MRI: Earth's Field NMR &
Magnetic Resonance Imaging

Interim Handout

Earth Field NMR Experiment

University of Toronto Advanced Physics Lab

Experiment location: MP239
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INTRODUCTION TO NMR

Many nuclei are known to possess a non-zero spin angular momentum, $\boldsymbol{I}$, and, parallel to $\boldsymbol{I}$, a nuclear dipole moment, $\boldsymbol{\mu}$. These two vector quantities are, to a good approximation, nuclear constants independent of environment. The gyromagnetic ratio γ which relates these two quantities is defined by

$$\boldsymbol{\mu} = \gamma \boldsymbol{I} \tag{1}$$

The energy of interaction of these magnetic dipole moments with external and local internal magnetic fields is quantized resulting in discrete energy levels. The energy differences correspond to radio frequency (r.f.) quanta, and an appropriate r.f. field will induce magnetic dipole transitions between them. They study of these levels and of the transitions between them is called Nuclear Magnetic Resonance (NMR).

The frequency, v, and the frequency spread Δv of the required r.f. radiation may be measured and controlled with precision. Typically, a 1 milliwatt, 30 MHz generator produces the order of 10^{22} photons per second in the Δv range. In such a radiation field the quantum theory predicts that spontaneous emission processes are completely negligible in comparison to stimulated emission and absorption processes. Since stimulated emission is identical and indistinguishable from the radiation present in the radiation field itself, only the net effect, (absorption - stimulated emission) is observable.

Before applying the r.f. field, the spin system will, in general, be parallel the external magnetic field and is in thermal equilibrium with its surroundings (called the LATTICE) at a temperature T. The populations of the nuclear energy levels are then proportional to the Boltzmann factor $e^{-En/kT}$. Typically, the population difference between the two proton spin levels in water in a field of 10^4 gauss is about 1 part in 10^6. Since the transition probabilities for stimulated emission and absorption are equal, it is these minute inequalities in population that make absorption slightly larger than stimulated emission and lead to a net absorption of energy by the spin system from the r.f. field.

The Resonance Condition

We shall assume that there is a constant external magnetic field $\boldsymbol{B_o}$ in the z direction. The nuclei that will be investigated in this experiment are the hydrogen nuclei or protons in water. The angular momentum $\boldsymbol{I}$ of the proton is 1/2 so the quantum mechanically allowed projections of this vector along the z axis are

$$I_z = \pm 1/2\hbar \tag{2}$$

The energy of interaction of the magnetic moments with the magnetic field is given by

$$E = -\boldsymbol{\mu} \bullet \boldsymbol{B_o} \tag{3}$$

which from equation (1) gives

$$E = -\gamma \boldsymbol{I} \bullet \boldsymbol{B_o} \tag{4}$$

Using equation (2) this gives

$$E = -\gamma I_z B_o = \pm 1/2\gamma \hbar B_o \qquad (5)$$

The difference in energies of the two levels is then

$$\Delta E = \gamma \hbar B_o \qquad (6)$$

Resonance occurs when the energy of the r.f. photons, hv_o is equal to the energy separation of the levels given in equation (6).

$$hv_o = \gamma \hbar B_o \qquad (8)$$

or

$$\omega_o = \gamma B_o \qquad (7)$$

This frequency can induce transitions between the energy levels and is referred to as the Larmor frequency.

In the classical picture, a sinusoidal varying magnetic field, $\boldsymbol{B_1}$, corresponding to the Larmor frequency changes the magnetization direction of the nuclei into a transverse plane with respect to the static magnetic field, $\boldsymbol{B_o}$. The spins then precess about $\boldsymbol{B_o}$ *at* ω_o.

Experimentally, $\boldsymbol{B_1}$ is obtained by locating the sample in a coil whose axis is perpendicular to the direction of $\boldsymbol{B_o}$. In a frame of reference rotating at the Larmor frequency, the only field seen is the field $\boldsymbol{B_1}$ which is constant in the rotating frame.

In this experiment relaxation mechanisms are studied by measuring the recovery of the magnetization from $\boldsymbol{B_1}$ to $\boldsymbol{B_o}$ after it has been disturbed by a r.f. pulse at the Larmor frequency.

The Meaning of π/2 and π pulses

In equilibrium the magnetic moments are aligned with $\boldsymbol{B_0}$ which is taken to be the direction. The resulting magnetization is called longitudinal magnetization. When a r.f. pulse is applied at the resonant frequency, the only magnetic field seen by the nuclear magnetic moments is $\boldsymbol{B_1}$ and they will precess about $\boldsymbol{B_1}$. By controlling the amplitude and/or duration of an r.f. pulse, it is possible to rotate the magnetization into the *x-y* plane. This is called a π/2 pulse (or 90^o pulse) and the resulting magnetization is called transverse magnetization. Similarly a pulse of the same amplitude but twice as long will simply reverse the longitudinal magnetization. This is called a π pulse (or 180^o pulse).

A π/2 or π pulse, thus, disturbs the thermal equilibrium of the system; therefore, the transverse magnetization must return to zero and the longitudinal magnetization must return to its equilibrium value.

The Meaning of the Time Constants T_1 and T_2

The time constant for the longitudinal magnetization to recover its equilibrium value in the applied field is called the spin-lattice or the longitudinal relaxation time, T_1. The time constant which describes the decay of the magnetization in the *x-y* plane independent of magnetic field inhomogeneity effects is called the spin-spin or the transverse relaxation time, T_2.

After a π/2 pulse, magnetic moments precess in the *x-y* plane about the z axis. The axis of the sample coil is perpendicular to the *z* axis so the precessing transverse magnetization will induce an emf at the Larmor frequency in the sample coil. The signal is a free precession signal and decays away with time. This is called a free induction decay (FID).

Immediately after the application of a π/2 pulse, all the magnetic moments point in the same direction in the *x-y* plane. If there are inhomogeneities in the static magnetic field over the dimensions of the sample then different magnetic moments will precess at different rates. In other words, some components of the magnetization start getting ahead of the average and some start getting behind. This results in a shortening of the transverse relaxation time. The time constant which describes the decay of the magnetization in the *x-y* plane when magnetic inhomogeneities are included is designated T_2^*. The exponential shape of the free induction tail depends on T_2^* which is always smaller than T_2. In the limit of very homogeneous fields, T_2^* approaches T_2. One can get around the effects of field inhomogeneities and measure T_2 directly by using the technique of spin echoes which is explained later.

