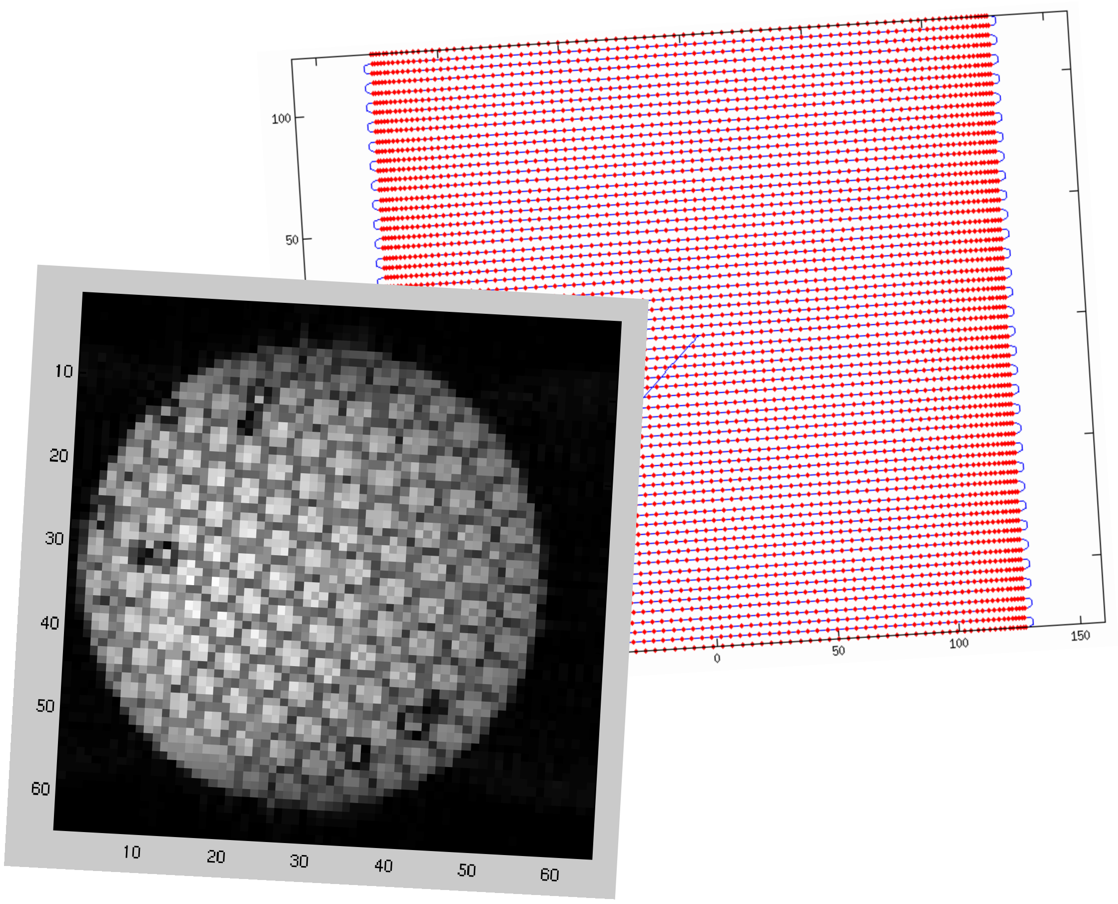
Join us on Wed May 19 at 19:00 UTC

Pulseq – that's the way you do it!



...dream of a sequence in the morning...



...check the images in the afternoon!