Experiments

Table of Contents

Experiment instruction

Experiment 1-1: *Larmor Frequency*

OBJECTIVE OF THE EXPERIMENT

One of the most important parameters in magnetic resonance experiments is the Larmor frequency f_L. It depends on the gyromagnetic ratio γ and the field strength of the magnet B_0.

The Larmor frequency can be calculated by:

$$f_L = \frac{\gamma}{2\pi} \cdot \mathrm{B}_0$$

$\gamma = 26{,}75 \cdot 10^7 \frac{rad}{s \cdot T}$ for ^{1}H nuclei.

In this experiment, we want to adjust the transmitter and receiver frequency (system frequency) of the magnetic resonance tomography device.

The pulse sequence for this measurement contains a simple 90° RF pulse for excitation of the spins. In this experiment you can freely adjust the frequency of the RF pulse. If the frequency of the RF pulse matches the Larmor frequency, the spins will get excited and rotate in the XY plane. This induces an electrical current in the receiver coil and a free induction decay of the signal can be observed (Figure 1).

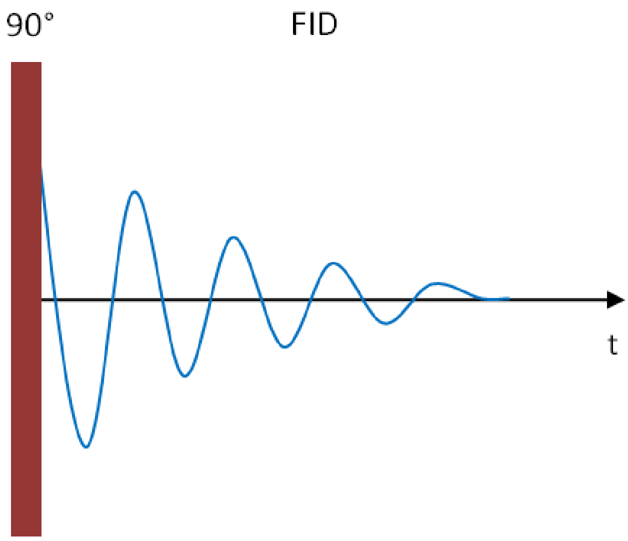

Figure 1: Pulse sequence for the experiment *MR frequency*

The field strength of the magnet slightly changes with its temperature. Due to this temperature drift, it is advised to regularly calibrate the frequency by repeating this experiment.

It is recommended to adjust the frequency before performing any further experiment.

PREPARATION

In this experiment, the 10 mm oil sample is used. Place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson *Larmor Frequency*. The panel *Parameters* shows the sliders for the frequency and the repetition time. Please compare your panel with Figure 2.

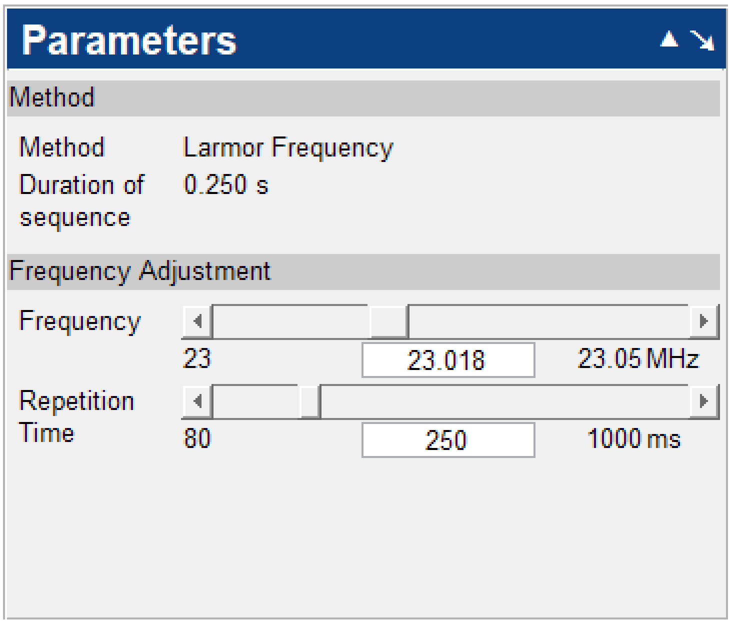

Figure 2: Parameters for experiment *Larmor frequency*

With the slider *Frequency* you can adjust the transmitter and receiver frequency of the tomograph.

Using the oil sample a repetition time of 250 ms is correct.

Press *Start* to start the measurement.

A label on top of the magnet indicates the frequency of the magnet at the specified temperature.

TASKS

(1) Change the system frequency by varying the slider *Frequency*.
What do you observe?

Please note that the oscillation frequency of the real and imaginary parts of the displayed signal is not the Larmor frequency. It is due to difference between the Larmor frequency and the system frequency.

(2) Now calibrate the frequency. An optimum calibration is achieved when the number of visible oscillations in the real and imaginary parts of the FID is as low as possible. Take a note of the frequency f_L and calculate the field strength B_0 of the magnet.

What is the exact field strength B_0 of the permanent magnet?

(3) How does the presence of iron close to the sample influence the magnet?

Adjust the frequency as mentioned in (2). Take a piece of iron and bring it close to the magnet. What can be observed?

(4) What can be observed when changing the sample?

Simply exchange the test tube with oil against the one with water. Keep the repetition time at 250 ms.

(5) Why is it important to observe the real and imaginary part of the FID? For this purpose, enable or disable the checkbox *Real & Imaginary Part* in the *Data Display* panel while measuring.

Calibrate the system frequency as described in (2).

<u>It is recommended to calibrate the system frequency prior to each experiment.</u>

Experiment instruction

Experiment 1-2:
Excitation Angle

OBJECTIVE OF THE EXPERIMENT

One of the key requirements for magnetic resonance experiments is to know the 90° pulse duration. The highest NMR signal can be obtained when the pulse tips the magnetization exactly 90° into the x-y-plane of the frame of reference (see "Experiment Preparation"). The amplitude of the NMR signal depends on the pulse duration of the RF pulse. Further experiments rely on the 90° pulse duration being correctly set.

For the determination of the correct 90° pulse duration, an RF pulse with adjustable duration is transmitted. Directly after the excitation of the sample, the signal of the FID is acquired. Figure 3 shows the sequence and exemplary measurement signal for this experiment.

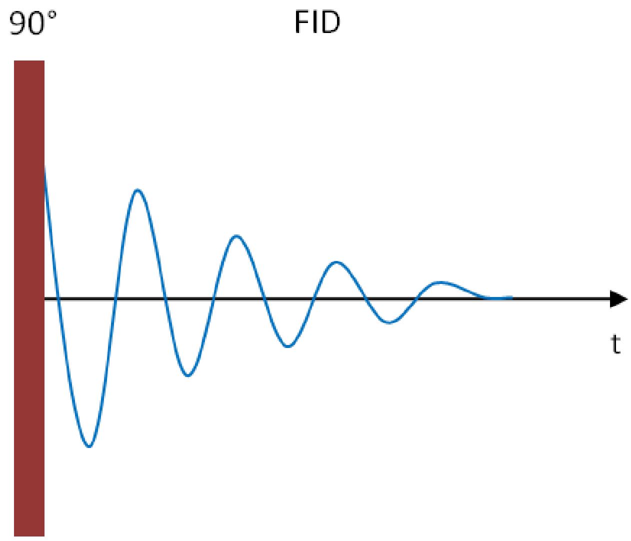

Figure 3: Sequence for the experiment *Excitation Angle*

PREPARATION

In this experiment, the 10 mm oil sample is used. Place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson *Excitation angle*. The panel *Parameters* shows the slider for the duration of the 90° excitation pulse and a *Save* button. Please compare your parameter panel with Figure 4.

Please make sure the checkbox for the real/imaginary part is selected.

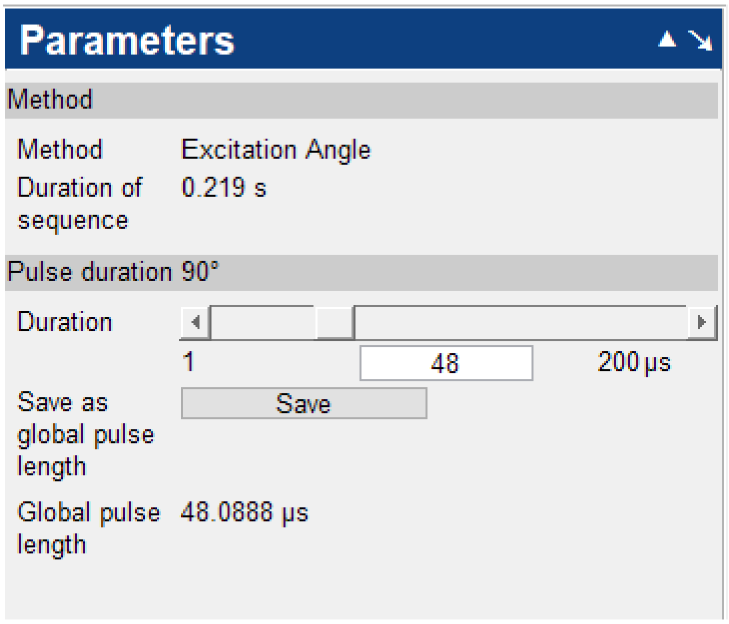

Figure 4: Parameters for experiment *Excitation Angle*

With the slider *Duration*, you can adjust the duration of the 90° RF pulse.

After having found the correct 90° pulse duration, press the *Save* button to set this value for all other experiments.

Press *Start* to start the measurement.

TASKS

(1) Change the pulse duration of the 90° RF pulse by varying the slider *Pulse duration 90°*.

What do you observe?

(2) What duration will give the best 90° pulse and why?

Set the pulse duration to an optimum 90° pulse **and** press the *Save* button. This setting will be used for further experiments.

Experiment instruction

Experiment 1-3:
B_0 Homogeneity (Magnet Shim)

OBJECTIVE OF THE EXPERIMENT

Objective of this experiment is to observe the dependency of the FID duration on the homogeneity of the magnetic field.

After an excitation pulse is applied, the amplitude of the FID stays at a constant level as long as all spins rotate with the same frequency. In practice this is not the case. There are static as well as time-dependent disturbances of the magnetic field B_0.

The simplest case of static disturbances is the inhomogeneity of the magnetic field B_0. This means that the field strength that the spins observe depends on their location. Thus, the precession frequency is different depending on the location of the respective spins. The observed signal is a superposition of all of these different frequencies. The more inhomogeneous the magnetic field, the more different frequencies superimpose and the faster the signal decays.

To improve the homogeneity of the static magnetic field, it can be superimposed by additional magnetic fields. These fields are generated by the so-called shim coils. The field generated by the shim coils has to be adjusted such that the signal after applying a 90° RF excitation pulse takes as long as possible before disappearing.

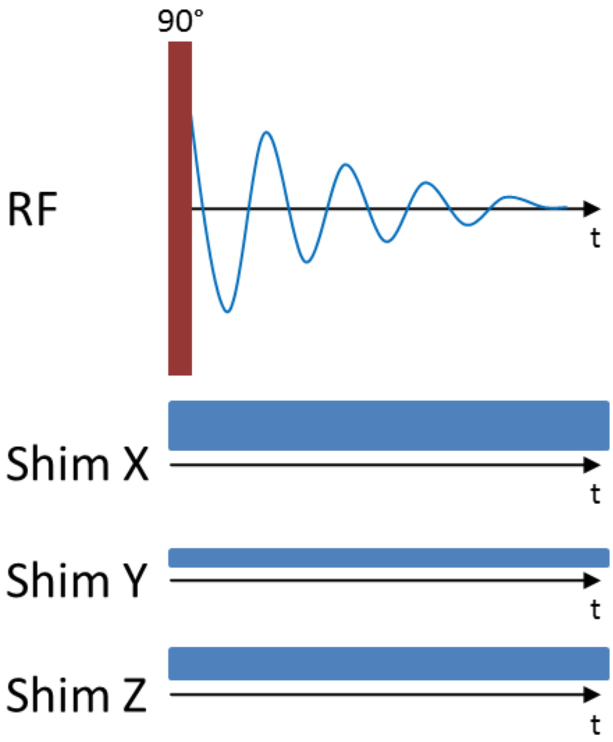

Figure 5: Sequence for experiment *B_0 Homogeneity (Magnet Shim)*

PREPARATION

In this experiment, the 10 mm oil sample is used. Place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson *B_0 Homogeneity (Magnet Shim)*. The panel *Parameters* shows three sliders for the additional magnetic fields that will be generated by the corresponding shim coils. Additionally, the button *Set 0* can be used to re-set all additional fields to 0 and re-start the experiment. Please compare your panel with Figure 6.

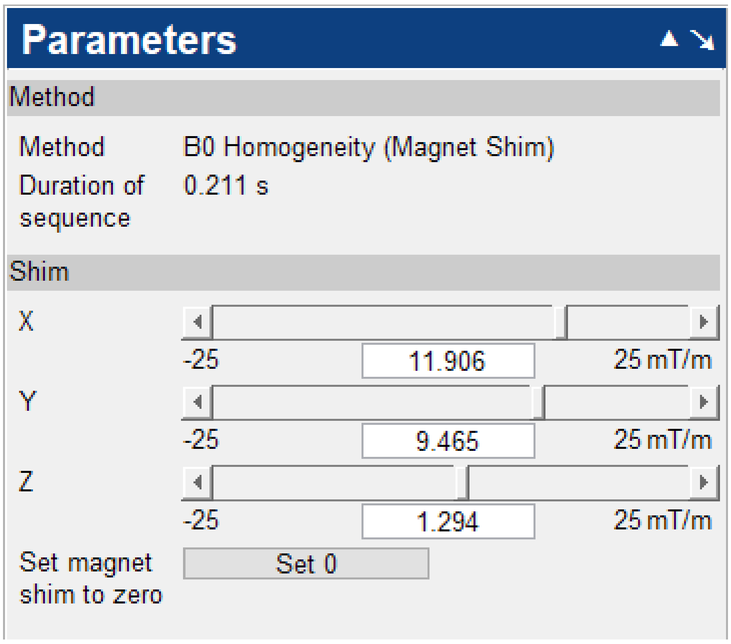

Figure 6: Parameters for experiment *B_0 Homogeneity (Magnet Shim)*

The unit of the shim field is mT/m.

Set all parameters to 0 mT/m by pressing the button *Set 0* before running this experiment.

Press *Start* to start the measurement.

TASKS

(1) Change the strengths of the shim fields.

What do you observe?

(2) Adjust the sliders to improve the homogeneity of the magnetic field. It might be necessary to adjust all sliders several times to achieve the maximum homogeneity.

To do so, follow these instructions:

- Set all shim values to zero by pressing the button *Set 0*.
- Start the procedure by adjusting slider *X* until the decay of the FID cannot be extended any further.
- Now, adjust the slider for *Y* to extend the duration of the decay as far as possible.
- Do the same with *Z*.
- Re-start with *X* and repeat this procedure until the decay cannot be improved any further.

Note down the values for linear shim in *X*, *Y* and *Z*.

Try hard to find the best linear shim values in X, Y and Z to achieve the best possible shim.

<u>These settings will be used in the following experiments and greatly influences the results!</u>

Experiment instruction

Experiment 1-4:
Quantity Determination

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to observe the impact of the substance quantity in the test tube on the signal amplitude.

For this experiment the pulse sequence of experiment 1-1 *Larmor frequency* is used. A 90° RF pulse is used for excitation. The measurement is repeated continuously with a user defined repetition time. After each measurement the FID is displayed. Figure 7 shows the pulse sequence for this measurement.

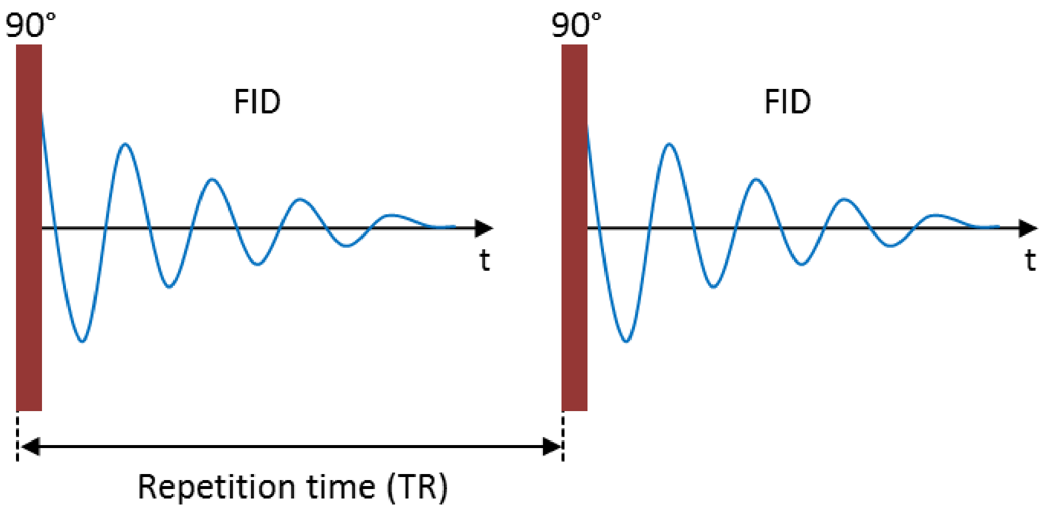

Figure 7: Sequence for experiment *Quantity determination*

PREPARATION

In this experiment, the 10 mm and 5 mm water samples are used. At first, place the test tube labeled *10 mm Water* into the bore of the magnet.

Select the lesson *Quantity Determination*. The panel *Parameters* shows the slider for the repetition time of the experiment. Please compare your panel with Figure 8.

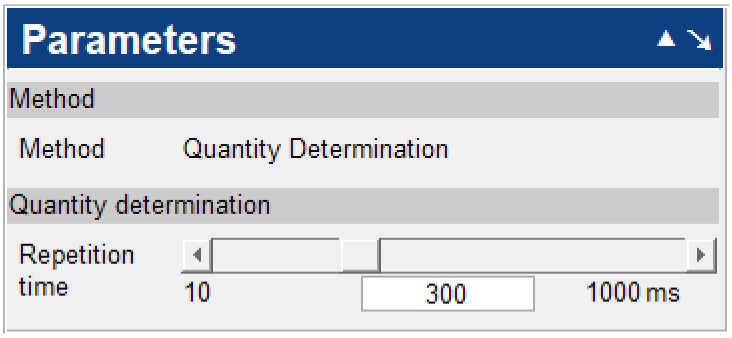

Figure 8: Parameters for experiment *Quantity Determination*

With the slider *Repetition time* you can adjust the time between experiments.

Set the repetition time to 5000 ms (i.e. 5 seconds).

Press *Start* to start the measurement.

TASKS

(1) Determine the amplitude of the FID directly after the 90° pulse. You might use the *data cursor* mode to get a reading from the graph in the *Data Display* panel. Please note that the duration for the 90° pulse is set to the value determined in experiment 1-2 *Excitation Angle*. Make sure that you have successfully completed the lesson *Excitation Angle* before doing this experiment.

Which signal amplitude do you observe?

(2) Repeat the measurement with the 5 mm test tube. Which signal amplitude do you observe now?

(3) Compare the signal amplitudes from (1) and (2).

(4) Why should you set the repetition time to at least 5 seconds when determining the amplitude of the water? Try setting the repetition time to smaller values.

Experiment instruction

Experiment 1-5:
Spin Echo

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to generate a spin echo signal.

The spins in the sample are affected by static as well as time-dependent inhomogeneities. The larger these disturbances, the shorter is the decay time of the FID. Please refer to the results of the experiment *B_0 Homogeneity (Magnet Shim)*.

If the disturbances are constant over time – like for example the inhomogeneity of the magnetic field – the phase relationship that got imprinted onto the spins with the 90° RF pulse remains even if the total signal disappears. A 180° RF pulse re-phases the signal by “reversing” the precession motion of the spins. The signal amplitude reaches a maximum after which it decreases again. This maximum is called spin echo.

The sequence for this experiment is shown in Figure 9. At first, the sample is excited by a 90° RF pulse *P1* which generates an FID. After some time, a 180° RF pulse *P2* is applied to start re-phasing the signal. The time when the spin echo signal has its maximum is called echo time. This time depends on the time delay between the 90° and the 180° pulse.

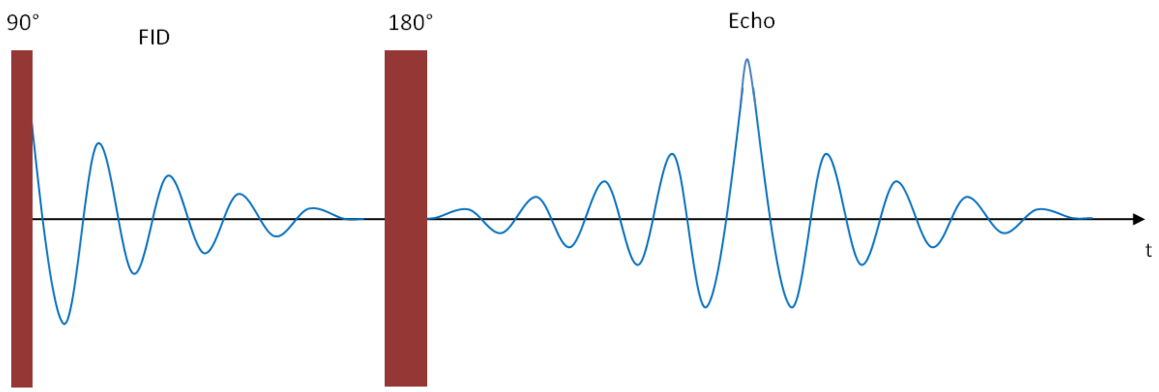

Figure 9: Pulse sequence for experiment *Spin Echo*

PREPARATION

In this experiment, the 10 mm oil sample is used. Place the test tube named *10 mm Oil* into the bore of the magnet.