There may be contributions to T_2 from several processes. Since each nucleus possesses a small magnetic dipole moment, there will be a magnetic dipole- dipole interaction between each pair of nuclei. Each nuclear magnet finds itself not only in the applied steady field $\boldsymbol{B_o}$, but also in a small local magnetic field $\boldsymbol{B_{local}}$ produced by the neighboring nuclear magnets. The magnetic field of a magnetic dipole falls off rapidly with distance so that only the nearest neighbors make important contributions to the local magnetic fields. Since the nuclei are in random motion, the local magnetic fields will vary from nucleus to nucleus. Consider nuclei with their spins in the *x-y* plane interacting with nuclei whose spins are aligned along the z axis, the direction of $\boldsymbol{B_o}$. The total magnetic field $\boldsymbol{B_o} + \boldsymbol{B_{local}}$ experienced by nuclei with their spins in the *x-y* plane will vary from nucleus to nucleus. Hence the precessional frequency of these nuclei will also vary. This will result in a spreading out of the spins in the *x-y* plane similar to the effect of inhomogeneities in the static field $\boldsymbol{B_o}$ which was mentioned above. It is this dipole- dipole interaction which gives rise to the name spin-spin relaxation.

Consider also the dipole-dipole interaction which is the reverse of the above process and which results in spin exchange. Magnetic moments in the *x-y* plane are precessing about the z axis at the Larmor frequency. In the rotating frame of reference a nucleus with its spin along the z axis will see a magnetic field due to a magnetic moment in the *x-y* plane. Since this field does not change its direction, the magnetic moment which was originally aligned along the z axis will precess about it and may end up with its magnetic moment in the *x-y* plane. The energy for this transition comes of course from the nucleus whose magnetic moment was initially in the *x-y* plane. There is a mutual exchange of energy in this spin-exchange process. Although there is no change in the energy of the system, the phases of the spins in the *x-y* plane is disturbed and hence T_2 is shortened.

The term spin-lattice relaxation time T_1 refers to processes in which nuclei with their spins in the *x-y* plane give up their energy to the surroundings or lattice and return to their equilibrium direction along the *z* axis. The rate at which magnetization decays (or builds up) in a static field depends on the mechanisms available for the spins to transfer energy to something else, namely the other repositories for thermal energy such as the translations, rotations, and vibrations, collectively called the lattice.

It is to be noted that in our discussions of spin-lattice relaxation, we assume that the spin system has a very small heat capacity so that the spin energy cannot disturb the lattice temperature.

How to Measure T_2

If one could assume that the constant magnetic field $\boldsymbol{B_o}$ were completely uniform then after the application of a π/2 pulse, the variation of the *z* component of the local field would cause different spins to precess at different rates. Any magnetization *Mx* created by a π/2 pulse would disappear (relax) by a fanning out of the spins in the *x-y* plane according to

$$M_x = M_{xo}\, e^{-t/T2} \tag{9}$$

The value of T_2 could be obtained directly from the shape of the exponential free induction tail.

If $\boldsymbol{B_o}$ is not completely uniform, which is always the case, different spins situated in different field regions will have different Larmor precessional frequencies. Thus spins will dephase in a much shorter time T_2^*. T_2^* is related to T_2 by

$$(T_2^*)^{-1} = (1/T_2)^{-1} + \gamma \Delta B_o \tag{10}$$

The shape of the induction tail can be used to determine the field inhomogeneity.

The technique of spin echoes permits one to eliminate the effects of field inhomogeneities. A π/2 pulse will generate a transverse magnetization which because of the Larmor precession, will induce a voltage in a coil with its axis perpendicular to $\boldsymbol{B_o}$. This signal will decay as the magnetization fans out. Now a π pulse applied at time τ later will cause a further precession about the *x* axis in the rotating frame so that quickly precessing nuclei now find themselves behind the slowly precessing nuclei. A time *τ* still later, nuclei will re-phase and produce a signal in the detector coil. This is a spin echo. The loss in amplitude of the signal is due solely to any irreversible process and will occur at the time rate T_2. Repeated π/2, π pulses with different delay times *τ* can thus be used to measure T_2.

Another technique is to use the Carr-Purcell pulse sequence which is a π/2 pulse followed by π pulses at 1τ, 3τ, 5τ, ... Echoes appear at 2τ, 4τ, 6τ, ... All from the original transverse magnetization produced by the first π/2 pulse. The Carr-Purcell sequence has an advantage beside a savings in time. If times involved are long enough for diffusion to be important, then when nuclei diffuse to region where $\boldsymbol{B_o}$ is different they will not re-phase for the echo since their Larmor frequencies will be different. For a discussion of the effects of diffusion see Abragam pages 58-63.

How to Measure T_1

Although there are several ways to measure T_1, only the two most common double pulse sequence techniques will be presented. In each of these sequences, the first pulse prepares the spins and the second pulse measures the magnetization after a waiting period. These are the inversion recovery sequence or π-π/2 sequence and the saturation recovery sequence or π/2-π/2 sequence.

The π-π/2 Sequence

In the inversion recovery method the π pulse inverts the spin population and thus the magnetization and the recovery therefore goes from $-M_0$ to M_0 according to

$$M(t) = M_o(1-2e^{-t/T1}) \tag{11}$$

where M_0 is the thermal magnetization after waiting for a time much longer than $T1$. Practically, "a long time" is approximately $7T_1$.

The height of the induction tail of the second pulse is measured for various pulse separation times. This method has the advantage that T_1 can, in principle, be obtained from one measurement. The induction tail is zero on the second pulse when $M(z) = 0$. If t_0 is the time separation between pulses when the induction tail of the second pulse is zero then

$$0 = 1 - 2e^{-to/T1} \tag{12}$$

and hence

$$T= t / ln(2) \tag{13}$$

The difficulty with a single measurement process is that one has assumed that the magnetization changes according to equation (9). A more rigorous method would be to plot $M_0-M(t)$ against t on a semi-log plot. If the plot is a straight line then one will have much more confidence in the value of T_1 obtained. As an aside, one should not plot $1 - M(t)/M_0$ against t since any mis-estimation in the baseline for the signal will lead to an apparently non-exponentially.

Part 1: Introduction to NMR – Free Induction Decay

1. Background theory on EFNMR instrumentation

This experiment is performed using the Terranova-MRI EFNMR apparatus. Conventional NMR instrumentations generate a large static magnetic field $\boldsymbol{B_o}$ (> 0.3T) to achieve bulk magnetization in the sample. The Terranova-MRI EFNMR apparatus, however, is relying on the highly homogeneous Earth's magnetic field $\boldsymbol{B_E}$ (54μT). When properly aligned, the outermost pre-polarization coil of the probe magnifies $\boldsymbol{B_E}$ by 350 times and increases bulk nuclear magnetization, $\boldsymbol{M_z}$, of the sample along the direction of the Earth's field (assumed to be along the longitudinal z direction). This is the equilibrium magnetization of the sample. When the innermost B_1 coil generates a 90^o RF pulse at the Larmor frequency ($\omega = \gamma B_E$) for a particular duration, a magnetic field $\boldsymbol{B_1}$ in the transverse plane is generated. This field rotates the sample's magnetization into the x-y plane, resulting in a transverse magnetization, $\boldsymbol{M_{xy}}$. As $\boldsymbol{B_1}$ is removed, $\boldsymbol{M_{xy}}$ starts to precess about the z direction at the Larmor frequency with a decay. This precession is detected by the B_1-coil to generate the Free Induction Decay (FID) spectrum (see Figure 1). The software takes the Fourier Transform of this signal to generate a frequency spectrum with a peak at the Larmor frequency.

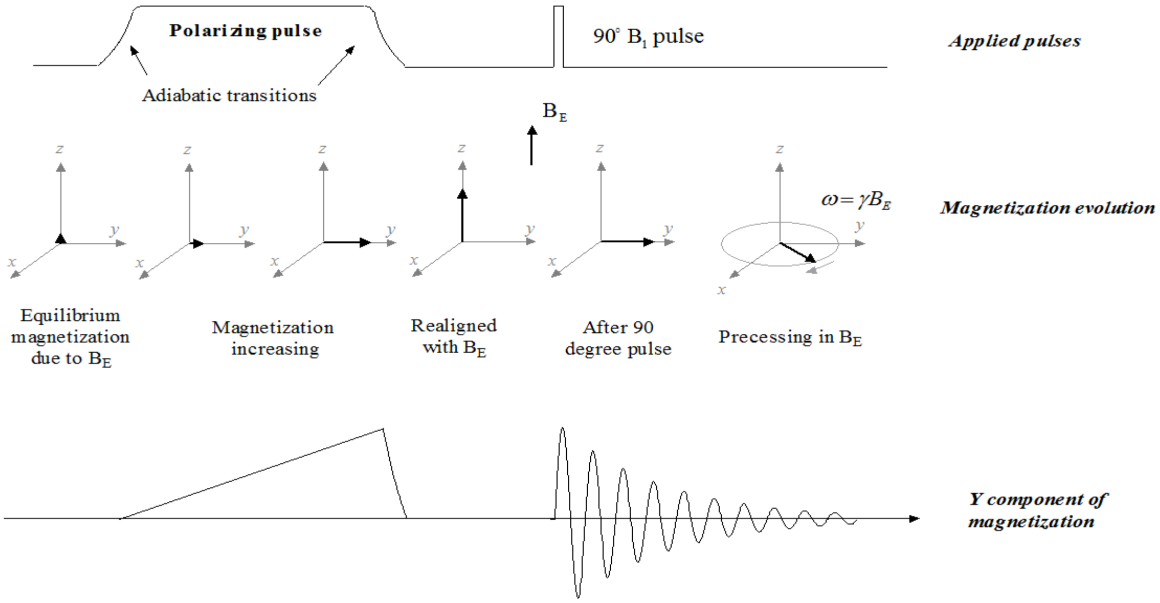


Figure 1: 90^o pulse sequence diagram

System capacitance

In this instrumentation, the innermost B_1-coil behaves as both the excitation and detection coil. When connected to the spectrometer, the B_1-coil forms a parallel LCR circuit. The B1 coil is an inductor with an inductance, L, and an internal resistance, R. it is connected in parallel to a fixed capacitance, C, within the spectrometer. The circuit will resonate at a frequency w_0 given by:

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad (1)$$

By changing the B_1 capacitance value in the software, the B1-coil can be tuned to generate a RF pulse at the Larmor frequency.

Macros used for instrument tuning and signal optimization

Excitation coil analysis – *AnalyzeCoil* macro

The *AnalyzeCoil* experiment characterizes the transmitting/receiving B_1-coil for instrument tuning purposes. By applying impulses to the B_1-coil over a range of capacitance values, the resonance response of the coil is determined. An analysis of this response calculates the inductance and the parasitic capacitance of the coil. Note that this macro needs to be run without any sample in the probe. Record the B_1 inductance and B_1 capacitance as displayed in the CLI window. These values will be used in other experiments to determine the self-resonance of the coil.

Shimming – *AutoShim* macro

Earth's magnetic field is naturally highly homogeneous. However, the field is so weak (~50μT) that its homogeneity is easily disrupted by the proximity of ferrous objects or other sources of magnetic field. Inhomogeneity can cause phase coherence loss and lead to rapid signal decay. Local magnetic field inhomogeneities introduce a range of Larmor frequencies across the sample. Each spin then will precess at a Larmor frequency associated with its position. Magnetic field homogeneity can be greatly improved using shimming. Shimming is the process of iteratively applying weak position dependent magnetic fields across the sample until the applied fields cancel the underlying inhomogeneity of the static field. This is achieved by passing small currents through a collection of coils designed to generate magnetic fields of specific geometries such as a magnetic field that changes linearly along one axis (field gradient). The apparatus employs three shim coils, which correspond to field gradients along the x, y and z axes. Shimming parameters are very sensitive to changes in the environment; therefore when the probe has been moved or large metal objects in the vicinity of the probe have been moved, the shimming process must be repeated. The software contains the macro *Autoshim*, which performs shimming in an automated manner by running a series of the pulse and collects sequence.

B_1 pulse duration

The B_1Duration macro runs a series of pulse and collect sequences with varying excitation pulse durations. A pulse duration corresponding to a tip angle of 90° yields the maximum signal. In the plot of signal amplitude versus ***B_1*** pulse duration, the first maximum yields the optimal 90° pulse duration.

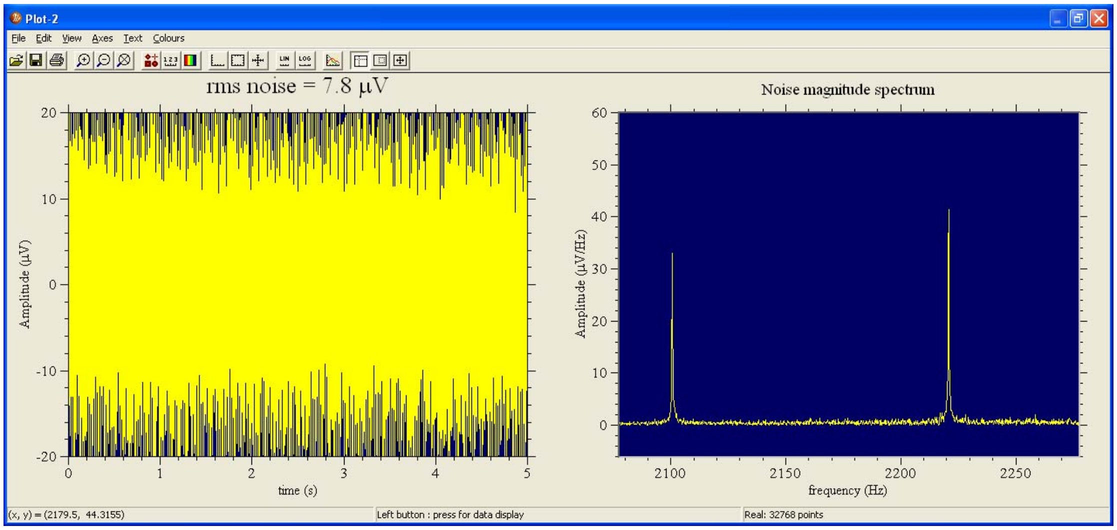
2. Pre-lab preparation

2.1 Suggested lab preparation

1. Watch the following videos:
   Introductory NMR & MRI: Video 04: Acquiring a Free Induction Decay (FID)
   http://www.youtube.com/user/magritek#p/u/7/MPXbDDRumwM
   Introductory NMR & MRI: Video 05: Field Homogeneity
   http://www.youtube.com/user/magritek#p/u/6/o8PzreUSbVE