Select the lesson *Spin Echo.* The panel *Parameters* shows the sliders for the duration of the 90° pulse and for the second pulse. Furthermore, there is a slider to adjust the Echo time. Please compare your panel with the parameter panel shown in Figure 10.

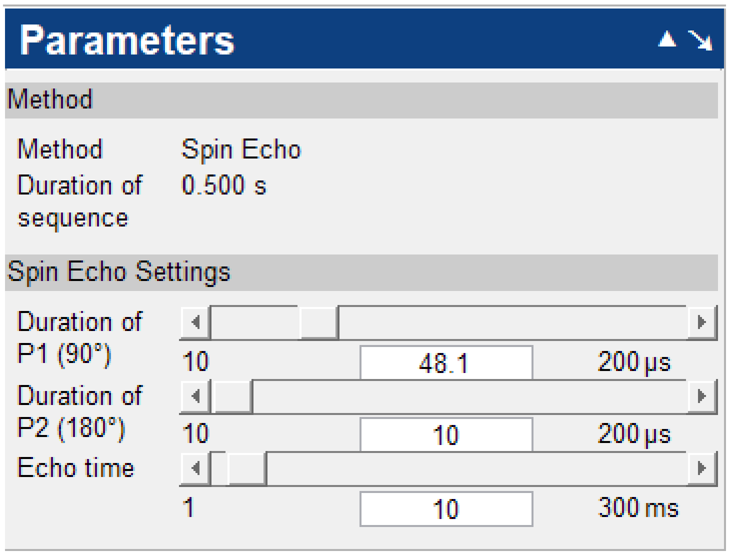

Figure 10: Parameters for experiment *Spin Echo*

With the slider *Duration of P1 (90°)*, you can adjust the duration of the 90° pulse.

The slider *Duration of P2 (180°)* is for adjusting the duration of the second RF pulse (180°).

With the slider *Echo time*, the echo time can be set by varying the time between the two pulses.

Press *Start* to start the measurement.

TASKS

(1) Change the duration of the second pulse by varying the slider *Duration of P2 (180°)*.
What do you observe?

Adjust the control *Duration of P2 (180°)* to obtain an optimum spin echo.

(2) Now vary the pulse length of the 90° pulse with the slider *Duration of P1 (90°)*.

How does this affect the FID and the spin echo?

(3) Alter the echo time with the slider *Echo time*. What do you observe?
(Hint: spin echo amplitude)

(4) Set the duration of the first pulse to an optimum 90° pulse. An optimal 90° RF pulse is set when the FID amplitude has a maximum. A further indication for an optimal 90° RF pulse is the disappearance of the FID after the 180° RF pulse. Why?

Experiment instruction

Experiment 1-6:
Phase Cycling

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to understand the effects of phase cycling on the spin echo signal.

The sequence for this experiment is shown in Figure 11 (see also experiment *Spin Echo*). The phase of the 180° refocusing pulse can be changed between +90° and -90°. Additionally, the average of measurements with both pulse phases can be calculated and displayed.

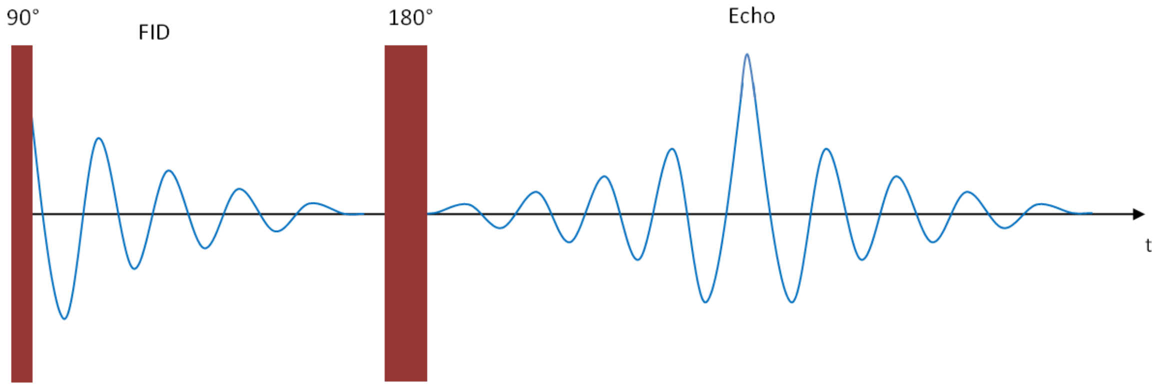

Figure 11: Pulse sequence for experiment *Phase Cycling*

PREPARATION

In this experiment, the 10 mm oil sample is used. Place the test tube named *10 mm Oil* into the bore of the magnet.

Select the lesson *Phase Cycling.* The panel *Parameters* shows the sliders for the echo time and the repetition time. Additionally, a dropdown list allows to select the phase of the 180° refocusing pulse. A check box allows to calculate and display the average of two phase cycled measurements. Please compare your panel with the parameter panel shown in Figure 12.

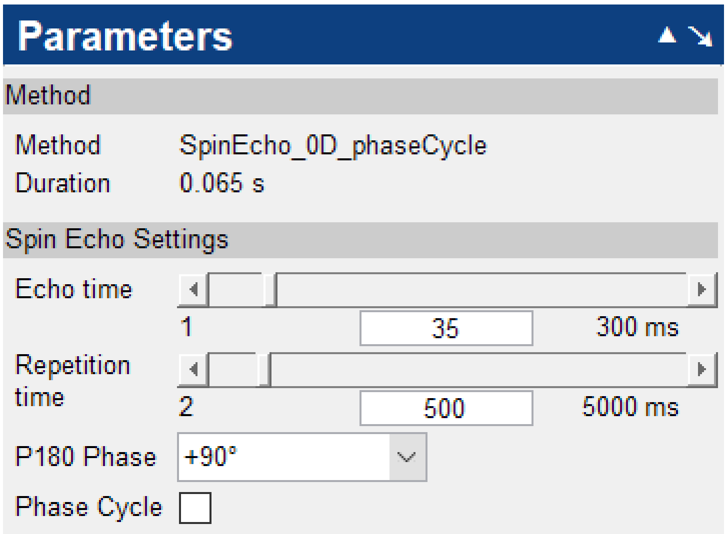

Figure 12: Parameters for experiment *Phase Cycling*

With the slider *Echo time*, you can set the echo time (i.e. time between 90° excitation pulse and echo maximum).

The slider *Repetition time* is for adjusting the time between two subsequent 90° excitation pulses.

The dropdown list *P180 Phase* allows to choose the phase of the 180° refocusing pulse with respect to the phase of the 90° excitation pulse.

The check box *Phase Cycle* activates a second spin echo measurement in which the phase of the 180° refocusing pulse is 180° behind the phase of the same pulse in the first measurement. The data display shows the average of the two measurements in this mode.

Press *Start* to start the measurement.

TASKS

(1) Start the measurement when *Phase Cycle* is not selected. Change the phase of the 180° refocusing pulse by selecting different values in the dropdown list *P180 Phase*.

What do you observe? (Make sure "Real&Imaginary Part" is selected in the Data Display panel.)

(2) Select the check box *Phase Cycle*.

How does this affect the FID and the spin echo?

Explain the effect.

Experiment instruction

Experiment 1-7:
Averages

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to observe and to learn how the signal-to-noise ratio (SNR) can be improved by summation of several single measurements.

If the FIDs of several identical measurements are acquired sequentially, the data can be averaged. By doing so, the noise of the signal cancels partially while the magnetic resonance signal adds coherently. This process takes advantage of the effect that the acquired NMR-signal of each acquisition is the same while the noise is random. The improvement of the SNR is proportional to the square root of the number of averages. For example: To double the SNR, the average of four equal experiments has to be taken.

The sequence for this experiment is shown in Figure 13.

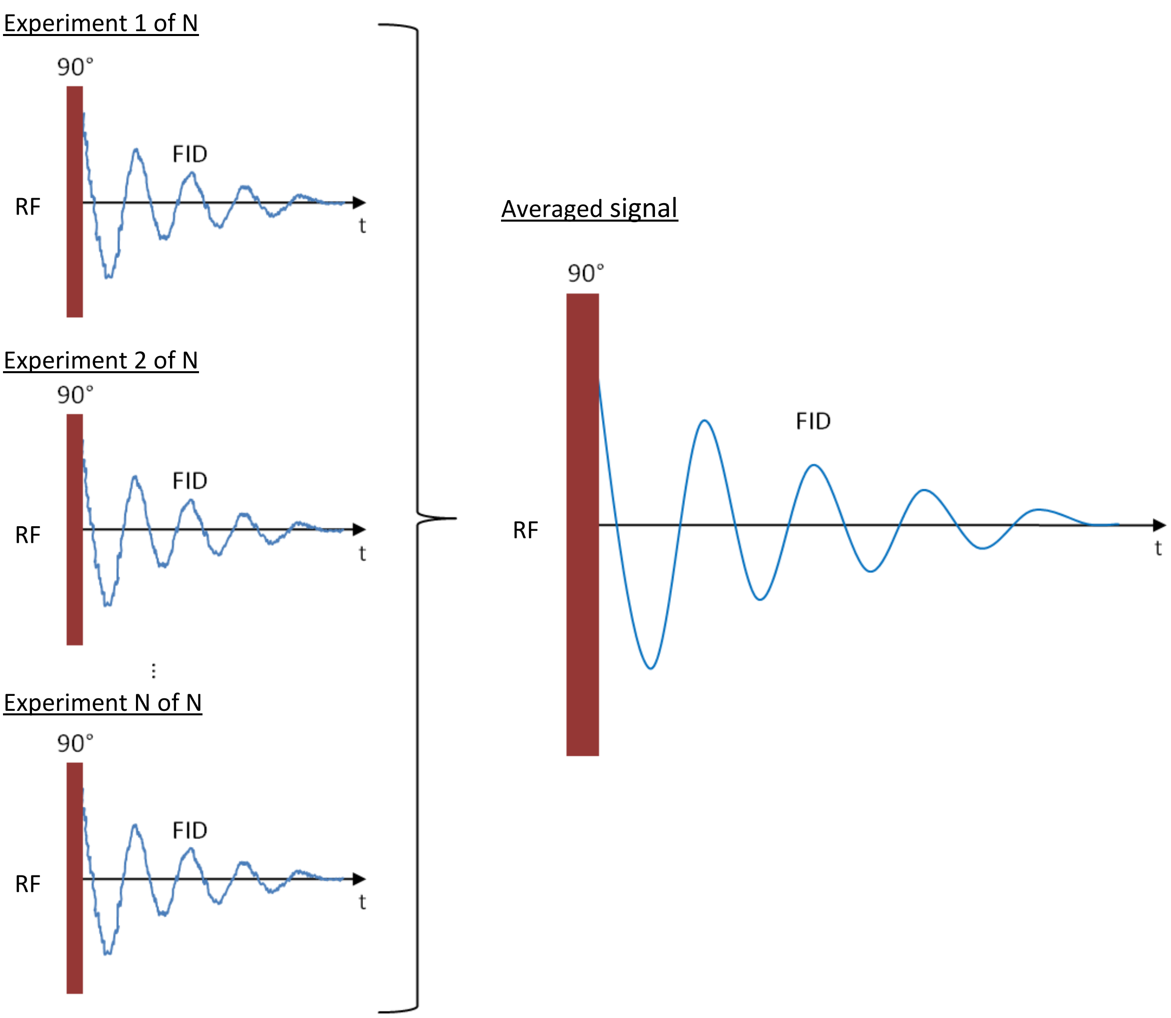

Figure 13: Pulse sequence for experiment *Averages*

PREPARATION

In this experiment, the 5 mm water and the 5 mm oil samples are used. First, place the test tube labeled *5 mm Oil* into the bore of the magnet.

Select the lesson *Averages.* The panel *Parameters* shows the slider *Repetition time* for the repetition time of this experiment. Furthermore, the slider *Averages* is used to adjust the number of averages. Please compare your panel with the parameter panel shown in Figure 14.

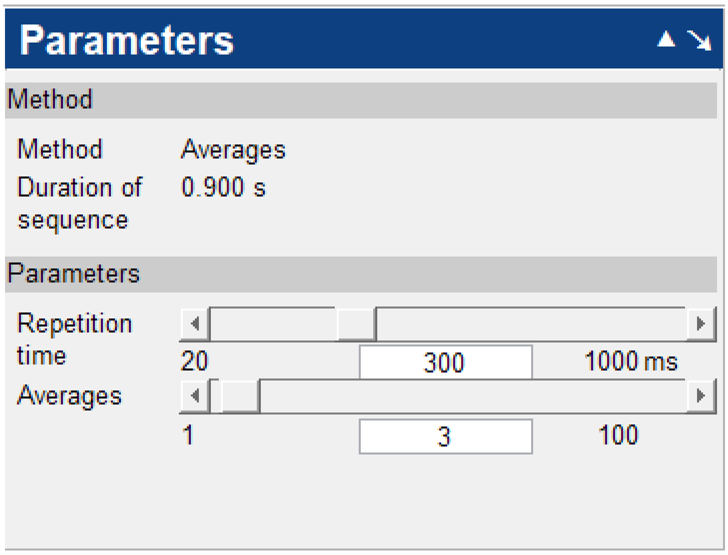

Figure 14: Parameters for experiment *Averages*

With the slider *Repetition time* you can adjust the duration between each single measurement.

The slider *Averages* is for adjusting the number of averages.

Press *Start* for starting the measurement.

TASKS

(1) Set the number of averages to 1 and increase it to 16. The repetition time is the time between two subsequent measurements (start to start).

What do you observe?

(2) Try to find a good balance between a short repetition time and number of averages to obtain a good signal in the shortest possible time.

Note your settings and results.

(3) Repeat this optimization for the water sample labeled *5 mm Water*.

Note your settings and results.

(4) How many averages are necessary to achieve a 10-fold SNR improvement?

(5) What is the disadvantage of averaging?

Experiment instruction

Experiment 1-8:
FID Spectrum

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to experience and understand the influence of shimming on the frequency spectrum of a signal.

Simplified, one would expect to detect a signal that only consists of spins that are precessing exactly at the one Larmor frequency of the magnet in perfect conditions. Among other influences, this is not the case because of inhomogeneities in the magnetic field B_0. Please, see also Experiment 1-3 *B_0 Homogeneity (Magnet Shim)*.

As discussed previously, the linear gradients can be used to improve the magnets homogeneity (shimming). In this experiment the following pulse sequence is used to acquire a shimmable FID:

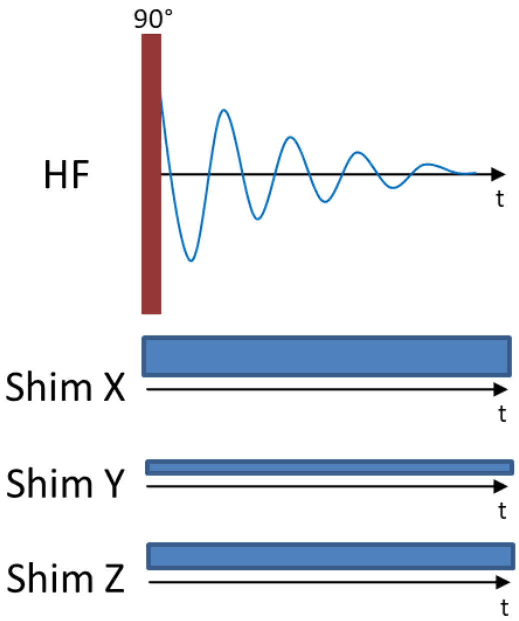

Figure 15: Pulse sequence for experiment *FID Spectrum*

The signal in the frequency domain (Figure 16) is similar to a Lorentz distribution. The width of the distribution at half the maximum value (full width half maximum = FWHM) is a measure for how broadly the frequencies are distributed in the spectrum.

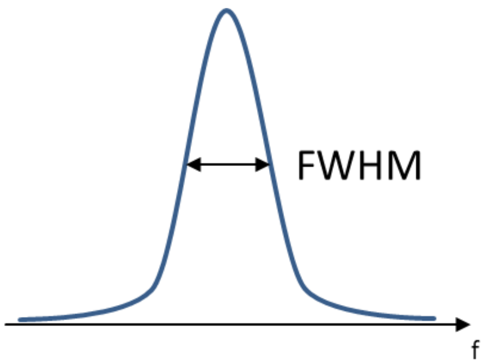

Figure 16: Exemplary frequency distribution of a signal

PREPARATION

For this experiment, place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson *FID Spectrum.* The panel *Parameters* shows the following controls (see Figure 17):

Repetition Time*:* The repetition time between the excitation pulses.
Acquisition Time*:* The duration for which the signal is acquired.
Averages*:* The number of averages for each cycle.
Preshots*:* The number of excitation pulses without acquisition before the actual experiment.
Continuous measurement*:* If this checkbox is selected, the experiment is run repeatedly after clicking the "Start" button until the "Stop" button is pressed to interrupt the measurement. If it is unchecked, only one single experiment is run.

The following additional controls are shown to offset some system parameters:

Frequency*:* An offset to the Larmor frequency (configured in the Experiment 1-1 "*Larmor Frequency*").
Shim X/Y/Z*:* Offset values to the linear shim amplitudes (configured in Experiment 1-3 "*B_0 Homogeneity (Magnet Shim)*").

Note that none of these settings affect other experiments.

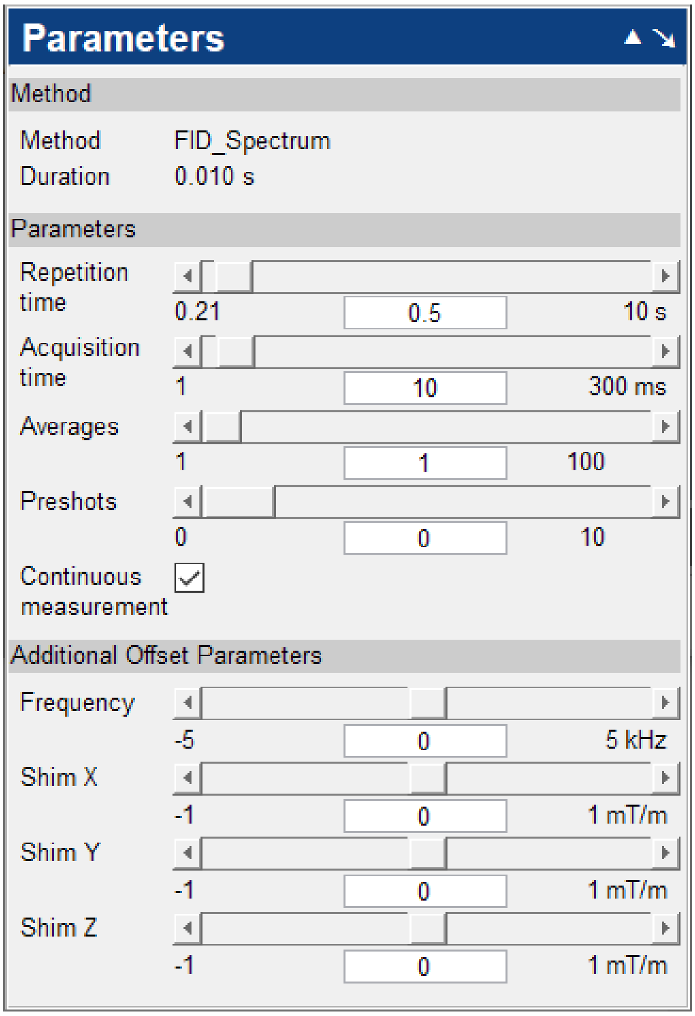

Figure 17: Parameters for experiment *FID Spectrum*

TASKS

(1) Run the experiment and select "Frequency Domain" in the drop-down list of the Data Display panel. A Lorentz distribution is fit to the acquired spectrum (dotted line). Take note of the FWHM of its peak.
Use the Shim X, Shim Y and Shim Z sliders and try to minimize the FWHM of the peak.
From what you see, do you think that the shim values you chose in Experiment 1-3 "*B_0 Homogeneity (Magnet Shim)*" have been optimal?

(2) Reduce the acquisition time to the shortest possible value. Observe the FHWM while you slowly increase the acquisition time. Try to explain your observation.
Also observe what is happening in the Time Domain to understand your observation.

Experiment instruction

Experiment 2-1:
T_1 Estimation

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to estimate the spin-lattice relaxation time T_1 of oil and water.

This can be done by comparing the signal amplitude of FIDs that are acquired with different repetition times TR.