2.2 Pre-lab questions

1. Calculate the Larmor frequency of the water sample, given that the gyromagnetic ratio for a hydrogen nucleus is $2.675\text{x}10^8 T^{-1} s^{-1}$.
2. How does inhomogeneity in the Earth's magnetic field affect the amplitude and the frequency spectrum of a free induction decay signal?
3. What are possible sources of magnetic field inhomogeneities in a lab environment?
4. Figure 2 displays the root mean squared (rms) value of noise detected by the EFNMR probe. Based on their frequencies, what do the two distinct noise peaks represent?



(x, y) = (2179.5, 44.3155)
Left button : press for data display
Real: 32768 points

Figure 2: *MonitorNoise* experiment output

3. Experiment protocol

3.1 Learning Objectives

In this section of the experiment, students will:

- Apply nuclear magnetic resonance (NMR) in Earth's magnetic field (EFNMR) to obtain a signature Free Induction Decay (FID) signal of hydrogen atoms in a water sample
- Optimize the quality of an NMR signal through shimming and parameter optimization
- Investigate the effects of field inhomogeneity and other implementation challenges

The experiment introduces the protocol for optimizing the NMR signal which will be used prior to all further experiments in order to ensure the highest quality results possible.

3.2 Evaluation

As expected in the Advanced Physics labs, students are expected to document as much of their observations and results in their lab notebooks as possible. Collecting screenshots of experiment results will also be useful. The approximate mark distribution for the lab is below.

1. Pre-lab questions (5%)
2. Results (40%)
3. Analysis and discussion (55%)

3.3 List of required materials and equipment

- Magritek EFNMR probe, spectrometer and computer with Prospa software
- 570ml bottle of water
- Magnetometer
- Probe platform (in this case, a strong cardboard box)
- Wooden probe stand

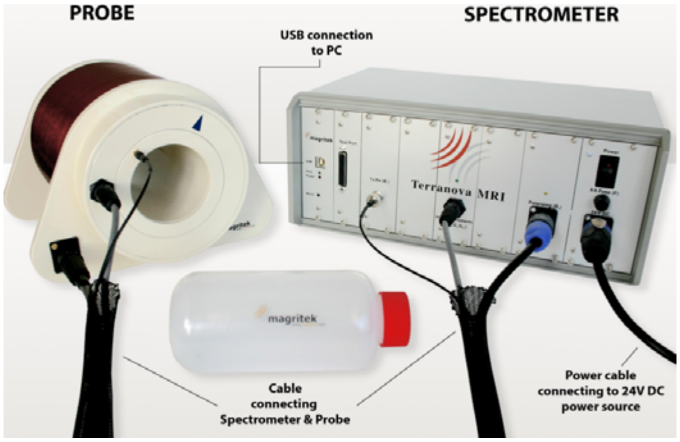


Figure 3: Key components of the EFNMR instrumentation

3.4 Safety considerations

- As part of setup, the probe stand and the probe (a combined weight of ~4 kg) have to be lifted to a height of ~1.3m for placement on the probe platform. Should you require assistance in lifting the probe onto the platform, ask the TA for assistance.
- To minimize trip hazards, ensure that the area around the EFNMR station is clear of any other objects.
- When running the experiments, do not let the coil temperature run beyond 40°C. Cease experimentation when the probe is warmer than body temperature and resume when the probe has cooled down sufficiently.

3.5 Experiment steps

Aligning the probe

1. Place the wooden probe stand on the provided platform. Place the probe on the stand (Figure 4).

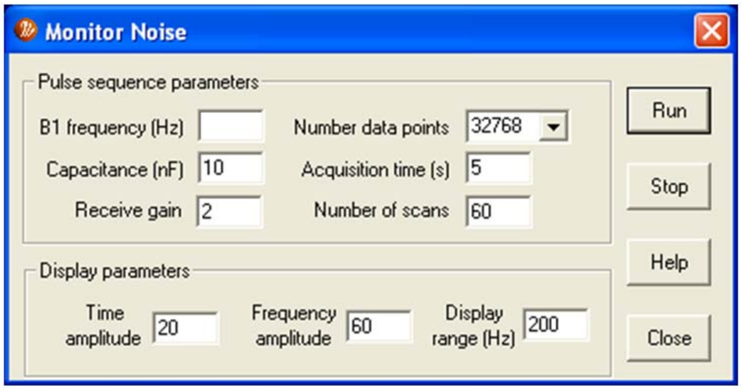
Figure 4. Final setup of the probe and stand on the NMR platform

2. Rotate the probe until the arrow on the probe aligns with a magnetometer pointed in the z-direction (Fig. 5a). Orient the probe stand at 90° to the Earth's magnetic field (Fig. 5b).

5a. 5b.

Figure 5. Alignment of the probe. Figure 2a shows the correct alignment of the probe in the z-direction. Figure 2b demonstrates the correct alignment of the probe wrt. the Earth's field.

3. Open the Prospa software and turn on the spectrometer. The spectrometer’s red power light and green USB light will both illuminate.
4. Under the *EFNMR* menu, open the *MonitorNoise* experiment in Prospa (Figure 6). Enter your calculated Larmor frequency in the “B1 frequency” field.



Pulse sequence parameters

B1 frequency (Hz):
Number data points: 32768
Capacitance (nF): 10
Acquisition time (s): 5
Receive gain: 2
Number of scans: 60

Display parameters

Time amplitude: 20
Frequency amplitude: 60
Display range (Hz): 200

Figure 6: *MonitorNoise* parameter screen

5. Minimize the noise of the probe by fine-tuning the probe’s alignment. Aim to achieve an rms noise signal of 7.5µV or less.
   Note 1: To view plots of the experiment output in real time, select *1D Window* under the *Window* menu. Additionally, a text read-out of the experiment results can be obtained by selecting *Command Line Interface* under the *Window* menu.
   Note 2: The maximum allowable noise signal is 8.5µV. Beyond this value, it will be difficult to obtain a good quality signal.

Tuning the probe capacitance

6. To tune the capacitance of the system, run the *AnalyzeCoil* experiment to obtain the self-capacitance (C_{coil}) and self-inductance of the coil (L_{coil}) from the CLI window. The *AnalyzeCoil* experiment characterizes the B_1 transmit/ receive coil by applying an impulse to the B_1 coil and detecting the response. This procedure is repeated over a range of capacitance values in order to determine the parameters of the B_1 coil.
   a. Calculate the total required capacitance (C_{total}) using the resonance circuit equation:

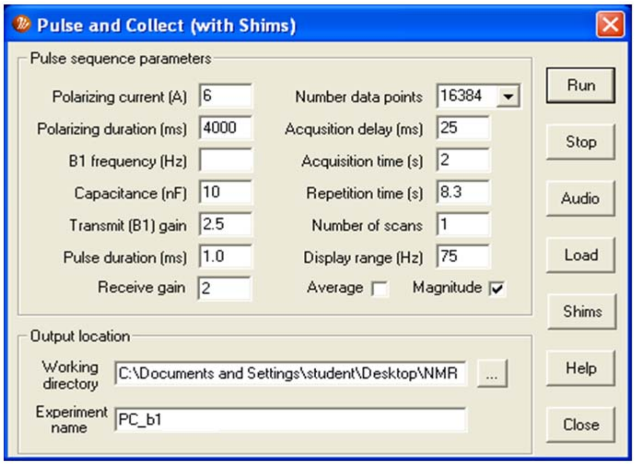
   $$\omega_o = \frac{1}{\sqrt{L_{coil} C_{total}}}$$

   , where ω_o is the desired resonance frequency.
   b. Calculate the new capacitance value: $C_{software} = C_{total} - C_{coil}$. Record this value for use in future experiments.

Note: There should be no water sample in the probe during the *AnalyzeCoil* experiment.

Obtaining a free induction decay signal

7. Open the *PulseAndCollect* experiment and enter your calculated Larmor frequency in the “B1 frequency” field and the calculated capacitance (Figure 7).



Polarizing current (A) 6
Polarizing duration (ms) 4000
B1 frequency (Hz)
Capacitance (nF) 10
Transmit (B1) gain 2.5
Pulse duration (ms) 1.0
Receive gain 2
Number data points 16384
Acqusition delay (ms) 25
Acquisition time (s) 2
Repetition time (s) 8.3
Number of scans 1
Display range (Hz) 75
Average ☐ Magnitude ☑
Working directory C:\Documents and Settings\student\Desktop\NMR
Experiment name PC_b1

Figure 7: *PulseAndCollect* parameter screen

8. Place the water sample in the probe and run the *PulseAndCollect* experiment. The presence of a distinct sample peak confirms that the machine has been set up correctly. Confirm the presence of the peak by removing the water sample from the probe and rerunning the experiment.
9. If the signal peak frequency falls within 10% of your calculated value, adjust the B_1 frequency to match the observed frequency. Also, calculate and enter the new required capacitance value. Rerun the *PulseAndCollect* experiment. Use these values for all the ensuing experiments during this lab period.

Optimizing the signal

10. Open the *Autoshim* experiment and set the B_1 frequency to the frequency of the signal obtained previously. It is important to limit the display range such that the noise peaks are not included in the scanned frequency. Choose a range between 50-100Hz. The *Autoshim* experiment runs for 10-20 minutes. Upon completion, save the new shim values. The updated shim values will be automatically applied to all future experiments.
11. Repeat the *PulseAndCollect* experiment and compare the signal with the pre-shim results
12. Obtain the correct pulse duration for the 90^o pulse by running the *B1Duration* experiment. The output is a plot of NMR signal amplitude versus pulse length. Determine the optimal pulse duration for the 90^o excitation pulse from this plot.
13. Re-run the *PulseAndCollect* experiment with the new pulse duration and compare the results with previous signals.
14. Investigate the effect of ferric objects on the probe. How does this affect the NMR signal?

3.6 Additional post-lab questions

1. Why is a homogeneous magnetic field important for NMR experiments? How is the FID signal affected when the magnetic field is inhomogeneous?
2. Comment on the stability of the peak during the experiments. What are the possible reasons for this observation?
3. Based on the resulting NMR signals, what was the effect of the various signal optimization steps? Comment on changes in amplitude signal, resolution and signal to noise ratio.

Part 2: Spin Echo

1. Background theory on EFNMR instrumentation

An NMR signal originates from the atoms relaxing to equilibrium magnetization as they precess along the z direction. This precession induces an emf in the detection coil at the Larmor frequency and is characterized by an exponential decay. The decay is attributed to loss of coherence in the signals due to two mechanisms - spin coupling between neighboring atoms and inhomogeneities in constant magnetic field B_o.

In this experiment the effect of inhomogeneous magnetic field is examined. Recall from Pulse and Collect experiment, the precession frequency of the atoms is at the Larmor frequency, $\omega=\gamma B_o$, which is linearly dependent on the local magnetic field B_o. Non-uniformity in the constant magnetic field then results in different precessional frequencies that vary depending on the atoms location and local magnetic field. Thus spins become de-phased and the signal decays at a faster rate captured in the time constant, T_2*.

Spin echo is a technique aimed at compensating for signal de-phasing due to inhomogeneity in magnetic field. After a 90^o excitation pulse, the transverse magnetization precesses same as in the Pulse and Collect experiment. However, precession of the atoms fans out due to non-uniformities in magnetic field. A 180^o pulse applied at time τ_E (echo time) flips magnetization of all atoms along y-direction, effectively reversing the direction of precession. This will cause the faster precessing atoms to be behind those precessing more slowly. After another τ_E the nuclei will be re-phased as the faster precessing atoms catch up in phase and produce a coherent NMR signal. This pulse sequence is illustrated in Figure 1.

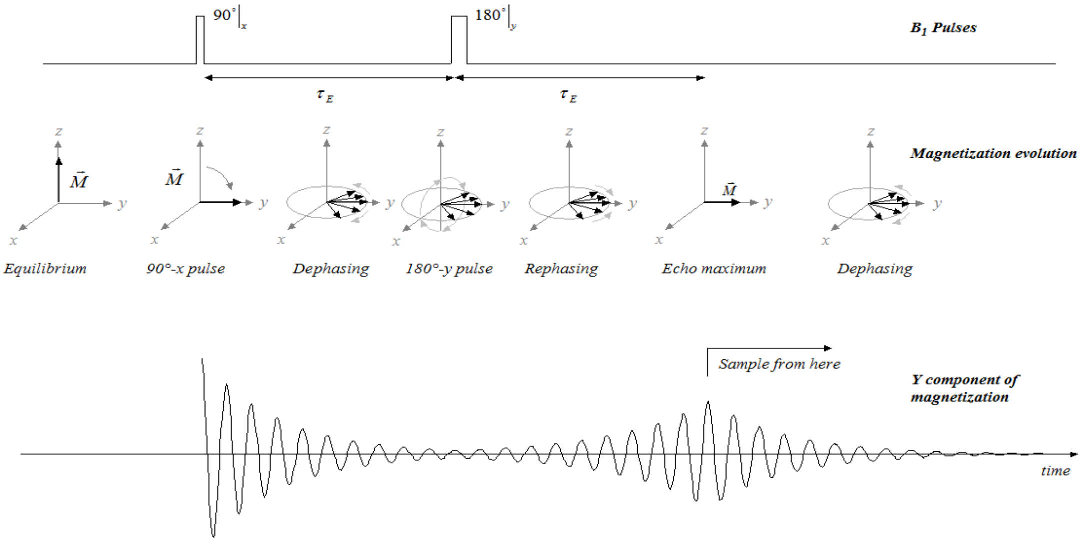


Figure 1: Pulse sequence diagram for a typical spin echo experiment

2. Pre-lab preparation

2.1 Suggested lab preparation

Watch Video 06: Spin echoes, CPMG and T_2 relaxation (10:10 min.)
http://www.youtube.com/watch?v=B2HMAJQJ7ok