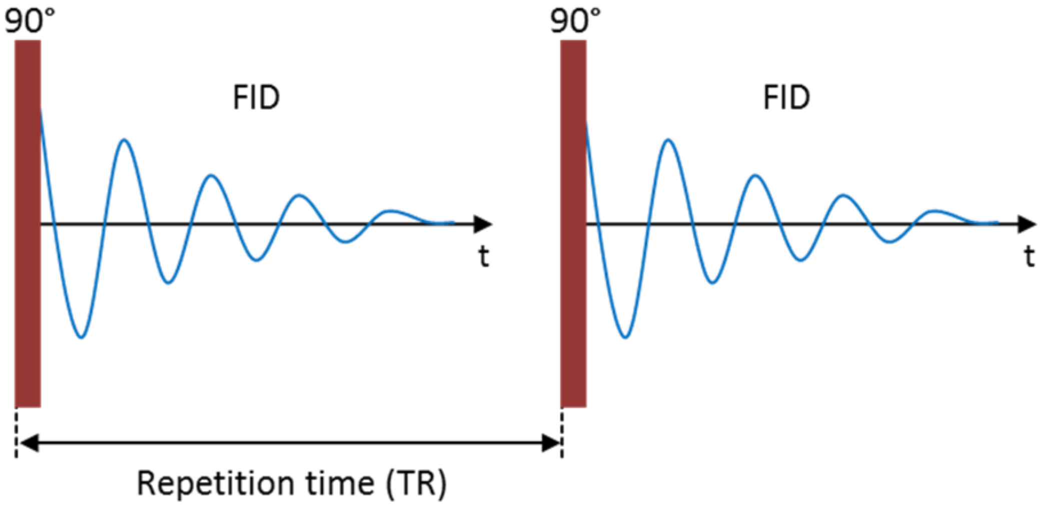

Figure 18: Pulse sequence for experiment T_1 *Estimation*

PREPARATION

In this experiment, the 10 mm water and the 10 mm oil samples are used. First, place the test tube labeled *10 mm Water* into the bore of the magnet.

Select the lesson T_1 *Estimation.* The panel *Parameters* shows the slider *Repetition time* for the repetition time of this experiment. Please compare your panel with the parameter panel shown in Figure 19.

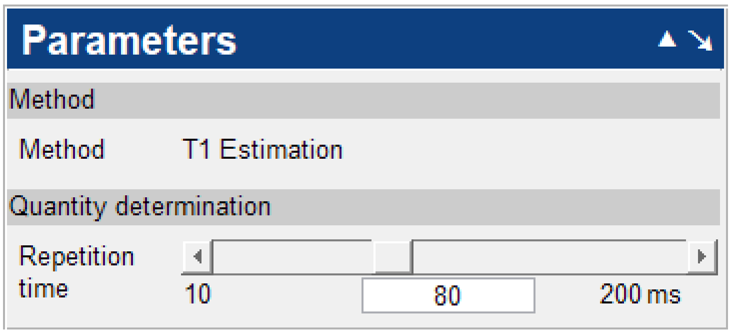

Figure 19: Parameters for experiment T_1 *Estimation*

With the slider *Repetition time* you can adjust the duration between consecutive measurements (start-to-start).

Press *Start* for starting the measurement.

TASKS

(1) Change the time between both pulses by varying the slider *Repetition time*.

What do you observe?

(2) Set the repetition time TR to 15 seconds. The signal amplitude should not change when TR is increased any further. Take a note of the value of the signal amplitude.

(3) Reduce the repetition time to a value where the signal amplitude is half the height of before. It is recommended to proceed as follows:
At first reduce the repetition time from 15 to 2 seconds. Observe the resulting FID amplitude and decide whether the repetition time has to be further decreased or increased again. Repeat this procedure with decreasing step widths until you find the repetition time where the amplitude is half as high as in (2). Take a note of the value of the repetition time $TR_{½}$.

(4) Calculate the spin-lattice relaxation time T_1 of water using the value of the repetition time.

(5) Now repeat the experiment with the oil sample and calculate the relaxation time T_1 for oil.

(6) Comment on your results and observations.

Experiment instruction

Experiment 2-2:
T_1 Measurement (Saturation Recovery)

OBJECTIVE OF THE EXPERIMENT

In this experiment, the spin-lattice relaxation time T_1 of various samples should be determined precisely.

The pulse sequence for this experiment is shown in Figure 20. It consists of several *measurement steps*. After a given *dwell time DT* starting with the first 90° RF pulse, a second 90° pulse is applied. The maximum signal amplitude of the FID after the second excitation pulse is measured and processed automatically by the computer. After the acquisition of the second FID, the measurement is paused for the *pause time*. This allows the sample to relax (i.e. reach thermal equilibrium).

This measurement is repeated a predefined number of times. In each of these measurement steps, the time between the two 90° pulses is increased to the number of the current measurement multiplied by the given dwell time DT.

The relation between the dwell time (delay between two pulses) and the signal intensity can be used to calculate the relaxation time T_1. This measurement can be applied to any sample. The relaxation time T_1 is specific to the measured substance.

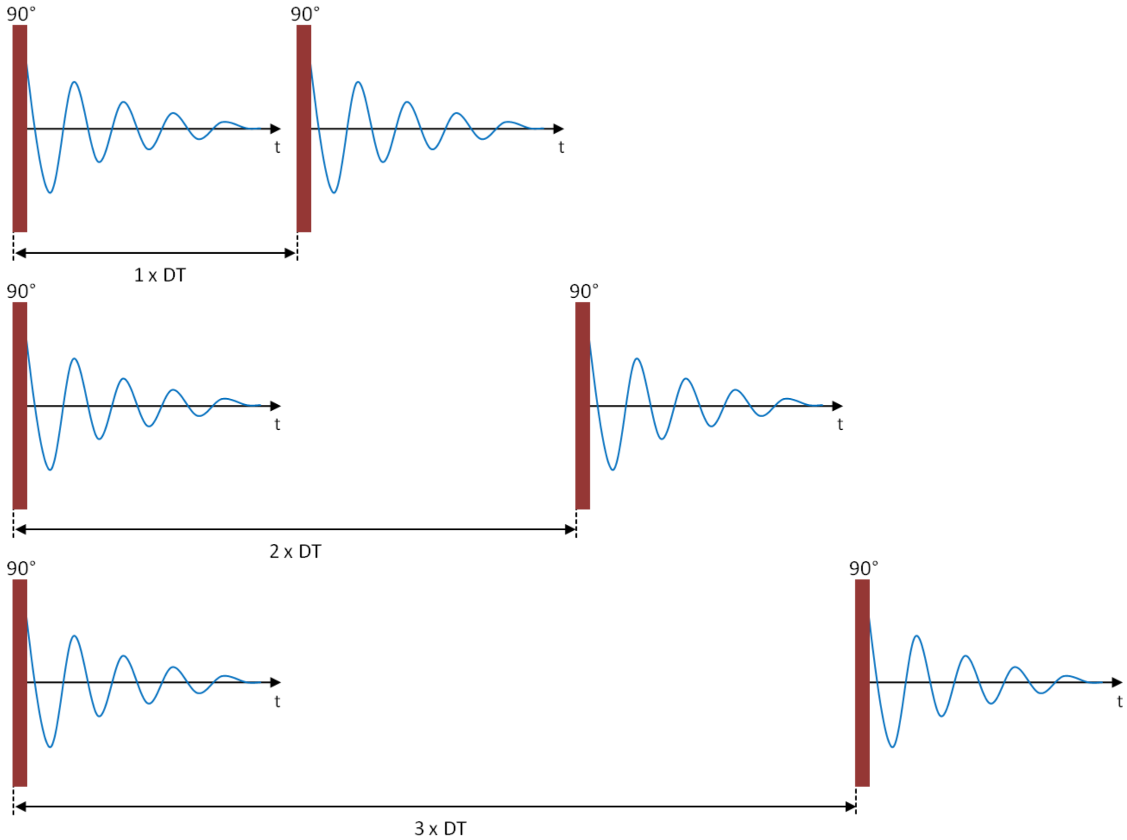

Figure 20: Pulse sequence T_1 *measurement*

PREPARATION

In this experiment, the 10 mm water and the 10 mm oil samples are used. Place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson T_1 *Measurement.* The panel *Parameters* shows the slider *Pause time* for setting the pause between measurement steps in this experiment. Furthermore, there is a slider *Time increment* for setting the value of the dwell time DT. The control *Number of points* is for defining the number of measurement steps.

Additionally, an evaluation section is displayed with the two buttons *Fit* T_1 and *Fit* $T_{1,1}$ *&* $T_{1,2}$.

Please compare your panel with the parameter panel shown in Figure 21.

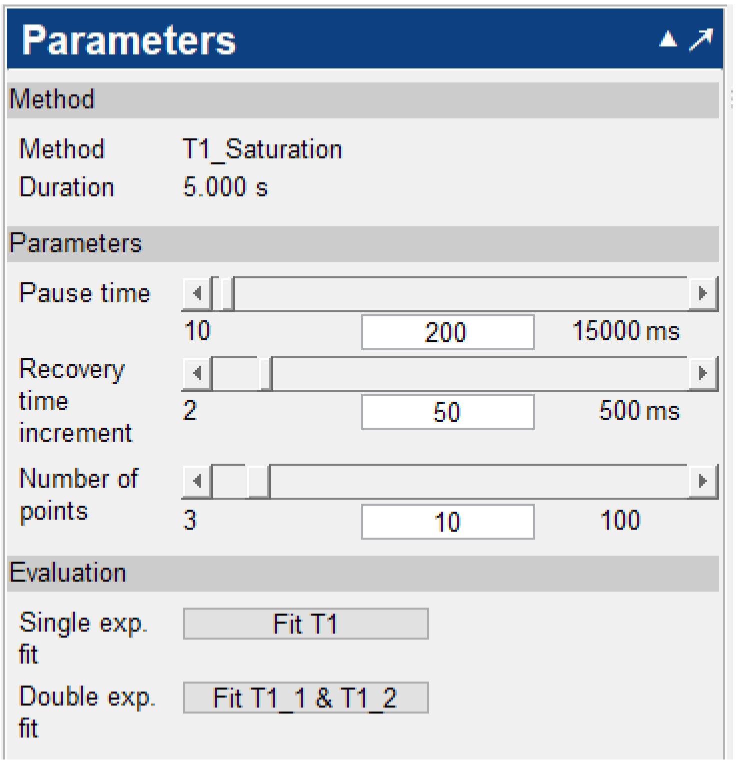

Figure 21: Parameters for experiment T_1 *Measurement*

With the slider *Pause time* you can adjust the pause after the second 90° pulse until the start of the next measurement step.

The slider *Recovery time increment* adjusts the dwell time DT which corresponds to the time between the two 90° pulses of the same measurement step.

The slider *Number of points* varies the number of measurement steps each with increasing dwell time DT.

TASKS

(1) Set the *pause time* to three times the value of T_1 estimated in experiment T_1 *Estimation*. Set the number of points to 24. Change the slider value for the time increment to the eighth part of the estimated T_1 value. Now, start the measurement.

(2) When the measurement has finished, you can evaluate the data as follows:

- Click the button *Fit* T_1 to automatically fit the measurement data with a single exponential curve. The fit routine compensates for a possible frequency drift during the measurement. The (compensated) values used for the fit are displayed with black dots. The best fit curve is displayed with a blue dashed line. The best fit value for T_1 is displayed in the graph.
- The button *Fit* $T_{1,1}$ & $T_{1,2}$ performs a double-exponential fit to the measured data. Judging by the results of the fit, does it make sense to fit with a double exponential curve? Why or why not?

(3) Note the value for T_1 (and potentially $T_{1,1}$ & $T_{1,2}$ with their respective contributions) and print or save the result.

(4) Repeat this experiment for the water sample (test tube *10mm Water*) and note the results.

(5) Comment on your observations.

Experiment instruction

Experiment 2-3: *T_1 Measurement (Inversion Recovery)*

OBJECTIVE OF THE EXPERIMENT

In this experiment, the spin-lattice relaxation time T_1 of various samples should be determined using an inversion recovery preparation.

This experiment is very similar to Experiment 2-2 T_1 *Measurement (Saturation Recovery)*. But instead of a 90° excitation pulse a 180° inversion pulse is used for preparation. The pulse sequence for this experiment is shown in Figure 22. It consists of several *measurement steps*. After a given *dwell time DT* starting with the 180° inversion RF pulse, a 90° excitation pulse is applied. The maximum signal amplitude of the FID after the second excitation pulse is measured and processed automatically by the computer. After the acquisition of the second FID, the measurement is paused for the *pause time*. This allows the sample to relax (i.e. reach thermal equilibrium).

This measurement is repeated a predefined number of times. In each of these measurement steps, the time between the 180° inversion pulse and the 90° excitation pulse is increased to the number of the current measurement multiplied by the given dwell time DT.

The relation between the dwell time (delay between two pulses) and the signal intensity can be used to calculate the relaxation time T_1. This measurement can be applied to any sample. The relaxation time T_1 is specific to the measured substance.

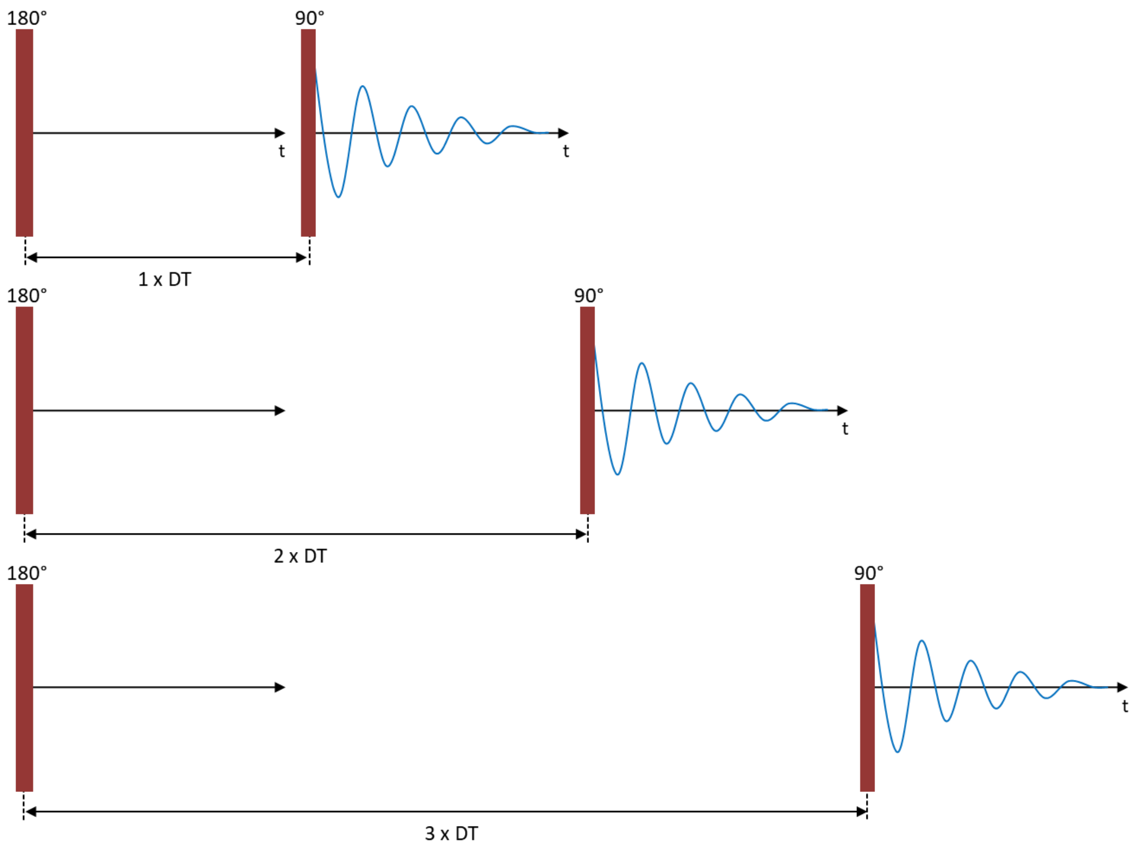

Figure 22: Pulse sequence T_1 *measurement (inversion recovery)*

PREPARATION

In this experiment, the 10 mm water and the 10 mm oil samples are used. Place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson T_1 *Measurement (Inversion Recovery).* The panel *Parameters* shows the slider *Pause time* for setting the pause between measurement steps in this experiment. Furthermore, there is a slider *Time increment* for setting the value of the dwell time DT. The control *Number of points* is for defining the number of measurement steps.

Additionally, an evaluation section is displayed with the two buttons *Fit* T_1 and *Fit* $T_{1,1}$ *&* $T_{1,2}$.

Please compare your panel with the parameter panel shown in Figure 23.

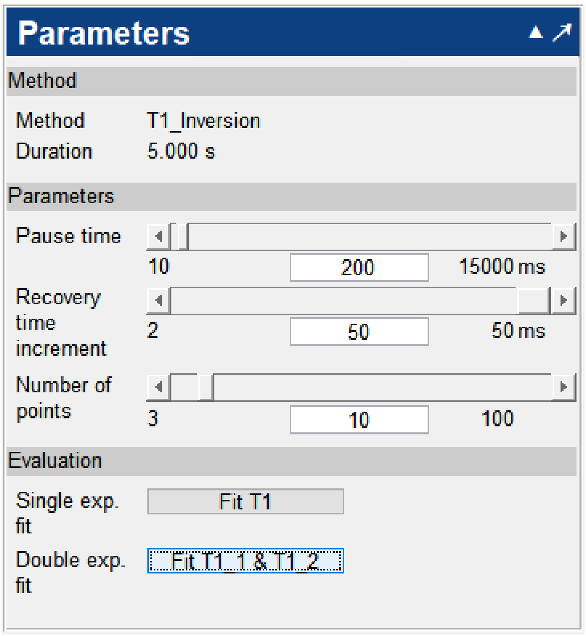

Figure 23: Parameters for experiment T_1 *Measurement (Inversion Recovery)*

With the slider *Pause time* you can adjust the pause after the second 90° pulse until the start of the next measurement step.

The slider *Recovery time increment* adjusts the dwell time DT which corresponds to the time between the 180° inversion pulse and the 90° excitation pulse of the same measurement step.

The slider *Number of points* varies the number of measurement steps each with increasing dwell time DT.

TASKS

(1) Set the *pause time* to three times the value of T_1 estimated in experiment T_1 *Estimation*. Set the number of points to 10. Change the slider value for the time increment to the third part of the estimated T_1 value. Now, start the measurement.

(2) When the measurement has finished, you can evaluate the data as follows:

- Click the button *Fit* T_1 to automatically fit the measurement data with a single exponential curve. The fit routine compensates for a possible frequency drift during the measurement. The (compensated) values used for the fit are displayed with black dots. The best fit curve is displayed with a blue dashed line. The best fit value for T_1 is displayed in the graph.
- The button *Fit* $T_{1,1}$ & $T_{1,2}$ performs a double-exponential fit to the measured data. Judging by the results of the fit, does it make sense to fit with a double exponential curve? Why or why not?

(3) Note the value for T_1 (and potentially $T_{1,1}$ & $T_{1,2}$ with their respective contributions) and print or save the result.

(4) Repeat this experiment for the water sample (test tube *10mm Water*) and note the results.

(5) Which inversion recovery time can be used to effectively suppress the signal of the respective sample?

Experiment instruction

Experiment 2-4:
T_2 Measurement

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to measure the spin-spin relaxation time T_2 of different samples.

This can be done by acquiring a series of spin echoes also known as spin echo train.

The pulse sequence for this experiment is shown in Figure 24. After the first spin echo, a second 180° refocusing pulse is applied which generates another spin echo at the time 2 × TE. The latter spin echo has smaller amplitude than the former. This is due to the relaxation time T_2. The maximum signal intensity of each echo is detected.

This can be repeated several times. After each 180° pulse an Echo with consecutively lower amplitude can be observed. This is called an *Echo train*.

After the data is acquired a curve fitting algorithm can be applied to calculate the relaxation time T_2 of the sample.

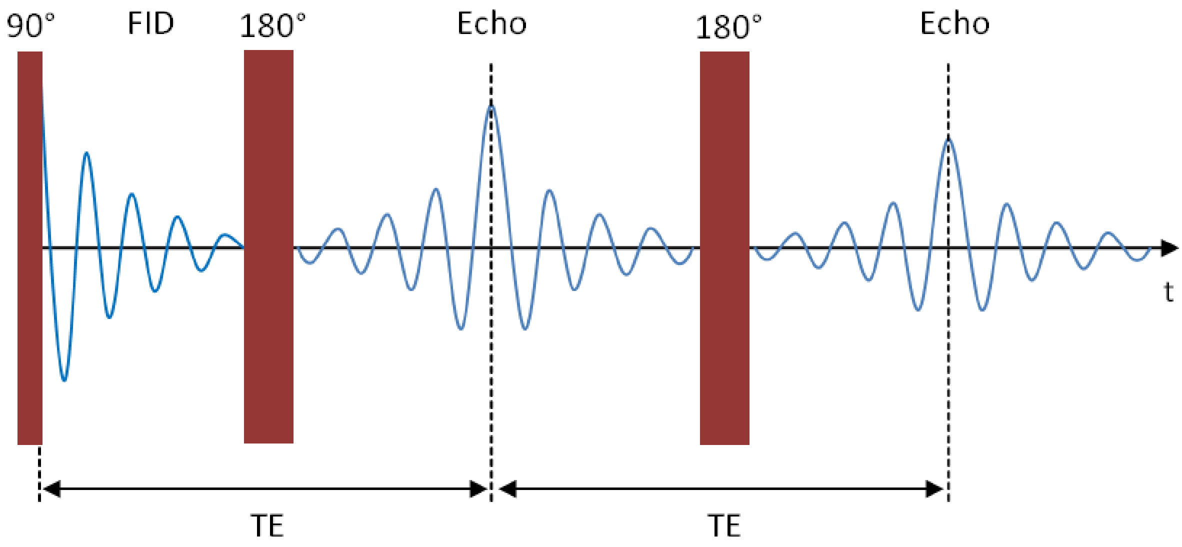

Figure 24: Pulse sequence for experiment T_2 *Measurement*

PREPARATION

In this experiment, the 10 mm water sample and the 10 mm oil sample are used. First, place the test tube labeled *10 mm Oil* into the bore of the magnet.

Select the lesson T_2 *Measurement.* The panel *Parameters* shows the sliders *Number of echoes* and *Echo time*.

Additionally, an evaluation section is displayed with the two buttons *Fit* T_2 and *Fit* $T_{2,1}$ *&* $T_{2,2}$.

Please compare your panel with the parameter panel shown in Figure 25.

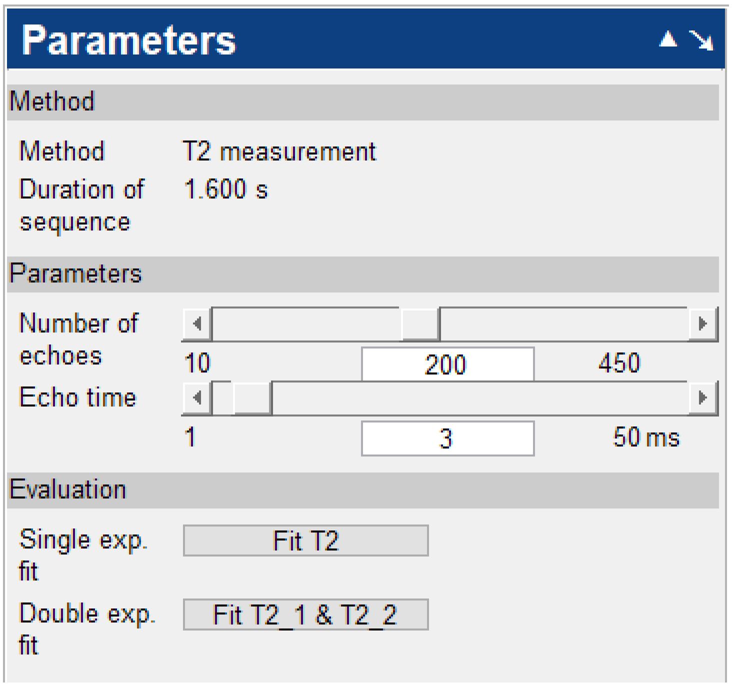

Figure 25: Parameters for the experiment T_2 *Measurement*

With the slider *Number of echoes* you can set the number of echoes to generate in this experiment. (Note: the duration for this experiment is the product of N*umber of echoes* and *Echo time*).

The slider *Echo time* is for adjusting the time between two spin echoes in the echo train.

TASKS

(1) Set the *Number of echoes* to approximately 250 and the *Echo time* to 2 ms.

Start the measurement.

(2) When the measurement has finished, evaluate the data as follows:

- Click the button *Fit* T_2 to automatically fit the measurement data with a single exponential curve. The fit routine compensates for a possible frequency drift during the measurement. It also takes into account that the 180° pulse could be slightly off (see *Experiment 1-2 Excitation Angle*). In this case, it is possible that the echo amplitude "crosses" the zero line. The (compensated) values used for the fit are displayed with black dots. The best fit curve is displayed with a blue dashed line. The best fit value for T_2 is displayed in the graph.
- The button *Fit* $T_{2,1}$ & $T_{2,2}$ performs a double-exponential fit to the measured data. Judging by the results of the fit, does it make sense to fit with a double exponential curve? Why or why not?

(3) Note the value for T_2 (and potentially $T_{1,1}$ & $T_{1,2}$ with their respective contributions) and print or save the result.

(4) Repeat this experiment for the water sample (test tube *10 mm Water*) with an increased echo time.

(5) Comment on your observations.

Experiment instruction

Experiment 2-5:
Ernst Angle

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to measure the Ernst angle of a sample at a given repetition time.

For this experiment, an excitation pulse with configurable flip angle α is repeated periodically at a rate of the repetition time TR. Figure 26 schematically shows the pulse sequence of this experiment.

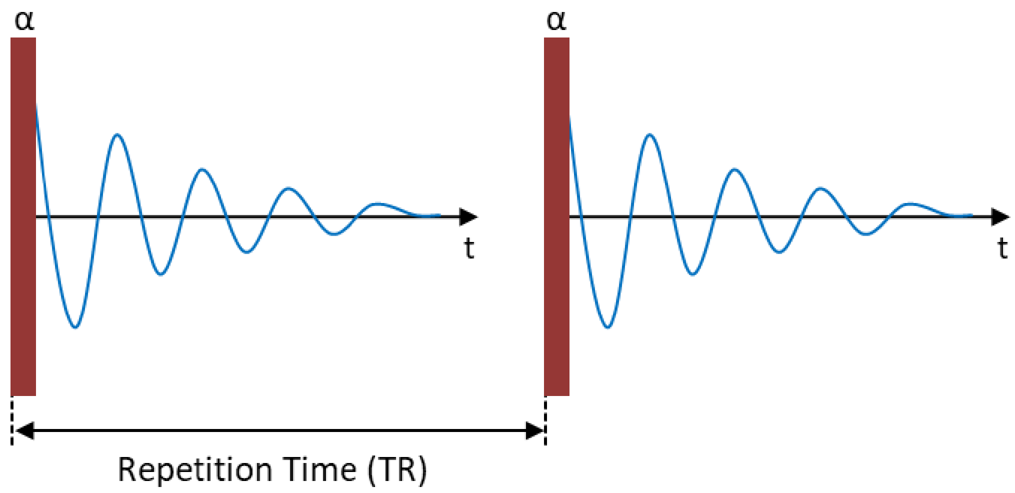

Figure 26: Pulse sequence for experiment *Ernst Angle*. The pulses are repeated several times.

PREPARATION

In this experiment, the 10 mm test tube containing water is used. Insert this sample into the bore of the magnet.

Select the experiment *Ernst Angle*. The panel *Parameters* shows the following controls:

Repetition Time*:* The repetition time between the excitation pulses.
Excitation Angle*:* The flip angle α for the excitation pulse.

Please compare your panel with Figure 27.

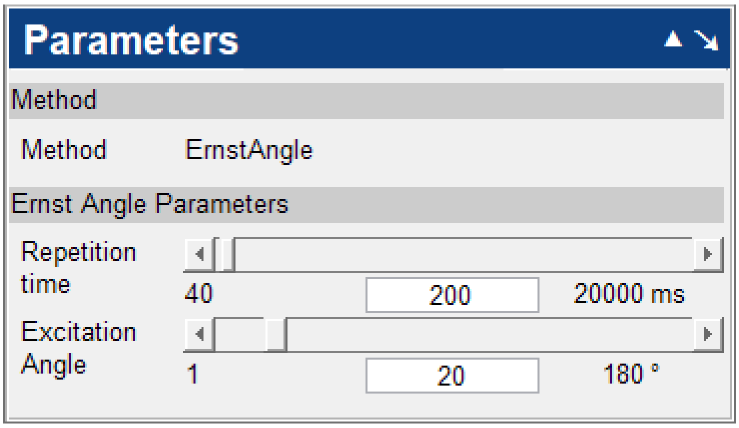

Figure 27: Parameter for experiment *Ernst Angle*

TASKS

(1) Set the repetition time to 200 ms and the excitation angle to 90°. Start the measurement.
What do you observe?

(2) Increase the excitation angle from 5° to 90° in steps of 5° and take note of the MR signal amplitude after each step. You might use the “data cursor” tool and add a data tooltip to the first sample in the Data Display to get a better reading of the signal amplitude.

(3) Plot the acquired signal amplitude in dependency of the excitation angle (e.g. with a spreadsheet program). From your measurement, give a value for the Ernst Angle of the water sample at that repetition time.

(4) Using the measured Ernst Angle, give an estimate for the T1 value of the water sample.
Formula:

$$T_1 = -\frac{T_R}{\ln\left(\cos \alpha_E\right)}$$

Experiment instruction

Experiment 3-1:
Profile 1d

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to measure a spatial profile of the sample.

The spatial encoding of the signal is done by applying additional magnetic fields which are generated by the gradient coils. The resulting magnetic field is a superposition of the main field B_0 and the field generated by the gradient coils. This implies a change in the Larmor frequency dependent on the position in the magnet. Applying a frequency analysis (**F**ast **F**ourier **T**ransform - **FFT**) on the acquired data allows to assign the signal to its location in the sample.

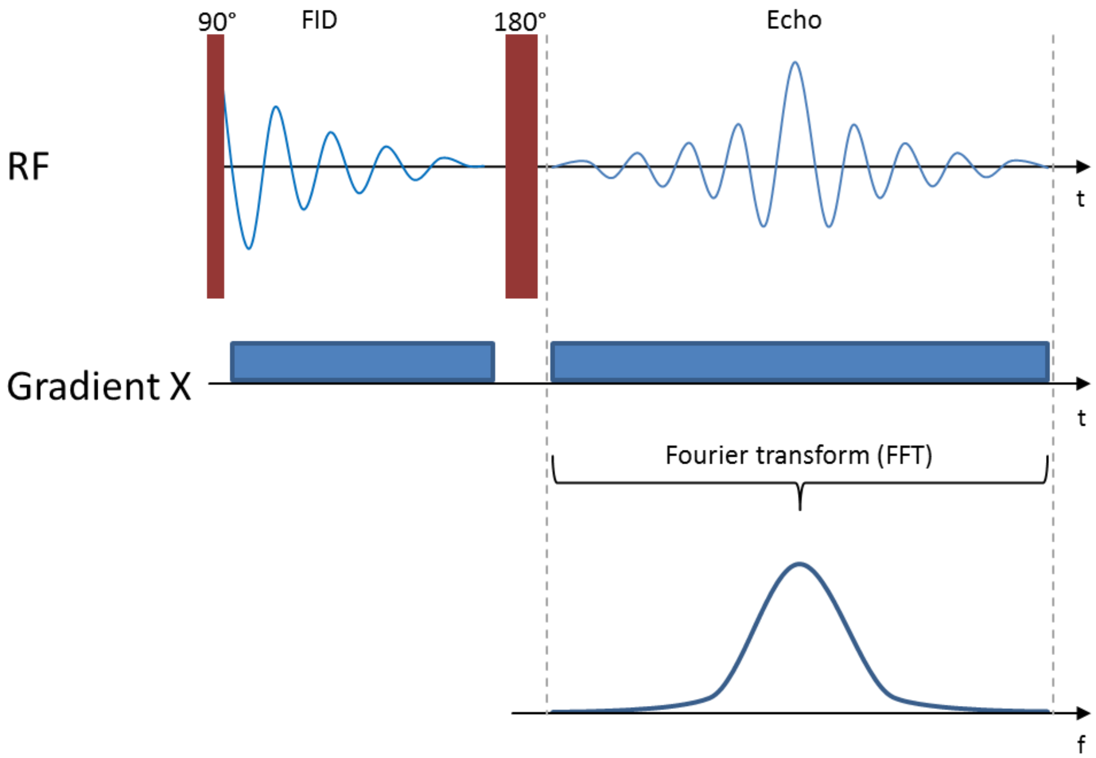

Figure 28: Pulse sequence for experiment *Profile 1d*

PREPARATION

In this experiment, the 5 mm water and the 5 mm oil samples are used.

Place both test tubes into the bore of the magnet such that they are in one line and parallel with the rear edge of the magnet.

Select the lesson *Profile 1d*. The panel *Parameters* shows the slider for the repetition time and three sliders for adjusting the gradient field. Please compare your panel with Figure 29.

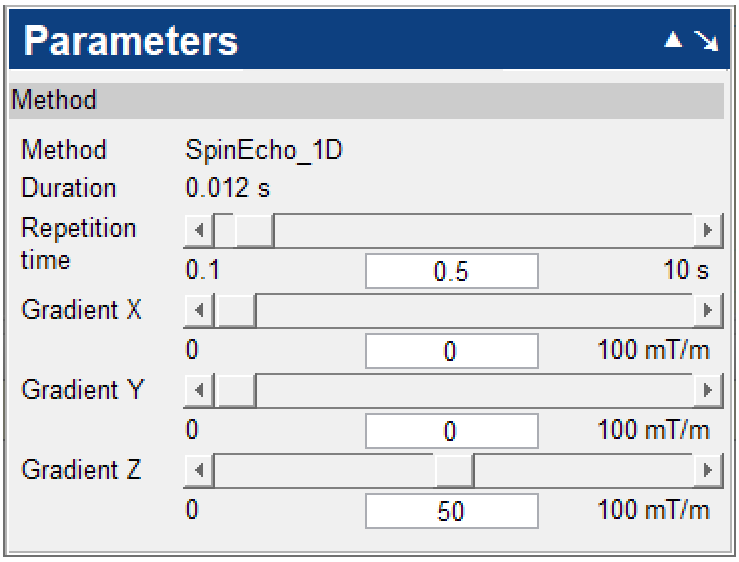

Figure 29: Parameters for experiment *Profile 1d*

With the slider *Repetition time* you can adjust the time between experiments.

Changing the gradient field strength can be done by varying the sliders for *Gradient X, Gradient Y* and *Gradient Z*.

Set the repetition time to 1 second and check that all gradient controls are set to 0.

Press *Start* to start the measurement.

TASKS

(1) Change the gradients by varying the sliders *Gradient X, Gradient Y* and *Gradient Z* in turn.

What do you observe?

(2) Adjust the slider until you see the profile of the two test tubes. Rotate the sample by 90°.

What do you observe?

(3) Put the test tubes back into the previous position. Apply a sensible gradient in z-direction. Use the data cursor tool to get a reading of the signal in the frequency domain and calculate the diameter of the test tubes (gyromagnetic ratio of protons: ≈ 42.6 MHz/T).

(4) Explain why it is necessary to apply the gradient between the 90° and the 180° pulses.

Experiment instruction

Experiment 3-2: *Contrast*

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to understand how the echo time and the repetition time affect the contrast in an image.

The experiment is very similar to Experiment 3-1 (*Profile 1d*): A readout encoded spin echo is acquired and a Fourier transform is used to calculate the signal in the frequency domain. Setting different echo times and repetition times lead to different signal amplitudes depending on the T_1 and T_2 relaxation times of the sample.

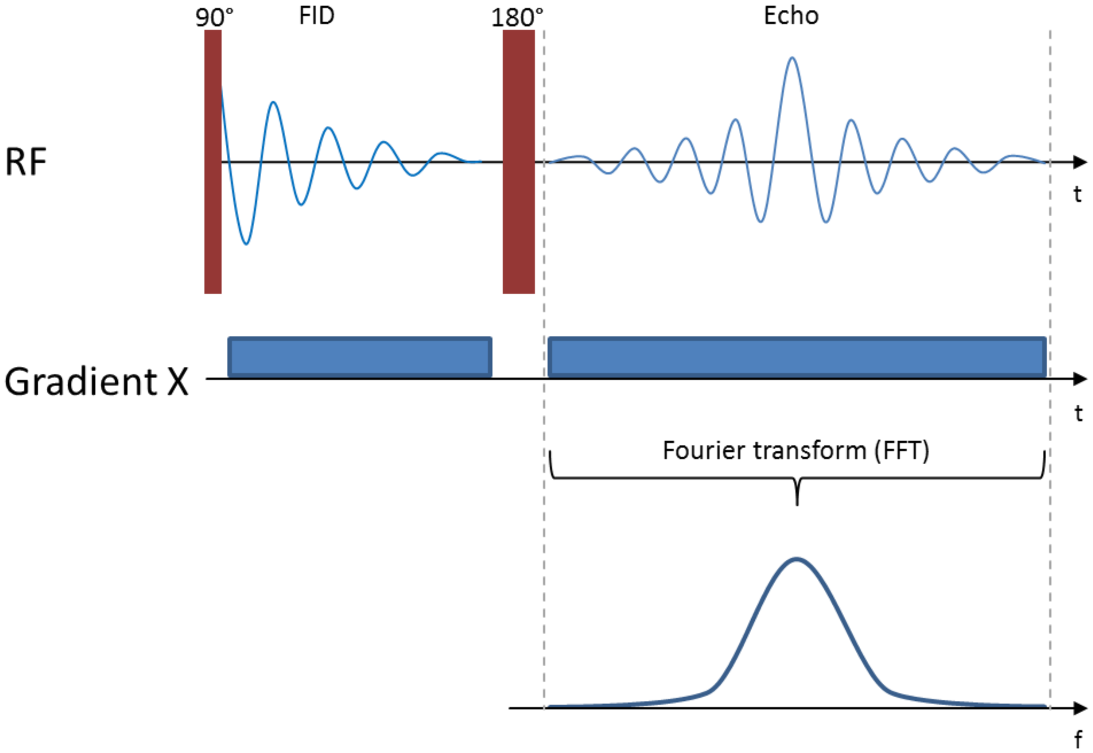

Figure 30: Pulse sequence for experiment *Contrast*

PREPARATION

In this experiment, the 5 mm water and the 5 mm oil samples are used.

Place both test tubes into the bore of the magnet such that they are in one line and parallel with the rear edge of the magnet.

Select the lesson *Contrast*. The panel *Parameters* shows the sliders for the repetition time, the echo time, and three sliders for adjusting the gradient field. Please compare your panel with Figure 31.

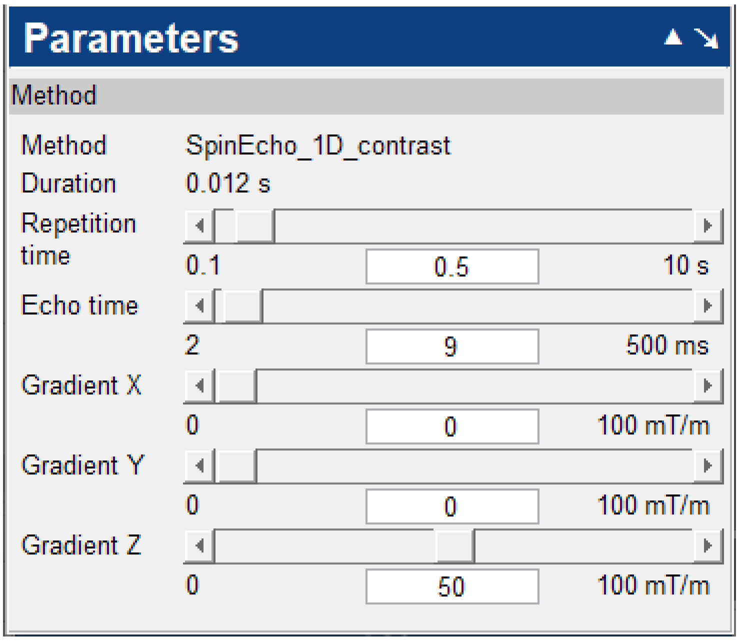

Figure 31: Parameters for experiment *Contrast*

With the slider *Repetition time* you can adjust the time between experiments.

The slider *Echo time* sets the time of the (read encoded) spin echo.

Changing the gradient field strength can be done by varying the sliders for *Gradient X, Gradient Y* and *Gradient Z.*

Press *Start* to start the measurement.

TASKS

(1) Set the sliders to apply a gradient in z-direction with reasonable strength.
Set the repetition time to 0.5 s and the echo time to 9 ms.
Identify which of the peaks in the frequency domain corresponds to which sample.
Why is one of the peaks higher than the other?

(2) With the same gradient settings and without moving the samples, set the repetition time to 3 s and the echo time to 70 ms.
Observe which of the peaks in the frequency domain is higher with the changed contrast settings.
Explain what you observe.

Experiment instruction

Experiment 3-3:
Gradient Echo

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a Gradient Echo.

For this experiment, an excitation pulse is followed by (optional) de-phasing and re-phasing gradients:

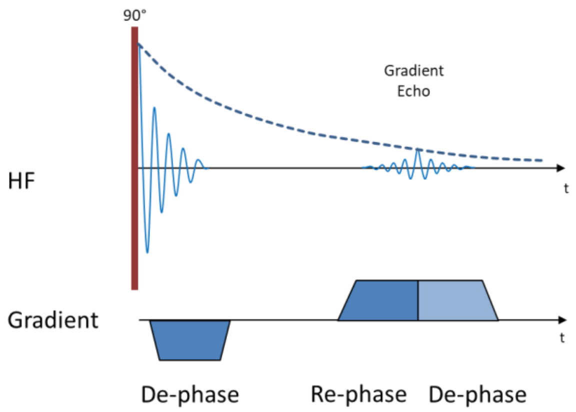

Figure 32: Pulse sequence for the gradient echo experiment.

PREPARATION

In this experiment, the 10 mm test tube containing oil is used. Insert this sample into the bore of the magnet.

Select the experiment *Gradient Echo*. The panel *Parameters* shows the following controls:

Repetition Time*:* The repetition time between the excitation pulses.
Echo Time*:* The time when the re-phase gradient should reverse the de-phase gradient.
Gradient X, Y and Z*:* The gradient strength in x-, y- and z-direction.
De-phase gradient*:* Checkbox to activate the de-phase gradient (the first gradient block depicted in dark blue in Figure 32).
Re-phase gradient*:* Checkbox to activate the re-phase gradient (the second gradient block depicted in dark and light blue in Figure 32).

Please compare your panel with Figure 33.