2.2 Pre-lab questions

1. Do you expect any difference in signal obtained with spin echo versus that obtained with *PulseAndCollect*? If yes, what are the differences? If no, why not?
2. Which time constant can be measured using the spin echo? Explain how the constant can be measured.
3. In the last experiment, the *B1Duration* experiment ran a series of single pulse experiments at varying pulse lengths. The output is a plot of NMR signal amplitude versus pulse length which the experimenter was used to determine the optimal pulse duration for the 90^o pulse duration (Figure 2). The same plot can be used to determine the 180^o pulse. How would you determine the pulse duration for the 180^o pulse from the plot?

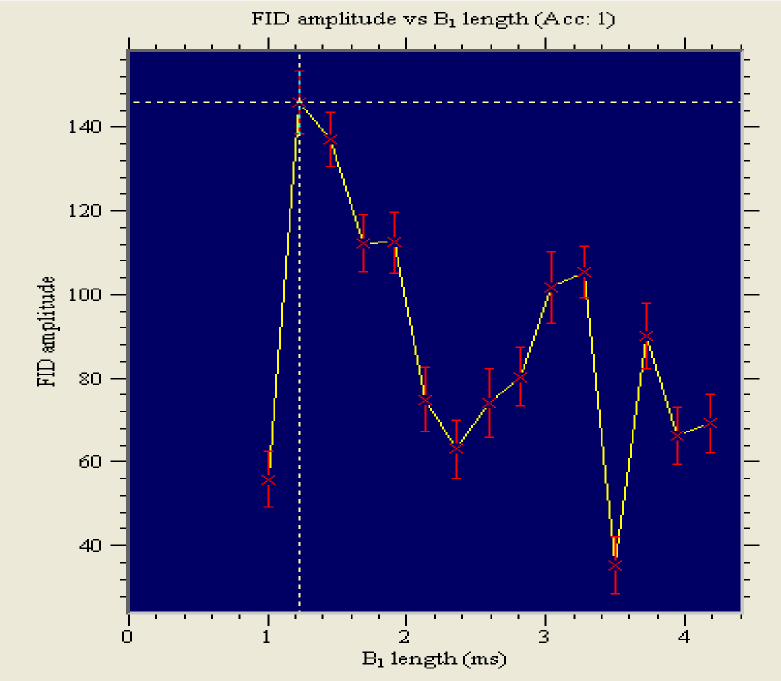


Figure 2: Plot of NMR signal amplitude versus pulse length (*B1Duration* experiment output)

3. Experiment protocol

3.1 Learning objectives

In this experiment, students will observe and explain the:

- Difference between results obtained from free induction decay (Pulse and Collect) and spin echo experiments
- Effect on critical parameters such as 90^{o} pulse and 180^{o} pulse durations and echo time on spine echoes
- Effect of inhomogeneity on spin echo and free induction signals

3.2 Evaluation

As expected in the Advanced Physics labs, students are expected to document as much of their observations and results in their lab notebooks as possible. Collecting screenshots of experiment results will also be useful. The approximate mark distribution is below.

1. Pre-lab questions (5%)
2. Results (40%)
3. Analysis and discussion (55%)

3.3 List of required materials and equipment

- As described in Part 1.

3.4 Safety considerations

- As described in Part 1.

3.5 Experiment steps

1. If starting this experiment in a new lab session, obtain an FID of the water sample and optimize the signal as described in the free induction decay experiment.

2. Obtain the correct pulse durations for the 90^{o} and 180^{o} pulses by running the *B1Duration* experiment.

3. Open the *SpinEcho* experiment dialogue and enter the pulse durations determined from the *B1Duration* experiment. Use an echo time of 100ms. Leave the other parameters unchanged.

4. Run the *SpinEcho* experiment and record the result for comparison with spin echo experiment you will run after shimming. Run the *PulseAndCollect* experiment as well and record the results. What are the differences between the signals obtained from these two pulse sequences?

5. Run the *AutoshimSE* experiment. This shimming program optimizes the shim values for spin echo experiments specifically. The experiment will automatically update the shim values upon completion (7-10 minutes). Record the new shim values.

6. Run the *SpinEcho* experiment. Record the result. How does the new signal compare with the signal obtained before shimming?

7. Run the *SpinEcho* experiment with echo times ranging from 50ms to 2000ms, recording the results of the integral under the peaks for each echo time (obtained from the experiment result summary in the command line interface window) and screenshots of the signals.

8. Investigate the effect of field inhomogneity on spin echo signals. Open the shim dialogue on the *SpinEcho* dialogue and change the shim values (e.g. by 10%) to make the field inhomogeneous – **do not save** these values. Record the new shim values. Run the *SpinEcho* experiment with echo times ranging from 50ms to 2000ms, recording the results of the integral under the peaks for each echo time and screenshots of the signals. How do the results compare to the results of the well-shimmed case?

9. Open the shim dialogue on the P*ulseAndCollect* experiment dialogue and enter the same shim values used to create inhomogeneity during the previous *SpinEcho* experiment. **Do not save** these values. Run the *PulseAndCollect* experiment and record the results for comparison with the well-shimmed case.