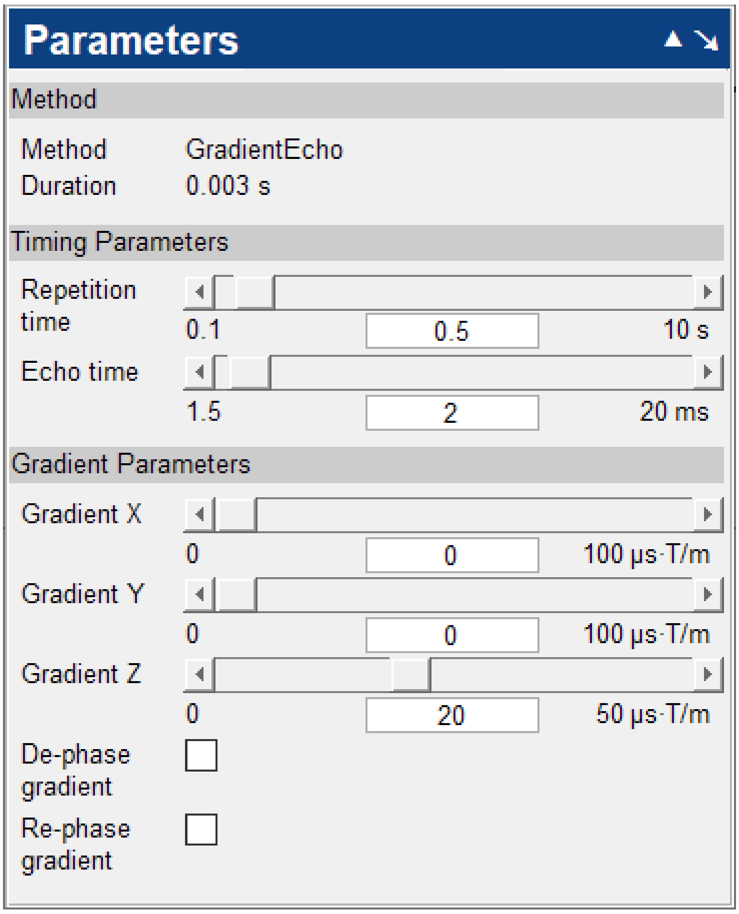

Figure 33: Parameter for experiment *Gradient Echo*

TASKS

(1) Start the measurement with both checkboxes un-ticked.
What do you observe?

(2) Tick the checkbox for the de-phase gradient.
What do you observe?

(3) Tick the checkbox for the re-phase gradient.
What do you observe?

(4) What do you observe when you change the gradient amplitude?

(5) Compare the maximum amplitude at the gradient echo with the amplitude that you observe without re-phase and de-phase gradient at different echo times.
What do you observe?

Experiment instruction

Experiment 3-4:
T_1 *Profile*

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a T_1 weighted profile of a sample.

This experiment combines the spatial information of the profile of the sample (compare with previous Experiment 3-1 *Profile 1d*) with the relaxation time T_1 of the sample.

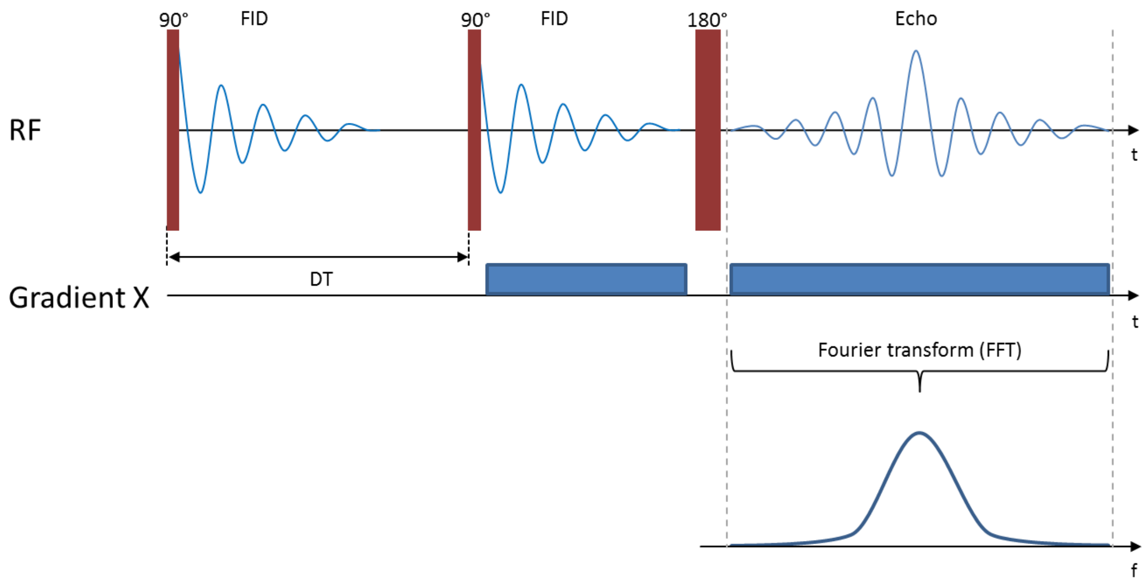

Figure 34: Pulse sequence for experiment T_1 *profile*

To obtain the information a sequence of measurements has to be performed. A single measurement consists of a 90° RF pulse, a dwell time DT and the acquisition of the profile like in Experiment 3-1 *Profile 1d*. After an adjustable pause time, the measurement is repeated. The dwell time DT increases with each single measurement. By this means, a T_1-weighted profile of the sample is obtained.

PREPARATION

In this experiment, the 5 mm water and the 5 mm oil samples are used. Place both test tubes into the bore of the magnet such that they are in one line and parallel with the rear edge of the magnet.

Select the lesson T_1 *Profile*. The panel *Parameters* shows the slider for the pause time and three sliders for adjusting the gradient field. Furthermore, there are sliders for the number of profiles and the time increment that will be used for the dwell time DT. Please compare your panel with Figure 35.

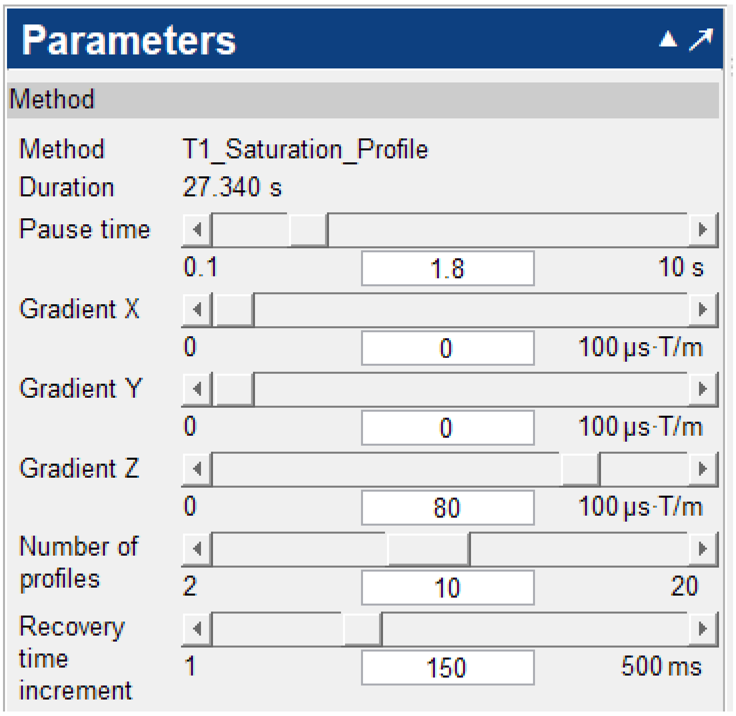

Figure 35: Parameters for experiment T_1 *Profile*

With the slider *Pause time* you can adjust the time between measurement steps.

Changing the gradient field strength can be done by varying the slider for *Gradient X, Gradient Y* and *Gradient Z*.

With the slider *Number of profiles,* the number of measurements can be adjusted.

The dwell time DT equals the value of *Recovery time increment.*

TASKS

(1) Set the pause time to 1 second. Set the sliders for the gradient to the values for which you obtained the profile in Experiment 3-1 *Profile 1d.*

(2) Choose a suitable value for DT. A typical value is one tenth of the estimated T_1 value for water. Set the number of points to a value where DT of the last measurement is higher than the estimated value for T_1.

(3) Start the measurement.

What do you observe?

(4) Print or save the resulting plot.

Which series of peaks corresponds to the water sample and which one to the oil sample? Why?

Experiment instruction

Experiment 3-5:
T_2 Profile

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a T_2 weighted profile of a sample.

This experiment combines the spatial information from the profile of the sample (compare with previous Experiment 3-1 *Profile 1d*) with the relaxation time T_2 of the sample.

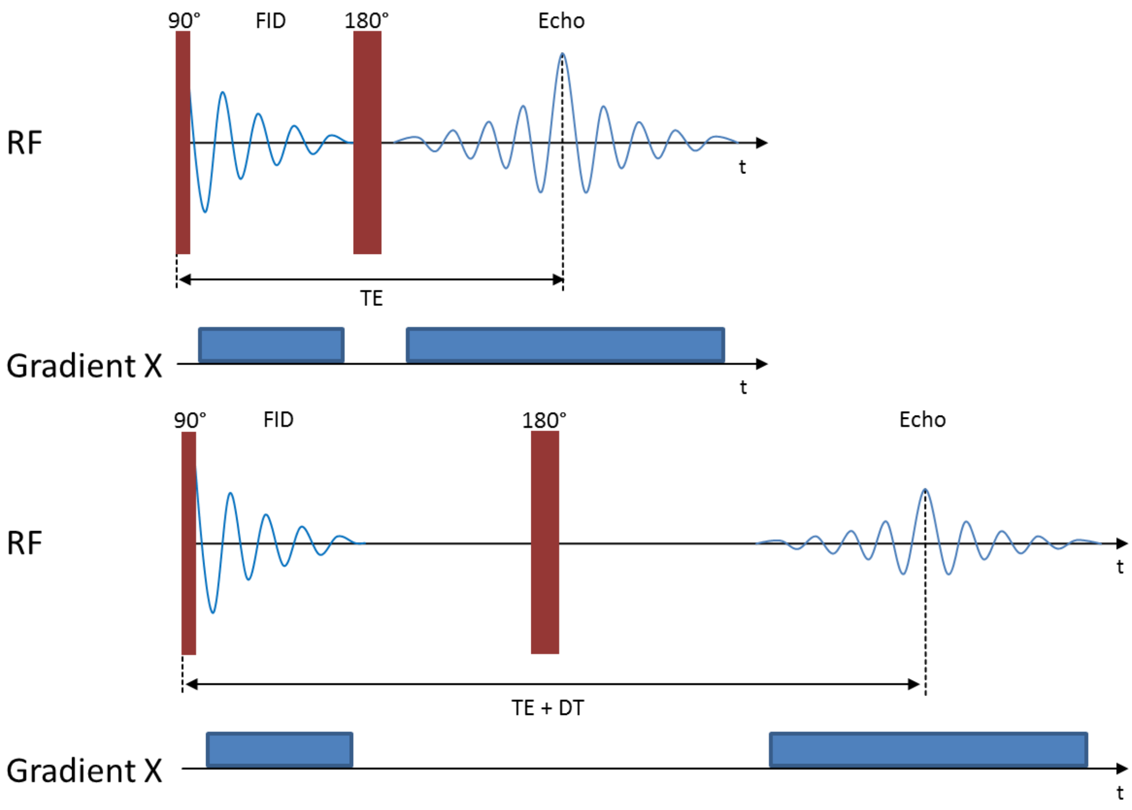

Figure 36: Pulse sequence for experiment *T_2 profile*

To obtain the information, a sequence of measurements has to be performed. A single measurement consists of a 90° RF pulse, a dwell time DT and the acquisition of the profile similar to Experiment 3-1 *Profile 1d*. After an adjustable pause time, the measurement is repeated. The echo time is increased by the dwell time DT for each subsequent measurement. By this means, a T_2-weighted profile of the sample is obtained.

PREPARATION

In this experiment, the 5 mm water and the 5 mm oil samples are used. Put both test tubes into the bore of the magnet so that they are in one line and parallel with the rear edge of the magnet.

Select the lesson T_2 *Profile*. The panel *Parameters* shows the slider for the pause time and three sliders for adjusting the gradient field. Furthermore, there is the slider for the number of profiles and the Echo time increment (dwell time) DT. Please compare your panel with Figure 37.

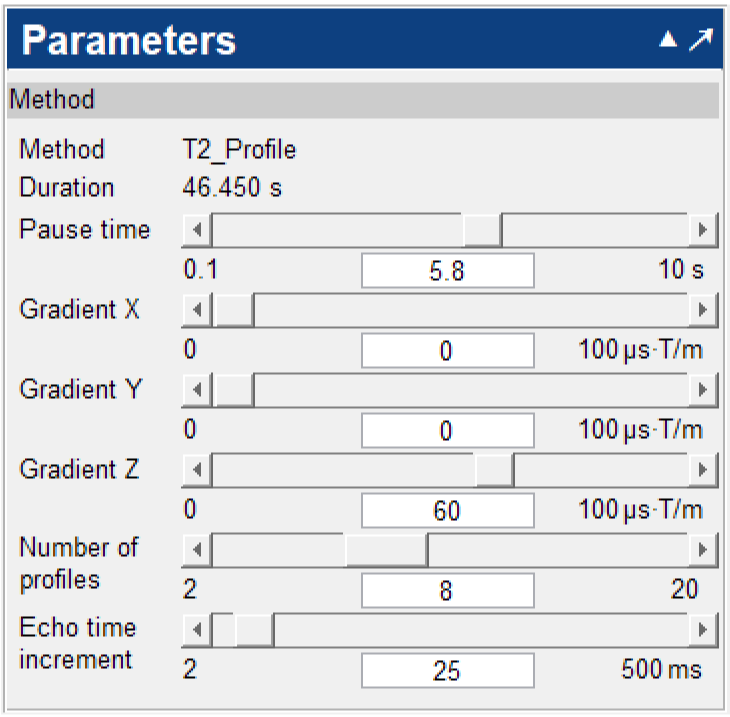

Figure 37: Parameters for experiment T_2 *Profile*

With the slider *Pause time*, you can adjust the time between experiments.

Changing the gradient field strength can be done by varying the slider for *Gradient X, Gradient Y* and *Gradient Z*.

With the slider *Number of profiles,* the number of echoes to acquire can be adjusted.

The dwell time DT can be set with the slider *Echo time increment.*

TASKS

(1) Set the pause time to 2 second. Set the sliders for the gradient to the values for which you obtained the profile in Experiment 3-1 *Profile 1d.*

(2) Choose a suitable value for DT, typically, a tenth of the T_2 value for oil obtained in Experiment 2-3 T_1 *Measurement (Inversion Recovery)*. Set the number of points to a value where the echo time of the last measurement is higher than T_2.

(3) Start the measurement.

What do you observe?

(4) Print or save the resulting plot.

Which series of peaks corresponds to the water sample and which one to the oil sample? Why?

Experiment instruction

Experiment 4-1:
Spin Echo 2d

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a 2d magnetic resonance image of a sample.

A 2-dimensional cross section of the sample is acquired. The acquisition is based on the spin echo method. In this measurement, the parameters can be set freely – similarly to clinical magnetic resonance tomography devices.

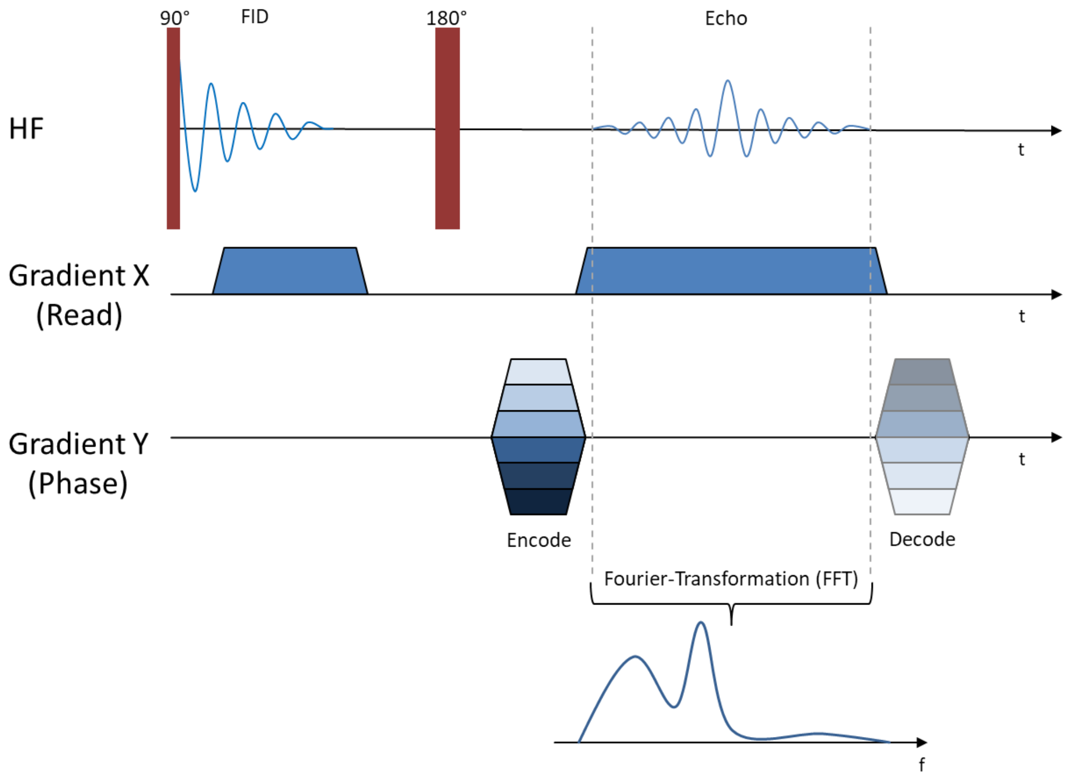

Figure 38: Pulse sequence for experiment *Spin Echo 2d*

The decode phase gradient in Figure 38 is not strictly necessary for this experiment. But it is sometimes of advantage to cancel the phase encoding before starting the next acquisition.

PREPARATION

In this experiment, both 5 mm test tubes containing water and oil and the 10 mm structure sample are used. At first, place both 5 mm test tubes into the bore of the magnet so that they are in one line and parallel with the rear edge of the magnet.

Select the lesson *Spin Echo 2d*. The panel *Parameters* shows the following controls:

***Data Points (Read)**:* The number of data samples acquired per phase step in read direction.

***Data Points (Phase)**:* The number of phase encoding steps in phase direction.

***Slice Orientation**:* The plane of the cross section through the sample.

***Image Size (Read)**:* The size of the image in read direction. This corresponds to the gradient strength applied in that direction. The lower this value, the higher is the amplitude of the read encoding gradient pulses.

***Image Size (Phase)**:* The size of the image in phase direction. This corresponds to the gradient strength applied in that direction. The lower this value, the higher is the amplitude of the phase encoding gradient pulses.

***Repetition Time**:* The repetition time for each phase encoding step.

***Echo Time**:* The echo time.

***Averages**:* The number of averages.

Please compare your panel with Figure 39.

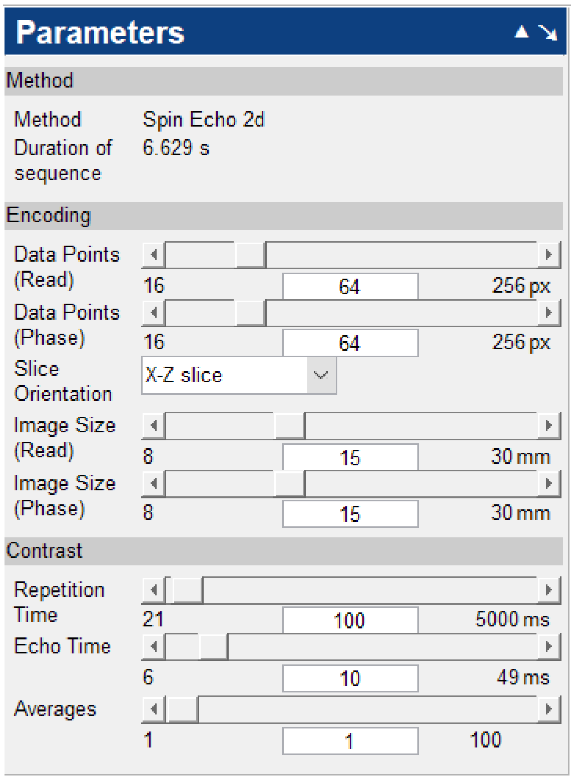

Figure 39: Parameters for experiment *Spin Echo 2d*

TASKS

(1) For the first magnetic resonance image, choose the parameters as follows:
- *Data Points (Read)*: 64
- *Data Points (Phase)*: 64
- *Slice Orientation*: X-Z-slice

(2) Set the gradient strength for the read and phase gradient to sensible values.
Furthermore, set sensible values for the repetition time and the echo time.

(3) Start the measurement. Save or print the acquired image.

(4) Use the slider at the left hand side of the "Data Display" panel to select a part of the k-space.
What can you observe in the image when progressively reducing the number of lines in the k-space?
Set the slider to remove half of the k-space (excluding and including the center line).
What can you see?

(5) Vary the values for the repetition time and the echo time and repeat the measurement.
What do you observe?

(6) Place the sample *10 mm Structure* into the bore of the magnet and repeat this measurement.
Save and/or print the acquired image.

Experiment instruction

Experiment 4-2:
Spin Echo 2d (Slice Selection)

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a 2-dimensional magnetic resonance image of a structured sample. A 2-dimensional cross section of the sample is acquired based on the spin echo method. In this measurement, the parameters can be set freely – similarly to clinical MRI scanners.

In contrast to the previous *Spin Echo 2d* imaging experiment, this sequence is more sophisticated. It offers the option to excite and record data from only a slice within the whole sample. The field of view including the slice thickness can be set directly in mm.