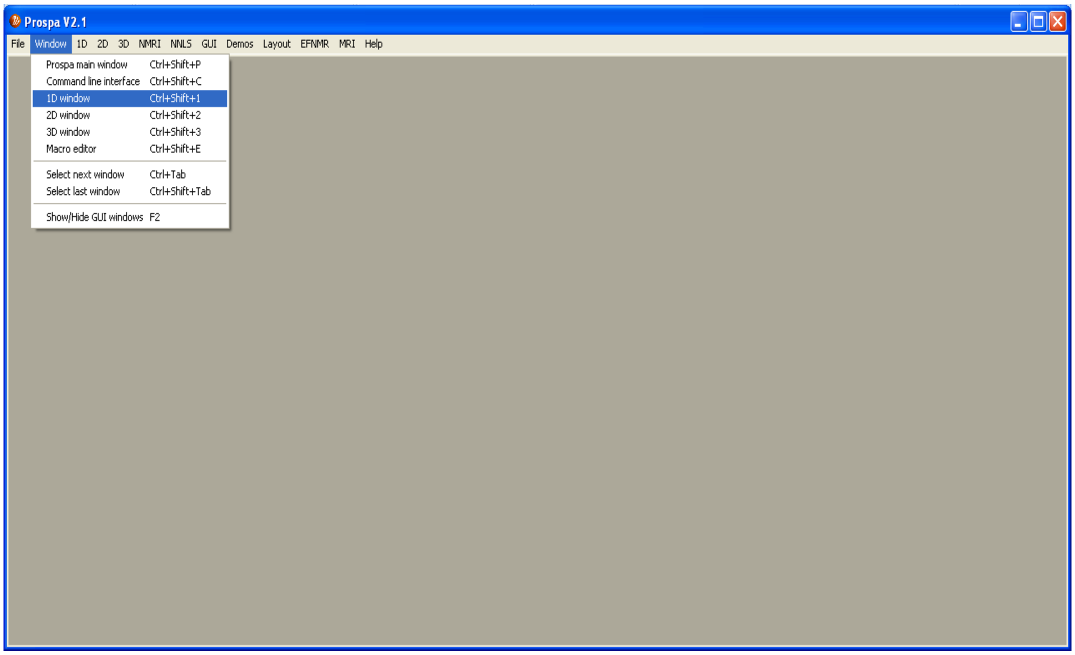
3.6 Additional post-lab questions

1. Plot the integral of the frequency peak versus echo times. Explain the relationship between these two values.

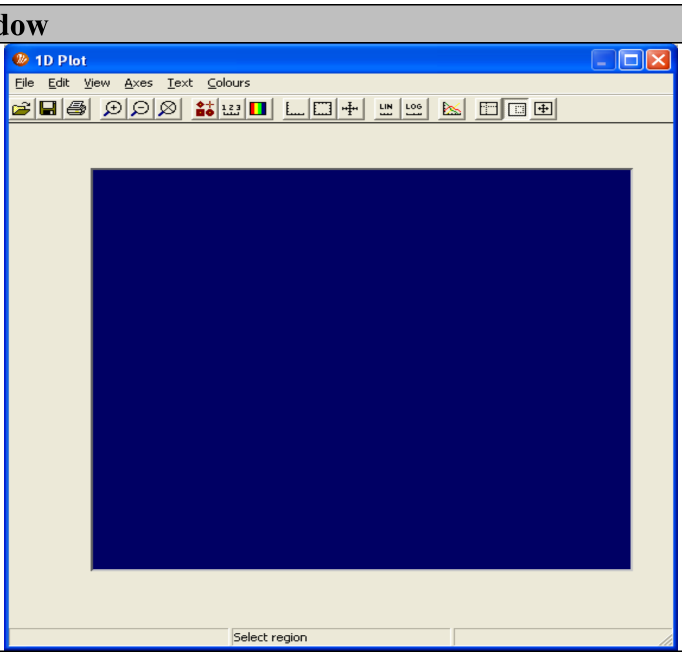
Appendix

A. Basic navigation in Prospa

Viewing the 1D Plot Window

Viewing the 1D Plot Window	
1.	Open the Prospa program from the Desktop.
2.	If the experiment window is not visible, open the *Window* menu and select “1D Window”. A blank 1D plot will appear. 

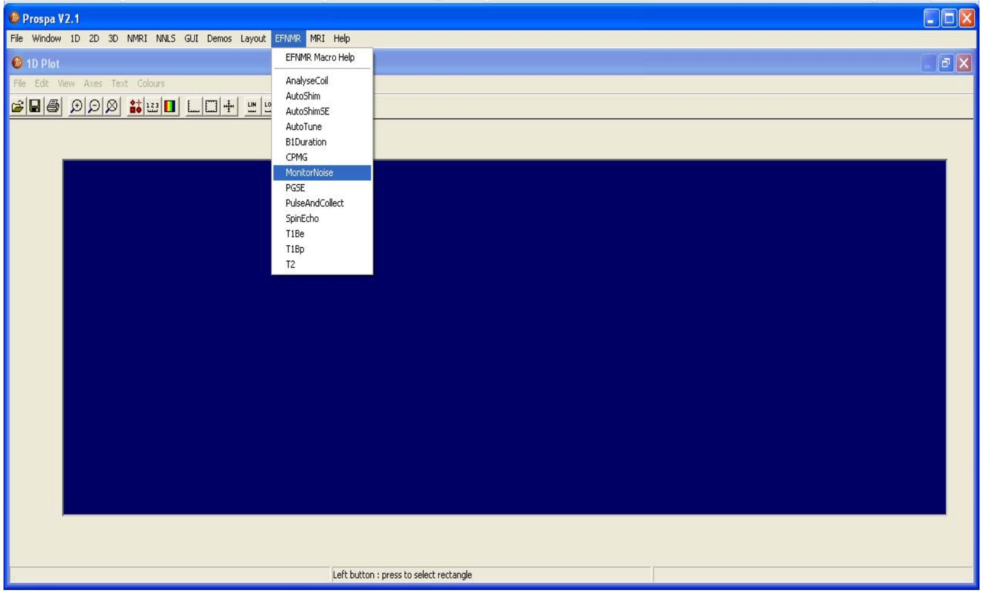
<table>
<tr><th colspan="2">Viewing the 1D Plot Window</th></tr>
<tr><td></td><td>



</td></tr>
</table>

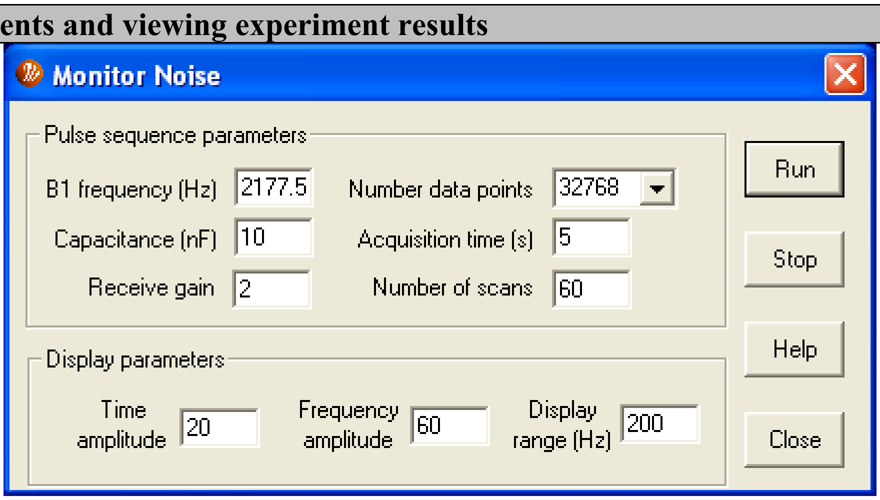
Running experiments and viewing experiment results

<table>
<tr><th colspan="2">Running experiments and viewing experiment results</th></tr>
<tr><td>1.</td><td>Open the *EFNMR* menu and select the experiment name.