The slice selection is established applying a slice selective RF excitation pulse. This is achieved by combining the RF pulse with an additional slice gradient. The slice gradient needs to be applied (negative gradient slope during RF pulse) even before the RF excitation pulse. This gradient generates some extra frequency encoding of the sample. The duration and frequency of the applied RF pulse determines the location and thickness of the slice that is exited. A side effect of this extra frequency encoding is the de-phasing of the signal. This de-phasing can be canceled by applying an additional gradient pulse in the opposite direction directly after the slice selective gradient.

The rest of the sequence is equivalent to Experiment 4-1 *Spin Echo 2d*.

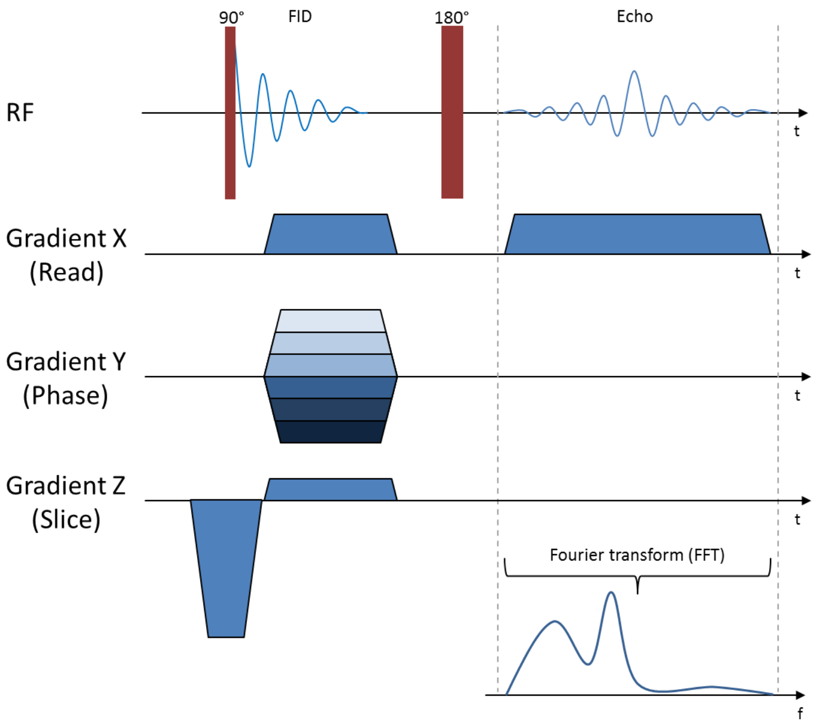

Figure 40: Pulse sequence for experiment *Spin Echo 2d (slice selection)*

Another feature of this experiment is the automated determination of the Larmor frequency. Before the sequence starts, the system frequency is analyzed and corrected if necessary in order to match the magnet's Larmor frequency. This offers the benefit that long time averaging can improve the signal to noise ratio without the negative impact of frequency drift. The correction is performed before each averaging step.

Additionally, the orientation of the slice can be changed with sliders for the Euler angles Alpha, Phi and Theta. Spoiler gradients can be applied in slice, phase and read direction to reduce the influence of the FID after the 180° pulse.

PREPARATION

In this experiment, the sample *10 mm Structure* is used. In a later part of the experiment, any sample that can be used for magnetic resonance and that fits into the magnet's bore can be used. We recommend using the empty test tube for sample handling.

First, place the structure sample into the magnet's bore so that the openings of the ladder point to the backside of the magnets case.

Choose the lesson *Spin Echo 2D (slice selection)*. It might be necessary to add the lesson to the list of experiments by clicking the Add button and selecting it from the list. The parameter panel shows the following settings (compare with Figure 41):

- Section **Encoding:** *Image Size (Read & Phase), Data Points (Read & Phase), Oversampling (Read & Phase), Slice Thickness & Offset* and *Max. Length AQ Window*.
- Section **Slice Orientation:** Euler angles *Alpha*, *Phi*, and *Theta*.
- Section **Contrast:** *Repetition Time*, *Echo Time*, and *Averages.*
- Section **Spoiler:** Factors in *Read*, *Phase*, and *Slice* direction. A factor of 1 means a dephasing of 360° at the ends of the FOV.

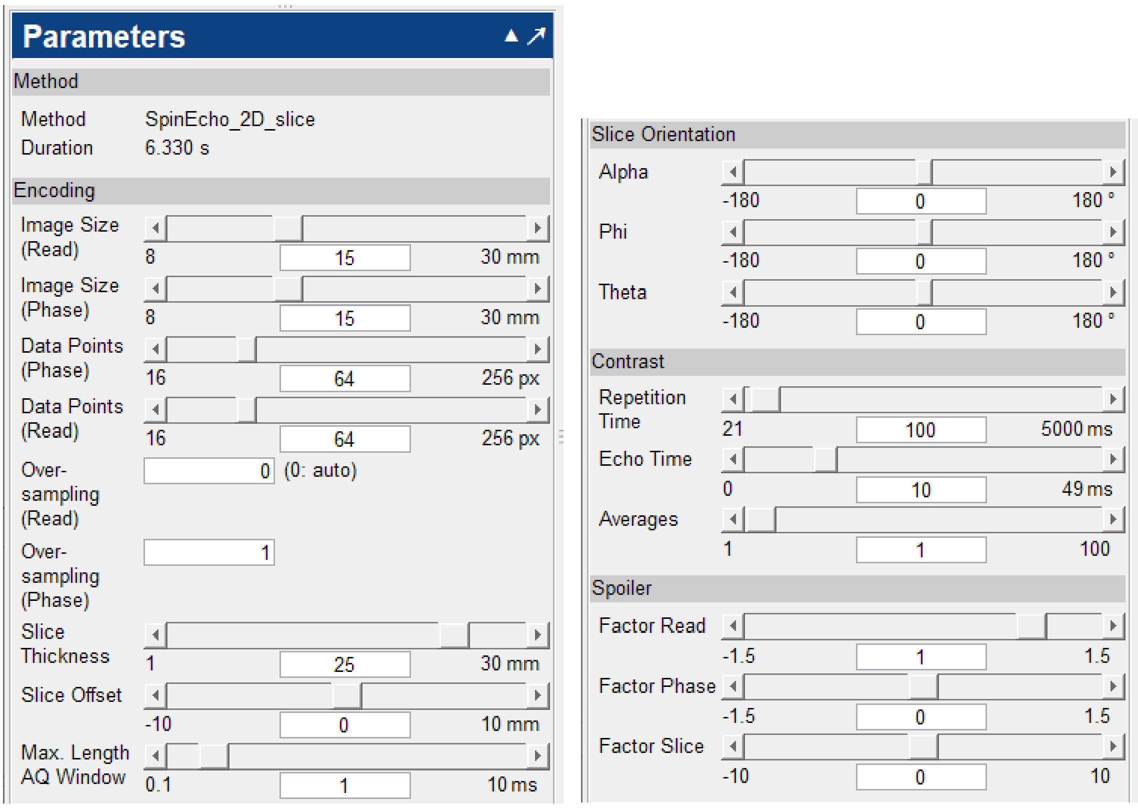

Figure 41: Parameters for experiment *Spin Echo 2d (slice selection)*

The settings in the sections *Encoding* and *Contrast* of the Parameters panel in Figure 41 are the same as in Experiment 4-1 *Spin Echo 2d* with the following additions: *Oversampling (Read)* and *Oversampling (Phase)* set the oversampling factor in these directions. If the read oversampling factor is set to 0, an even number is chosen such that the CIC decimation factor for one k-space pixel does not exceed a maximum value (8000 by default).

The additional slider *Slice Thickness* sets the effective thickness of the slice selective pulse. *Slice Offset* sets the offset to the center of the gradient system perpendicular to the slice.

Max. Length AQ Window sets the duration of the AQ window. The actual duration might be slightly shorter to match the system frequency and possible CIC decimation factors.

The Euler angles are defined such that *Alpha* rotates the slice around the X-axis. *Phi* rotates around the (rotated) Y-axis, and *Theta* around the (rotated) Z-axis.

Advanced users can change the spoiler factors in slice, phase and read direction.

Dependent on your specific hardware, not all combinations of parameters that can be set can also be used for an actual measurement. In case some parameter(s) prevent starting an experiment, an error message is displayed and the *Start* button is deactivated until a usable set of parameters is configured.

TASKS

(1) For the first image, choose the parameter as follows:

- *Data Points (Read)*: 64
- *Data Points (Phase)*: 64
- *Averages*: 4
- *Repetition Time*: ≈ 150 ms
- *Echo Time*: ≈ 7 ms
- *Image Size (Read)*: 20 mm
- *Image Size (Phase)*: 20 mm
- *Slice Thickness*: 10 mm

Press Start to start the measurement.

What resolution do these parameters achieve?

(2) Change the slice thickness to 5 mm and repeat the measurement.
What do you observe?

(3) How can you improve the image quality when reducing the slice thickness?
Try to improve the image quality by adjusting the corresponding parameters.
What do you observe?

(4) Try to experiment with the slice orientation by changing the parameters for *alpha*, *phi* and *theta* in the section *Slice Orientation*.

(5) Run some experiments with biological samples of your choice (for example: garden bean, rapeseed, rose hip, wet soil, corn, small plants or flowers, peanuts). For this, we recommend using the empty 10 mm test tube.

Use the knowledge you have gained in the experiments about T_1- and T_2-relaxation times. This will help you to set up the correct values for the repetition time and echo time.

Experiment instruction

Experiment 4-2:
Spin Echo 2d (Inversion Recovery)

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a 2-dimensional magnetic resonance image of a sample with different T_1-relaxation times. A 2-dimensional cross section of the sample is acquired based on the spin echo method with and without prior inversion recovery pulse. In this measurement, the parameters can be set freely – similarly to clinical MRI scanners.

In contrast to the previous *Spin Echo 2d (Slice Selection)* imaging experiment, this sequence offers the option to emit an additional 180° inversion pulse at an adjustable time before the excitation pulse.

The additional inversion pulse flips the magnetization from positive z-direction to negative z-direction. Depending on the T_1-relaxation time of the sample, it takes a varying time until the steady-state magnetization is restored. For certain recovery times, the magnetization at the excitation pulse is zero for a given relaxation time T_1. By carefully choosing a matching inversion recovery time, the signal from some tissues can therefore be suppressed.

The rest of the sequence is equivalent to Experiment 4-2 *Spin Echo 2d (Slice Selection)*.

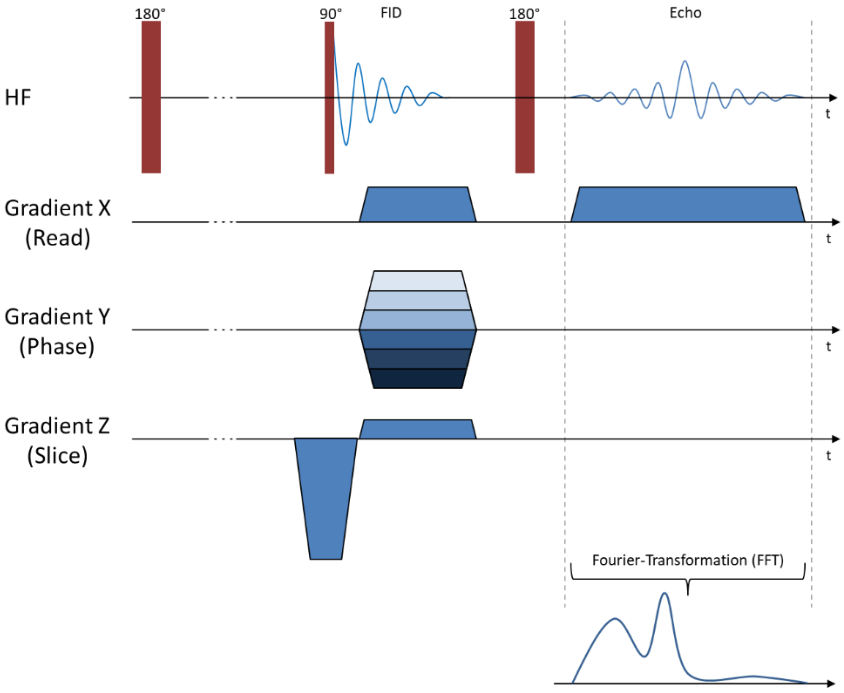

Figure 42: Pulse sequence for experiment *Spin Echo 2d (inversion recovery)*

Another feature of this experiment is the automated determination of the Larmor frequency. Before the sequence starts, the system frequency is analyzed and corrected if necessary in order to match the magnet's Larmor frequency. This offers the benefit that long time averaging can improve the signal to noise ratio without the negative impact of frequency drift. The correction is performed before each averaging step.

Additionally, the orientation of the slice can be changed with sliders for the Euler angles Alpha, Phi and Theta. Spoiler gradients can be applied in slice, phase and read direction to reduce the influence of the FID after the 180° pulse.

PREPARATION

In this experiment, the 5 mm water and the 5 mm oil samples are used. In a later part of the experiment, any sample that can be used for magnetic resonance and that fits into the magnet's bore can be used. We recommend using the empty test tube for sample handling.

First, place both samples next to each other into the magnet's bore.

Choose the lesson *Spin Echo 2D (Inversion Recovery)*. It might be necessary to add the lesson to the list of experiments by clicking the **Add** button and selecting it from the list. The parameter panel shows the following settings (compare with Figure 43):

- Section **Encoding:** *Image Size (Read & Phase), Data Points (Read & Phase), Oversampling (Read & Phase), Slice Thickness & Offset* and *Max. Length AQ Window*.
- Section **Slice Orientation:** Euler angles *Alpha*, *Phi*, and *Theta*.
- Section **Contrast:** *Repetition Time*, *Echo Time*, *Use Inversion Recovery*, *Inversion Recovery Time* and *Averages.*
- Section **Spoiler:** Factors in *Read*, *Phase*, and *Slice* direction. A factor of 1 means a dephasing of 360° at the ends of the FOV.

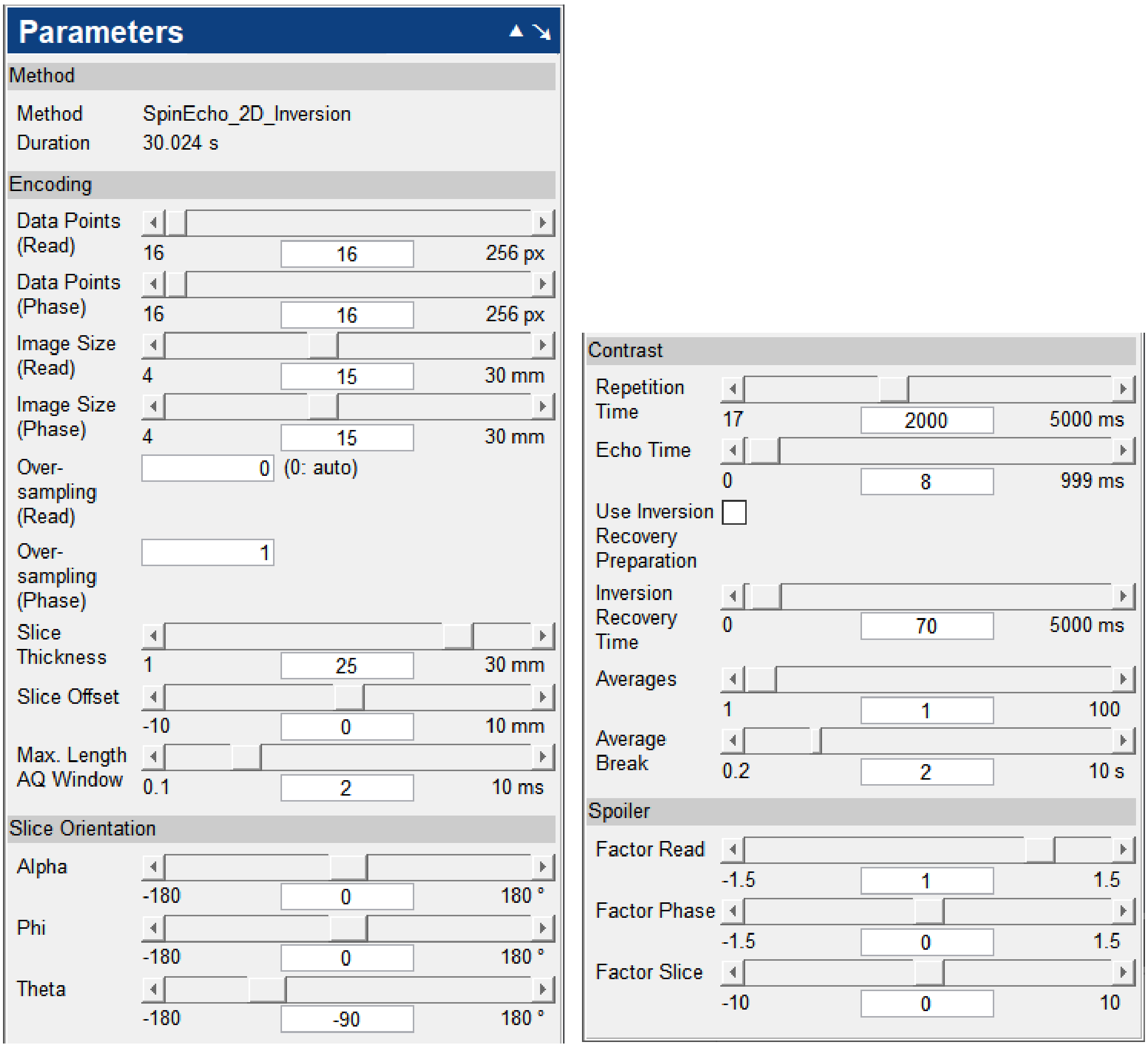

Figure 43: Parameters for experiment *Spin Echo 2d (Inversion Recovery)*

All settings in the Parameters panel in Figure 43 are the same as in Experiment 4-2 *Spin Echo 2d (Slice Selection)* with the following additions in the section **Contrast**: The checkbox *Use Inversion Recovery Preparation* selects whether the preparation pulse for inversion recovery is prepended to each excitation pulse.

The additional slider *Inversion Recovery Time* sets the time between the 180° inversion pulse and the 90° excitation pulse.

Dependent on your specific hardware, not all combinations of parameters that can be set can also be used for an actual measurement. In case some parameter(s) prevent starting an experiment, an error message is displayed and the *Start* button is deactivated until a usable set of parameters is configured.

TASKS

(1) For the first image, choose the parameter as follows:
   - *Data Points (Read)*: 16
   - *Data Points (Phase)*: 14
   - *Averages*: 1
   - *Repetition Time*: ≈ 2000 ms
   - *Echo Time*: ≈ 8 ms
   - *Image Size (Read)*: 16 mm
   - *Image Size (Phase)*: 16 mm
   - *Slice Thickness*: 10 mm
   - Deselect *Use Inversion Recovery Preparation*

   Press Start to start the measurement.

   Which of the two samples (water or oil) appears brighter in the resulting image? Why?

(2) Don't move the samples nor change any other measurement parameter. But select *Use Inversion Recovery Preparation* and set *Inversion Recovery Time* to 70 ms.
   Repeat the measurement.
   What do you observe? Which of the two samples (water or oil) appears brighter in the resulting image? Why?

(3) Optional: Given the results of Experiment 2-3 T_1 *Measurement (Inversion Recovery)*, which settings (repetition time, inversion recovery time) can be used to suppress the oil or the water signal in the image?

(4) Optional: Run some experiments with biological samples of your choice (for example: garden bean, rapeseed, rose hip, wet soil, corn, small plants or flowers, peanuts). For this, we recommend using the empty 10 mm test tube.

   Use the knowledge you have gained in the experiments about T_1- and T_2-relaxation times. This will help you to set up the correct values for the repetition time and echo time.

Experiment instruction

Experiment 4-3:
Spin Echo 3d

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to perform a measurement with a 3-dimensional MRI sequence based on the spin echo method. The accessible parameters can be set freely – similarly to clinical MRI scanners.

In the Experiment 4-2 *Spin Echo 2d (Slice Selection),* the slice selection was performed by applying a slice gradient during an RF excitation pulse (slice selective RF pulse).

Another possibility for encoding the MR signal in the third dimension is phase encoding. For this, we can add a second phase encoding gradient in that direction – Gradient Z. This Gradient Z increments its value each time the first phase encoding gradient Y has passed through all phase encoding steps.

The remaining part of the sequence is equivalent to Experiment 4-1 *Spin Echo 2d*.

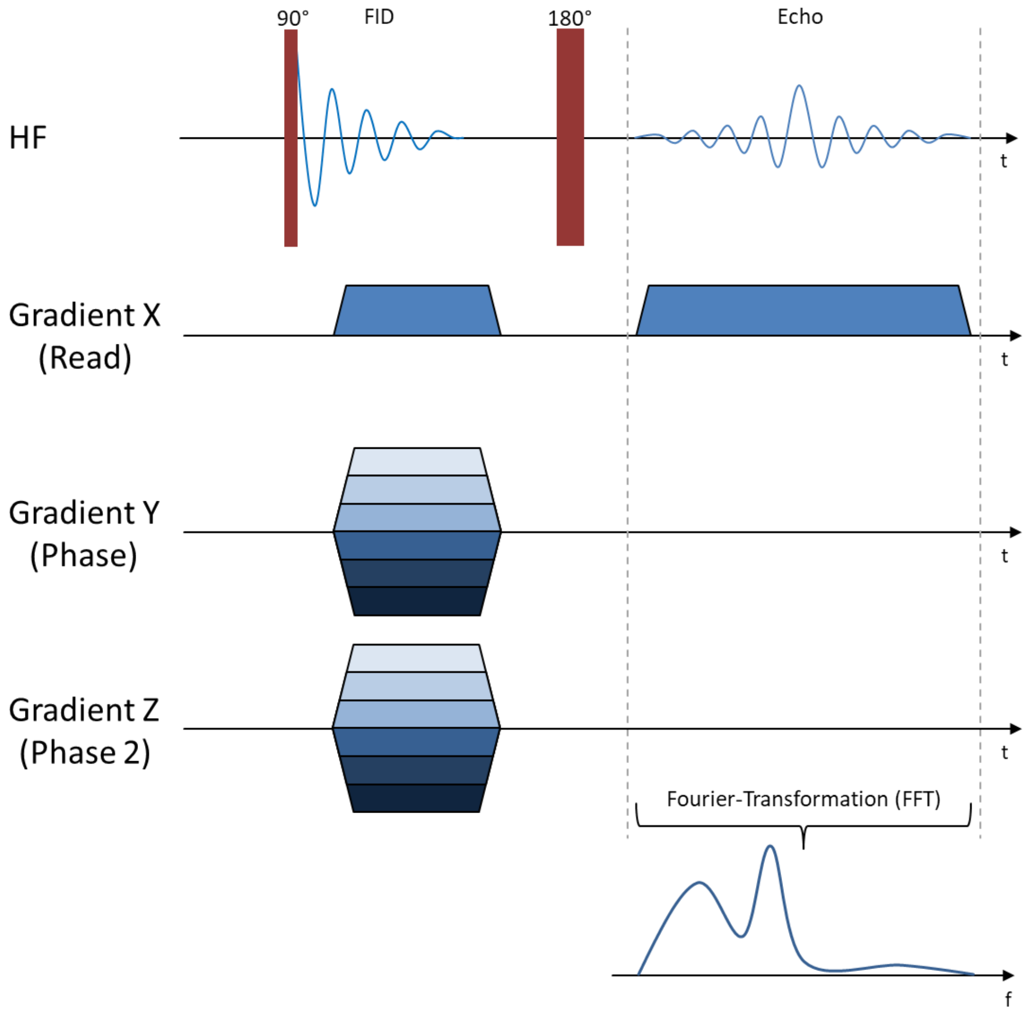

Figure 44: Pulse sequence for experiment *Spin Echo 3d*

Another feature of this experiment is the automated determination of the Larmor frequency. Before the sequence starts, the system frequency is analyzed and corrected if necessary in order to match the magnet's Larmor frequency. This offers the benefit that long time averaging can improve the signal to noise ratio without the negative impact of thermal frequency drift. The correction is performed before each averaging step.

PREPARATION

In this experiment, the sample *10 mm Structure* is used. In a later part of the experiment, any sample that is suited for MRI and that fits into the magnet‘s bore can be used. We recommend using an empty 10 mm test tube for sample handling.

First, place the structure sample into the magnet‘s bore so that the openings of the ladder point to the backside of the magnet case.

Choose the lesson *Spin Echo 3d*. It might be necessary to add the lesson to the list of experiments by clicking the Add button and selecting it from the list of available experiments. The parameter panel shows the following settings (compare with Figure 45):

- Section **Encoding:** *Image Size (Read, Phase and Phase 2), Data Points (Read, Phase and Phase 2), Oversampling (Read, Phase & Phase 2)* and *Max. Length AQ Window*.
- Section **Contrast:** *Repetition time*, *Echo time* and *Averages*.
- Section **Spoiler:** Factors in *Slice*, *Phase*, and *Read* direction. A factor of 1 means a dephasing of 360° at the ends of the FOV.

Most of the accessible settings in the sections *Encoding*, *Contrast* and *Spoiler* (see Figure 45) are the same as in Experiment 4-2 *Spin Echo 2d (Slice Selection)*. Additional settings are available for the encoding in the third dimension.

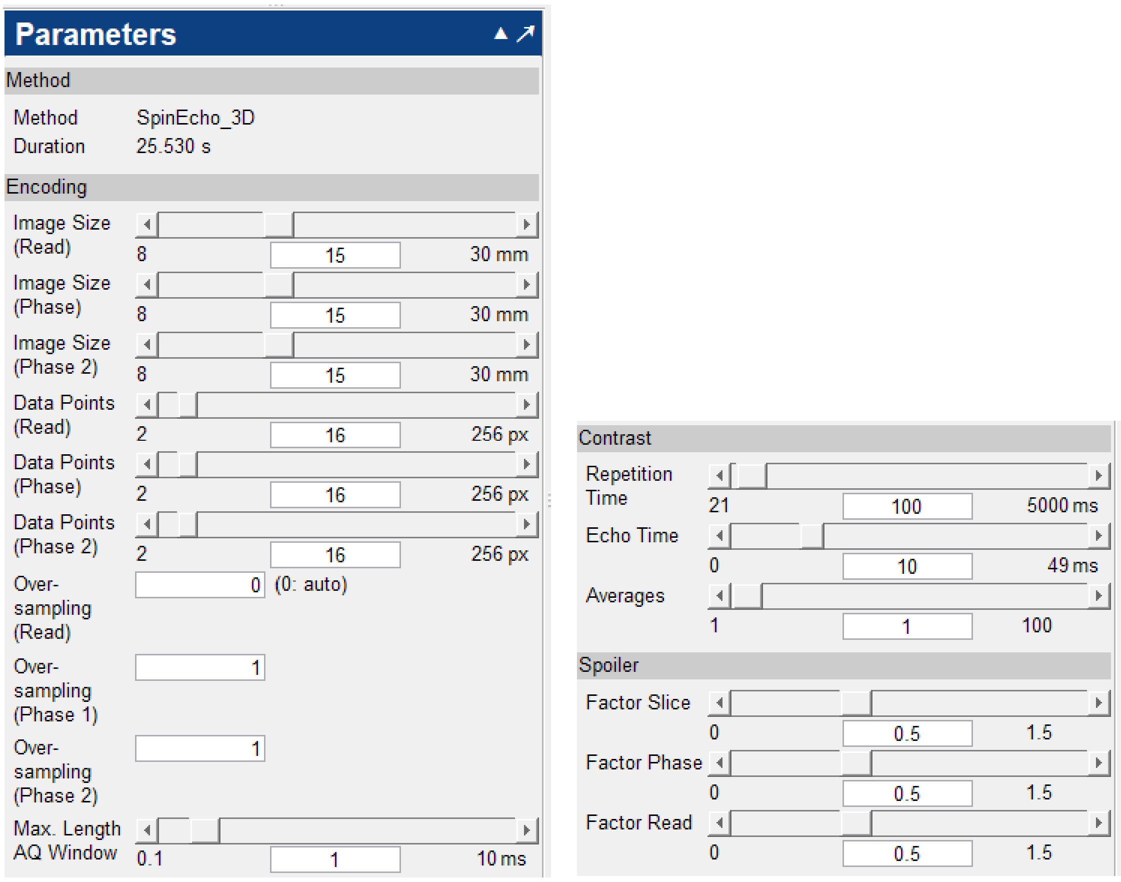

Figure 45: Parameters for experiment *Spin Echo 3d*

Advanced users can change the spoiler strength for all gradients.

As soon as the acquisition of the 3D image has been finished, the result is displayed in the Data Display panel.

Clicking the button *open external 3D viewer* will load the acquired 3D dataset in an external 3D visualization tool (VolView™). For more details about using VolView™, please refer to the document *VolView - Guide for 3D MRI visualization*.

Dependent on your specific hardware, not all combinations of parameters that can be set can also be used for an actual measurement. In case some parameter(s) prevent starting an experiment, an error message is displayed and the *Start* button is deactivated until a usable set of parameters is configured.

TASKS

(1) For the first 3-dimensional magnetic resonance image, choose the parameters as follows:

- *Image Size (Read)*: 20 mm
- *Image Size (Phase)*: 20 mm
- *Image Size (Phase 2)*: 30 mm
- *Data Points (Read)*: 16
- *Data Points (Phase)*: 16
- *Data Points (Phase 2)*: 16
- *Oversampling (Read)*: 0 (i.e. auto)
- *Oversampling (Phase)*: 1
- *Oversampling (Phase 2)*: 1
- *Max. Length AQ window*: 1 ms
- *Repetition Time*: ≈ 150 ms
- *Echo Time*: 7 ms
- *Averages*: 1
- *All Spoiler Factors: 0.5*

Press *Start* to start the measurement.

When the acquisition has finished, try to get familiar with the options for changing the mathematical processing / visualization of the data. Furthermore, change the slice orientation and choose different slices to get a feel for orienting in a sample.

(2) Increase the resolution by setting the values for Data Points (Read, Phase and Phase 2) to 32. What do you observe?

(3) Run some experiments with biological samples of your own choice (for example: garden bean, rapeseed, rose hip, wet soil, corn, small plants or flowers, peanuts). For this, we recommend using the empty 10 mm test tube.

Use the knowledge you have gained in the experiments about T_1- and T_2-relaxation times. This will help you to set up the correct values for the repetition time and the echo time.

Experiment instruction

Experiment 4-4: *FLASH 2d*

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a 2D magnetic resonance image of a sample.

A 2-dimensional cross section of the sample is acquired. The acquisition is based on the gradient echo method also called FLASH ("**F**ast **L**ow **A**ngle **Sh**ot"). In this measurement, the parameters can be set freely – similarly to clinical magnetic resonance tomography devices.

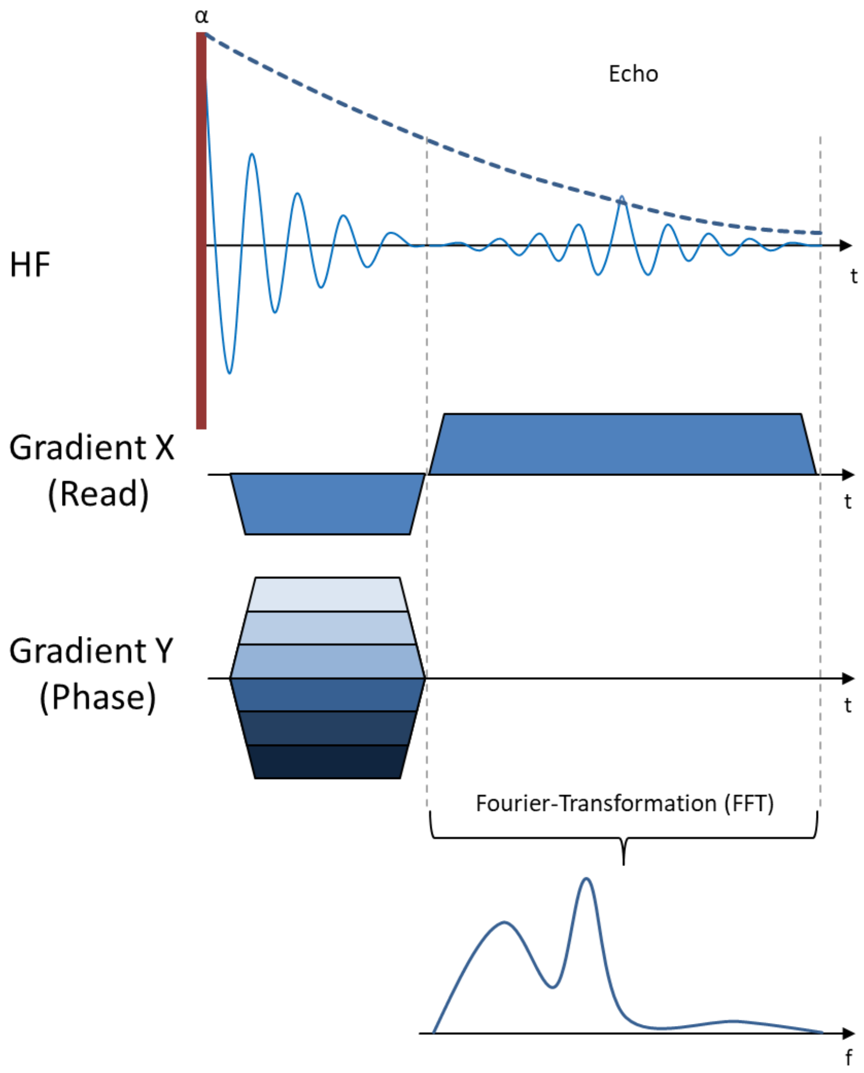

Figure 46: Pulse sequence for experiment *FLASH 2d*

For experts: In the actual pulse sequence, there is an additional acquisition window right after the excitation pulse. This is used to correct a possible frequency drift during the experiment.

PREPARATION

In this experiment, both 5 mm test tubes containing water and oil and the 10 mm structure sample are used. First, place both 5 mm test tubes into the bore of the magnet such that they are in one line and parallel with the rear edge of the magnet.

Select the lesson *FLASH 2d*. The panel *Parameters* shows the following controls:

Data Points (Read): The number of data samples acquired per phase step in read direction.
Data Points (Phase): The number of phase encoding steps in phase direction.
Slice orientation: The plane of the cross section through the sample.
Image Size (Read): The size of the image in read direction. This corresponds to the gradient strength applied in that direction. The lower this value, the higher is the amplitude of the read encoding gradient pulses.
Image Size (Phase): The size of the image in phase direction. This corresponds to the gradient strength applied in that direction. The lower this value, the higher is the amplitude of the phase encoding gradient pulses.
Repetition Time: The repetition time for each phase encoding step.
Echo Time: The echo time.
Excitation Angle: The flip angle α for the excitation pulse.
Averages: The number of averages.

Please compare your panel with Figure 47.

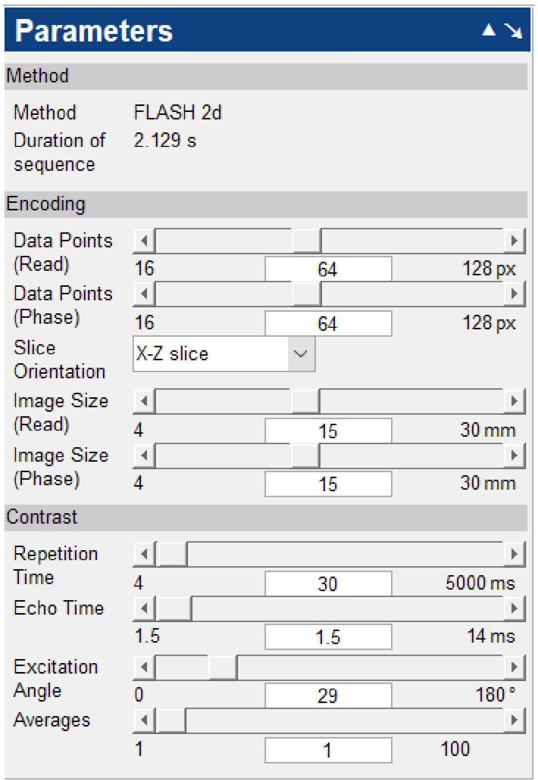

Figure 47: Parameter for experiment *Flash 2D*

Dependent on your specific hardware, not all combinations of parameters that can be set can also be used for an actual measurement. In case some parameter(s) prevent starting an experiment, an error message is displayed and the *Start* button is deactivated until a usable set of parameters is configured.

TASKS

(1) For the first FLASH image, choose the parameter as follows:
- *Data Points (Read)*: 64
- *Data Points (Phase)*: 64
- *Slice Orientation*: X-Z slice
- *Repetition Time*: 20 ms
- *Echo Time*: *1.5 ms*
- *Excitation Angle*: 10°
- *Averages*: 16

(2) Set the gradient strength for the read and phase gradient to sensible values.

(3) Start the measurement. Save or print the acquired image.

(4) Vary the values for the repetition time and the flip angle and repeat the measurement.
What do you observe?

(5) Place the sample *10 mm Structure* into the bore of the magnet and repeat this measurement. Save and/or print the acquired image.

(6) One essential parameter especially for FLASH is the setting of the flip angle (refer to the Experiment Preparation). Calculate an appropriate value for the sample and repeat the measurement.
Why is the flip angle important?

Experiment instruction

Experiment 4-5:
FLASH 2d (Slice Selection)

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to acquire a 2D magnetic resonance image of a structured sample.

A 2-dimensional cross section of the sample is acquired. The acquisition is based on the gradient echo method also called FLASH (“**F**ast **L**ow **A**ngle **S**hot”). In this measurement, the parameters can be set freely – similarly to clinical MRI scanners.

In contrast to the previous gradient echo method *Flash 2D*, this sequence is more sophisticated. It offers the option to excite only a slice within the whole sample. The field of view including the slice thickness can be directly set in mm.

The slice selection is established applying a slice selective RF excitation pulse in combination with an additional slice gradient. The slice gradient needs to be applied (negative gradient slope during RF pulse) even before the RF excitation pulse. This gradient generates some extra frequency encoding of the sample. The duration and frequency of the applied RF pulse determines the slice that is exited. A side effect of this extra frequency encoding is the de-phasing of the signal. This de-phasing can be canceled by applying an additional gradient pulse in the opposite direction directly after the slice selective gradient.

The rest of the sequence is equivalent to Experiment 4-4 *FLASH 2d*.

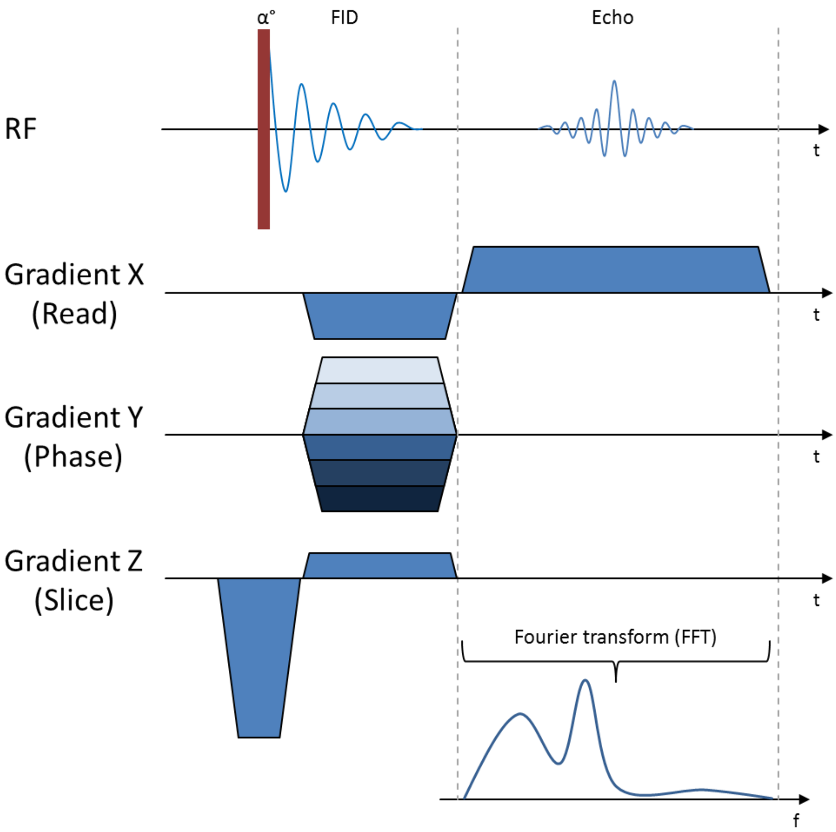

Figure 48: Pulse sequence for experiment *FLASH 2D (slice selection)*

Another feature of this experiment is the automated determination of the Larmor frequency. Before the sequence starts, the system frequency is analyzed and corrected if necessary in order to match the magnet’s Larmor frequency. This offers the benefit that long time averaging can improve the signal to noise ratio without the negative impact of frequency drift. The correction is performed before each averaging step.

PREPARATION

In this experiment, the sample *10 mm Structure* is used. In a later part of the experiment, any sample that can be used for magnetic resonance and that fits into the magnet's bore can be used. We recommend using the empty test tube for sample handling.

First, place the structure sample into the magnet's bore so that the openings of the ladder point to the backside of the magnets case.

Choose the lesson *Flash 2D (slice selection).* The parameter panel shows the following settings (compare with Figure 49):

- Section **Encoding:** *Data Points (Read & Phase), Image Size (Read & Phase), Oversampling (Read & Phase), Slice Thickness & Offset* and *Max. Length AQ window.*
- Section **Slice Orientation:** Euler angles *Alpha*, *Phi*, and *Theta*.
- Section **Contrast:** *Echo Time, Repetition Time*, *Excitation Angle, Estimated T1*, and *Averages.*
- Section **Spoiler:** Factors in *Slice*, *Phase*, and *Read* direction. A factor of 1 means a dephasing of 360° at the ends of the FOV.