</td></tr>
<tr><td>2.</td><td>After selecting an experiment, an experiment parameter screen will appear. Enter the parameters as instructed in the lab manual.</td></tr>
</table>

Running experiments and viewing experiment results



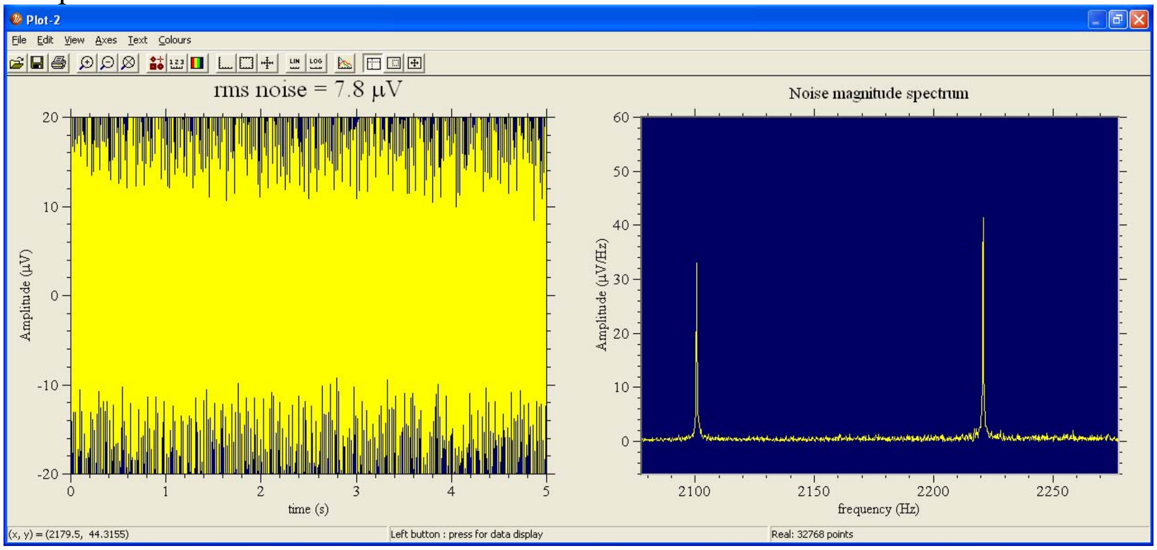
Pulse sequence parameters

B1 frequency (Hz) 2177.5
Number data points 32768
Capacitance (nF) 10
Acquisition time (s) 5
Receive gain 2
Number of scans 60

Display parameters

Time amplitude 20
Frequency amplitude 60
Display range (Hz) 200

3. Select “Run” to start the experiment. The experiment output will be displayed in the 1D Window as the experiment progresses. The experiment will automatically stop upon completion.



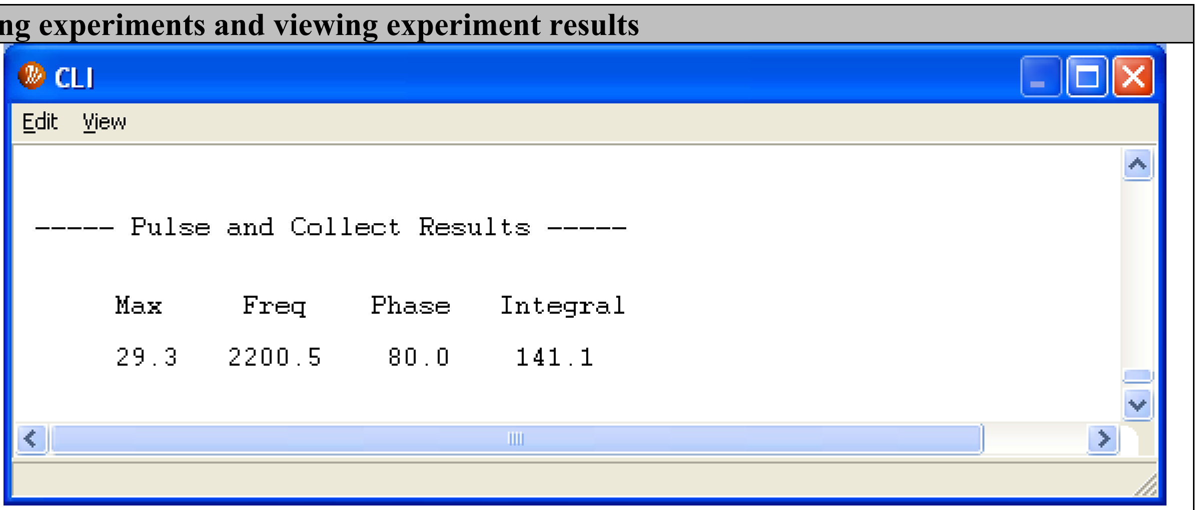
(x, y) = (2179.5, 44.3155)
Left button : press for data display
Real: 32768 points

Note: To stop an experiment before it is completed, select “Stop” in the experiment parameter screen. There will be a slight delay before the software halts the experiment. After this delay, the user can start a new experiment run or new experiment.

4. To obtain the coordinates of a point on the plot, select the “Display data value” button ▦. A cross hair cursor will appear in the 1D window. Click and drag the cursor until it snaps onto the point of interest. The coordinates will appear on the bottom left of the screen.

5. To view more detailed information on the experiment results, open the *Window* menu and select “Command Line Interface” or CLI. The command line interface screen will appear. The screenshot below is an example of the CLI after the *PulseAndCollect* experiment was executed.

Running experiments and viewing experiment results



```
----- Pulse and Collect Results -----


     Max      Freq     Phase    Integral

     29.3    2200.5     80.0     141.1
```

B. Suggested parameters for PulseAndCollect experiments

Parameters	Parameter description	Suggested initial values
B_1 frequency	Set to Larmor frequency of the sample. The Larmor frequency is dependent on the gyromagnetic ratio of the observed nucleus and the strength of the Earth's magnetic field.	1800Hz to 2500Hz
Pulse duration	Controls the tip angle of the excitation.	1.5ms
Acquisition time Number of data points	Determine the number of, and time between adjacently sampled points.	1s 16384 points
Acquisition delay	Time delay between the excitation of the sample and the detection of the signal	25ms
Average	A single scan can be used for the initial experiment. However, if difficulties arise in finding a strong signal it may be beneficial to employ many averages and thus improve the signal-to-noise ratio of the acquired FID and spectrum.	check
Display range	Controls the range of frequencies which will be displayed in the spectral window.	
Transmit B1 gain	Determines the amplitude of the B1 excitation pulse (volts). It dictates the tip angle of the excitation. If the transmit gain setting is decreased, the required length of the 90^o and 180^o pulse will increase.	2.5
Capacitance	Determines the resonant frequency of the B1 coil	10nF (4.4 -17.15nF)
Receive gain	Controls the degree of amplification of the received signal. If clipping occurs on the FID signal, reduce the receive gain.	2 (0-10)