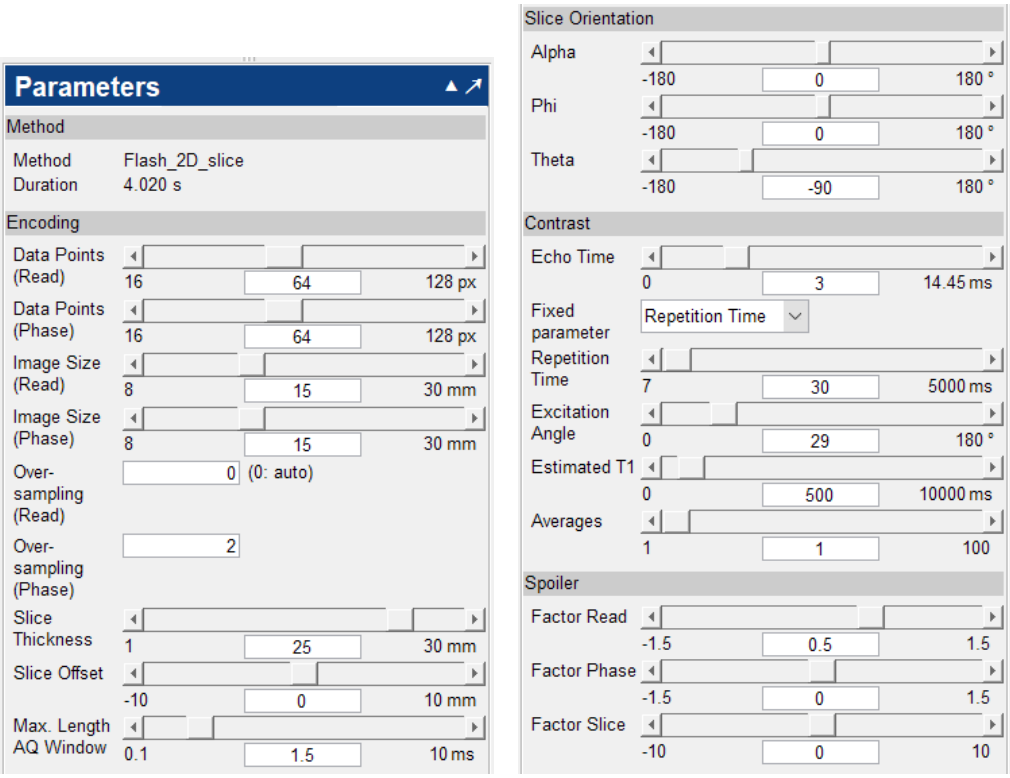

Figure 49: Parameters for experiment *FLASH 2D (slice selection)*

The accessible settings in the panels *Encoding* and *Contrast* of the register tab in Figure 49 (left) are the same as in Experiment 4-4 *FLASH 2d* with the following additions: *Oversampling (Read)* and *Oversampling (Phase)* set the oversampling factor in these directions. If the read oversampling factor is set to 0, an even number is chosen such that the CIC decimation factor for one k-space pixel does not exceed a maximum value (8000 by default).

The additional slider *Slice Thickness* sets the effective thickness of the slice selective pulse. *Slice Offset* sets the offset to the center of the gradient system perpendicular to the slice.

Max. Length AQ Window sets the duration of the AQ window. The actual duration might be slightly shorter to match the system frequency and possible CIC decimation factors.

Additionally, it is possible to set two independent parameters of the three parameters *Repetition Time*, *Excitation Angle* and *Estimated T1*. Chose one fixed parameter and change another parameter. The third parameter is adjusted such that the Ernst angle condition is fulfilled.

In the section *Encoding*, you can set the size and the slice thickness of the image you want to acquire. These controls have the same effect as *Read gradient* and *Phase gradient* of Experiment 4-4 *FLASH 2d*. In this experiment, the gradient field strength is calibrated to the RF coil size which allows setting the size in mm.

Beside these FOV settings, one can set the slice orientation via the Euler angles *Alpha*, *Phi*, and *Theta*. This allows choosing any desired slice orientation within the sample. The Euler angles are defined such that *Alpha* rotates the slice around the X-axis. *Phi* rotates around the (rotated) Y-axis, and *Theta* around the Z-axis.

Advanced users can change the spoiler factors in slice phase and read direction.

Dependent on your specific hardware, not all combinations of parameters that can be set can also be used for an actual measurement. In case some parameter(s) prevent starting an experiment, an error message is displayed and the *Start* button is deactivated until a usable set of parameters is configured.

TASKS

(1) For the first magnetic resonance image, choose the parameter as follows:

- *Data points*: 64
- *Phase steps*: 64
- *Averages*: 1
- *Repetition time*: 150 ms
- *Echo time*: 3 ms
- *Excitation Angle*: 10°
- *Slice thickness*: 10 mm
- *FOV read*: 20 mm
- *FOV phase*: 20 mm

What resolution do these parameters achieve?

Press *Start* for starting the measurement.

(2) Change the slice thickness to 5 mm and repeat this measurement.
What do you observe?

(3) How can you improve the image quality when reducing the slice thickness?
Try to improve the image quality by adjusting the corresponding parameters.
What do you observe?

(4) Try to experiment with the slice orientation by changing the parameters for *Alpha*, *Phi* and *Theta* in the *Slice Orientation* section.

(5) Run some experiments with biological samples of your choice (for example: garden bean, rapeseed, rose hip, wet soil, corn, small plants or flowers, peanuts). For this, we recommend using the empty 10 mm test tube.

Use the knowledge you have gained in the experiments about T1- and T2-relaxation times. This will help to set up the correct values for the repetition time and the echo time.

Experiment instruction

Experiment 4-6:
FLASH 3d

OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to perform a measurement with a 3-dimensional MRI sequence based on the gradient echo method also called FLASH ("**F**ast **L**ow **A**ngle **S**hot"). The accessible parameters can be set freely – equivalently to clinical MRI scanners.

In the Experiment 4-5 *FLASH 2d (Slice Selection),* the slice selection was performed by applying a slice gradient and an appropriate slice selective RF excitation pulse. The slice was selected by encoding it with the specific frequency.

Another possibility for encoding the MR signal in slice direction is phase encoding. For this, we can add a second phase encoding gradient into slice direction – Gradient Z. This Gradient Z increments its value each time the first phase encoding gradient Y has passed through all phase encoding steps.

The remaining part of the sequence is equivalent to Experiment 4-4 *FLASH 2d*.

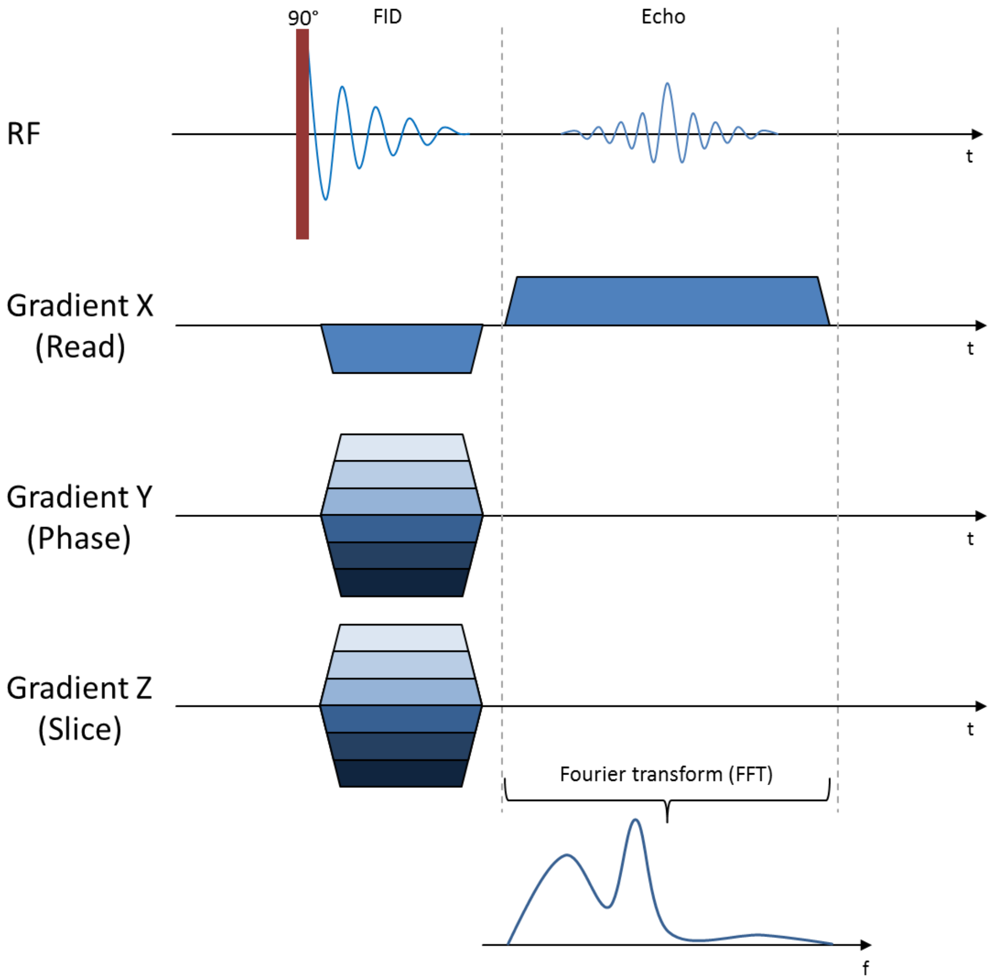

Figure 50: Pulse sequence for experiment *Flash 3D*

Another feature of this experiment is the automated determination of the Larmor frequency. Before the sequence starts, the system frequency is analyzed and corrected if necessary in order to match the magnet's Larmor frequency. This offers the benefit that long time averaging can improve the signal to noise ratio without the negative impact of thermal frequency drift. The correction is performed before each averaging step.

PREPARATION

In this experiment, the sample *10 mm Structure* is used. In a later part of the experiment, any sample that is suited for MRI and that fits into the magnets bore can be used. We recommend using an empty 10 mm test tube for sample handling.

First, place the structure sample into the magnet's bore so that the openings of the ladder point to the backside of the magnets case.

Choose the lesson *FLASH 3d*. It might be necessary to add the lesson to the list of experiments by clicking the Add button and selecting it from the list of available experiments. The parameter panel shows the following settings (compare with Figure 51):

- Section **Encoding:** *Data Points (Read, Phase and Phase 2), Image Size (Read, Phase and Phase 2)* and *Max. Length AQ window.*
- Section **Contrast:** *Repetition time*, *Echo time, Excitation Angle* and *Averages*.
- Section **Spoiler:** Factors in *Read*, *Phase*, and *Slice* direction. A factor of 1 means a dephasing of 360° at the ends of the FOV.

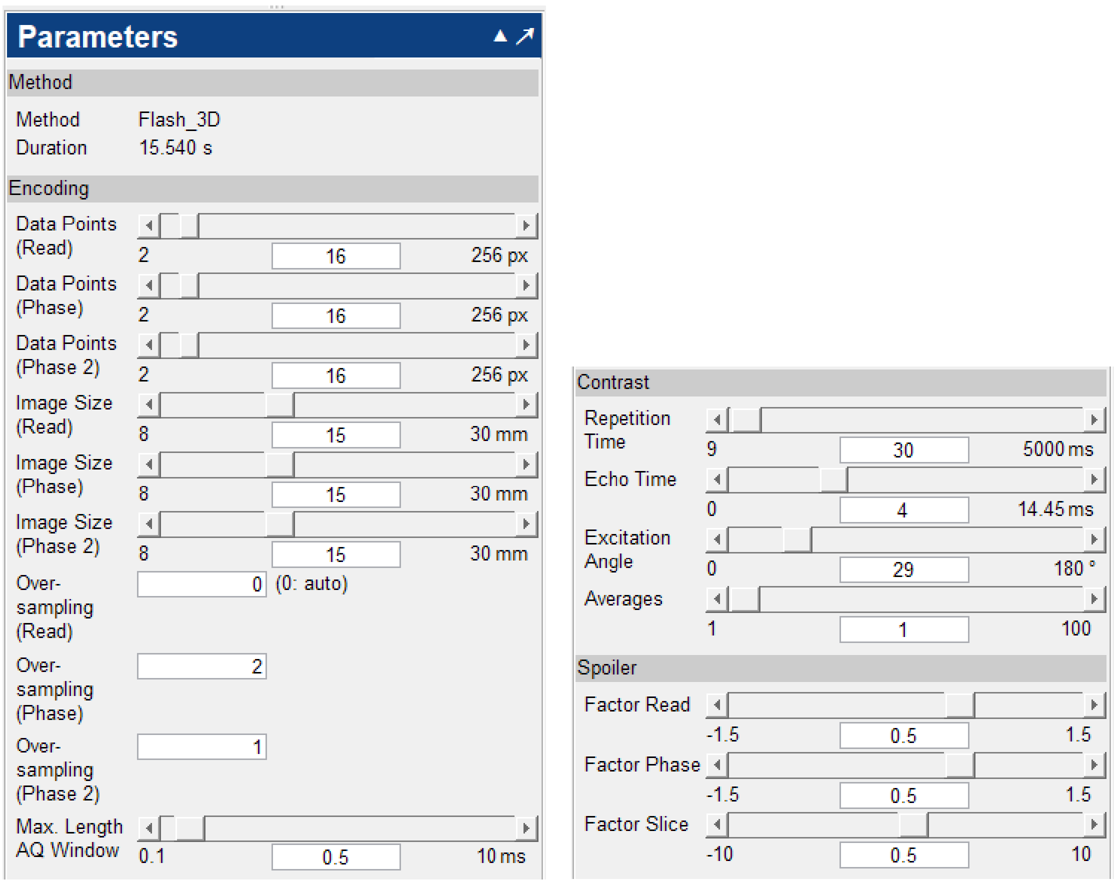

Figure 51: Parameters for experiment *Flash 3D*

Most of the accessible settings in the sections *Encoding*, *Contrast* and *Spoiler* are the same as in *Flash 2D (slice selection)*. Additional settings are available for the encoding in the third dimension.

Advanced users can change the spoiler strength for all gradients.

As soon as the acquisition of the 3D image has finished, the result is displayed in the Data Display panel.

Clicking the button *open external 3D viewer* will load the acquired 3D dataset in an external 3D visualization tool (VolView™). For more details about using VolView™, please refer to the document *VolView - Guide for 3D MRI visualization*.

Dependent on your specific hardware, not all combinations of parameters that can be set can also be used for an actual measurement. In case some parameter(s) prevent starting an experiment, an error message is displayed and the *Start* button is deactivated until a usable set of parameters is configured.

TASKS

(1) For the first 3-dimensional Flash image, choose the parameter as follows:

- *Data points*: 32
- *Phase steps*: 32
- *Phase steps 2*: 32
- *Averages*: 1
- *Repetition time*: 150 ms
- *Echo time*: 2 ms
- *Angle*: 25°
- *FOV read*: 20 mm
- *FOV phase*: 20 mm
- *FOV phase 2*: 30 mm
- *All Spoiler Factors:* 0.5

Press *Start* for starting the measurement.

When the acquisition has finished, try to get familiar with the options for changing the mathematical processing / visualization of the data. Furthermore, change the slice orientation and choose different slices to get a feel for orienting in a sample.

(2) Increase the resolution by setting the values for FOV read, FOV phase and FOV phase 2 to 50. Calculate the optimal flip angle for the sample and repeat the measurement.
What do you observe?

(3) Run some experiments with biological samples of your choice (for example: garden bean, rapeseed, rose hip, wet soil, corn, small plants or flowers, peanuts). For this, we recommend using the empty 10 mm test tube.

Use the knowledge you have gained in the experiments about T1- and T2-relaxation times. This will help to set up the correct values for the repetition time and the echo time.

Experiment instruction

Experiment 5-1:
Auto Shim

OBJECTIVE OF THE EXPERIMENT

This (optional) experiment allows to automatically find good shim values for the magnet. This is done by repeated acquiring an echo (or FID) while variating the shim values. The used algorithm tries to maximize the integral of the absolute value of the measured echo (or FID) amplitude.

It can be used to quickly set up the magnet for other experiments without manual shimming. See Experiment 1-3 *B_0 Homogeneity (Magnet Shim)*.

PREPARATION

For this experiment, a sample with sufficiently large SNR should be used. To keep the total duration of the optimization short, a sample should be used that has a not too long T1 relaxation time. Both conditions are fulfilled, e.g., by the *10 mm Oil* sample.

First, place the sample into the magnet's bore.

Choose the experiment *Auto Shim*. It might be necessary to add the experiment to the list of experiments by clicking the Add button and selecting it from the list of available experiments. The parameter panel shows the following settings (compare with Figure 52):

- *Echo Time (or tAQ for FID)*: Depending on whether an echo or an FID is used for the optimization (see *# of Echo* below), this is the echo time (or the acquisition duration) that is used during the optimization. It should match the T2 relaxation time (or T2*) of the used sample.
- *Start with current shim*: If this checkbox is ticked the optimization starts with the currently used shim values. If these shim values are already close to the optimum values, the total duration of the shimming process might be shorter. However, if the currently used shim values are far away from the optimum values, the shim process might not succeed. Un-tick the checkbox in this case to start with the optimization from scratch.
- *# of Echo to use (0 for FID)*: Select the number of the echo (in a CPMG echo train) for which the algorithm should try to maximize the amplitude. Set to 0 to maximize the amplitude of the FID. For most cases, it should be ok to maximize the amplitude of the first echo (1).
- *Repetition Time*: Repetition time for the iterations in the shim process. This should be long enough to allow for sufficient relaxation of the sample (e.g., approximately three times the T1 relaxation time).
- *Find Frequency at each n-th Echo (or FID)*: Shimming the magnet might have an impact on the center frequency of the acquired signal. If this checkbox is ticked, the "main" frequency of the received signal is determined in each step of the optimization. That frequency is used for the rf pulses and acquisition in the subsequent step. In some cases (e.g., low SNR or shim values far from the optimum), this might lead to issues. E.g., the echo might "disappear" during the shimming process. Untick the checkbox in this case and repeat the auto shim process (or try to manually find better shimming values and start from there).

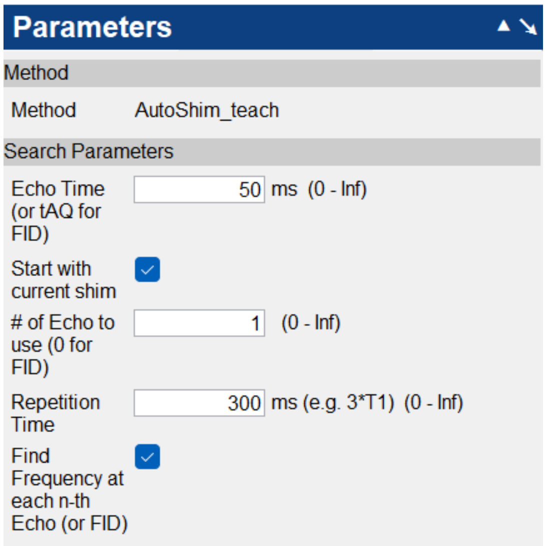

Figure 52: Parameters for experiment *Auto Shim*

The default values are set such that they should be working with the *10 mm Oil* sample.

TASKS

This is experiment is supplied only for convenience.

Experiment instruction

Experiment 5-2:
Auto Pulse Duration

OBJECTIVE OF THE EXPERIMENT

This (optional) experiment allows to automatically find good values for the rf pulse durations. This is done by iteratively increasing the excitation and inversion pulse duration while acquiring a 1d profile along the rf coil axis using a read encoded spin echo measurement.

It can be used to quickly set up the magnet for other experiments without manually determining the coil efficiency. See Experiment 1-2 *Excitation Angle*.

PREPARATION

For this experiment, a sample with sufficiently large SNR should be used. To keep the total duration of the optimization short, a sample should be used that has a not too long T1 relaxation time. Both conditions are fulfilled, e.g., by the *10 mm Oil* sample.

First, place the sample into the magnet's bore.

Choose the experiment *Auto Pulse Duration*. It might be necessary to add the experiment to the list of experiments by clicking the Add button and selecting it from the list of available experiments. The parameter panel shows the following settings (compare with Figure 53):

- *Est. T1 of sample*: The estimated T1 relaxation time of the used sample. This value is used to choose a matching repetition time to ensure sufficient magnetization of the sample at each repetition.
- *Smallest flip angle*: Given the currently set value for the 90° pulse duration, set a flip angle for the excitation pulse at which the process should start. The double of this angle is used for the inversion pulse at each step, respectively.
- *Largest flip angle*: Given the currently set value for the 90° pulse duration, set a flip angle for the excitation pulse at which the process should stop.
- *Number of flip angles*: The number of flip angles that should be checked starting from *Smallest flip angle* and ending at *Largest flip angle*.
- *Echo time*: Echo time for the spin echo measurement.
- *Size in read direction*: Size of the 1d-profile encoding along the rf coil axis.
- *Number of samples*: Number of samples in the read out window (i.e., number of non-zero-filled pixels along the 1d profile).

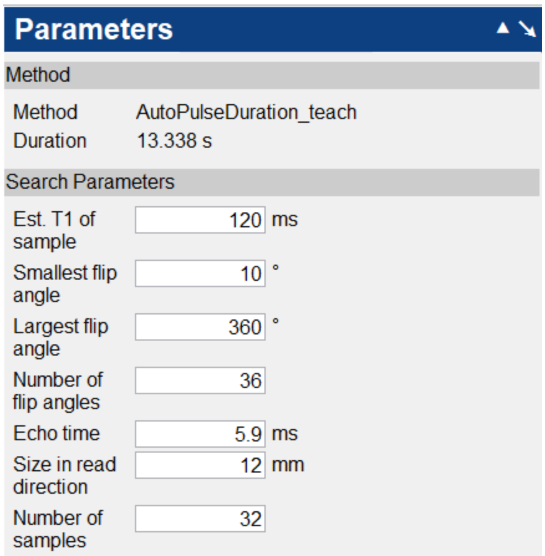

Figure 53: Parameters for experiment *Auto Pulse Duration*

The default values are set such that they should be working correctly with the *10 mm Oil* sample.

TASKS

This is experiment is supplied only for convenience.

INFORMATION

The instruction book from the practical course of the University of Würzburg authored by Dr. Eberhard Rommel served as a template for this document. In addition to the outline of the original document, some text passages have been adopted as they stand and translated into English. Some experiments have been added.

We hereby thank the author Dr. Eberhard Rommel for providing us the didactically valuable instruction book as a template.

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