BACHELOR

Designing RF-circuits

Thysen, J.

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Designing RF-circuits

Jo-Hendrik THYSEN (0839783)

Under the guidance of dr. ir. L. Pel

ir. P.A.J. Donkers

Research group: TPM

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1. Introduction

The NMR technique is a noninvasive technique which is used for medical applications, but also for building materials. Since the technique is nondestructive, samples don't have to be damaged. Another important characteristic is that it allows to gather information about both the nuclei themselves and the chemical environment of the nuclei. For each type of nucleus and/or specific environmental conditions, a special insert is necessary. This project has the goal to develop inserts for several types of nuclei. The different inserts allow the group TPM to expand the possibility of experiments. TPM focuses on a variety of experiments using the NMR technique. The study of the transport of chloride, sodium and lithium in porous materials, dehydration of salts and drying of paper are a few examples.

This report starts with a description of the principles of NMR: how it works, the cause of relaxation and the different pulse sequences. Next, the practical aspect of the inserts, like the components and design issues, will be treated. Furthermore, a series of measurements for every insert is exposed. Also the different parameters to obtain the measured data are tabulated in this section. The report ends with a discussion and conclusion in which some practical challenges are explained that appeared during the creation of the different inserts.
2. NMR

NMR stands for Nuclear Magnetic Resonance. It refers to the resonance phenomenon experienced by nuclei of certain atoms which occurs when they are immersed in a static magnetic field and exposed to a second oscillating magnetic field. This section clarifies the phenomenon and explains how to measure NMR signals.

2.1 Principle of NMR

An atom has a nucleus build up of protons and neutrons in accordance to the nuclear shell model [1,2]. Those particles possess a 1/2 spin summing up to a total spin of the nucleus. The spinning motion introduces a magnetic moment \( \mu \), represented by a magnetic moment vector, which can interact with an applied static magnetic field \( B_0 \); the magnetic moment will line up (more or less) with the external field because this is the state in which the interaction energy is lowest. In fact, because of a torque exerted on the magnetization vectors, a precession movement about the static field will occur at a certain frequency called the Larmor frequency [2,3,4]. Figure 1 depicts the spinning motion of a nucleus about the \( B_0 \)-field.

![Figure 1: The spinning nucleus introduces a magnetic moment \( \mu \). This magnetic moment precesses about the static magnetic \( B_0 \)-field at the Larmor frequency.](image)

Only nuclei with a spin are adequate for NMR experiments. Besides the parallel alignment, there are other specific orientations of the magnetic moment with respect to \( B_0 \), each representing a different energy state [5]. An atom can absorb energy, e.g. from a photon, to make a transition between such states. The frequency \( \nu \) of the absorbed photon is equal to the Larmor frequency. It can be calculated from the gyromagnetic ratio \( \gamma \) of the atom and the applied field \( B_0 \) according to:

\[
\nu = \gamma B_0. \tag{1}
\]

Some values for \( \gamma \) are given in table 1. Also the relative sensitivity of the nuclei is given in the table. The corresponding energy \( E \) is:

\[
E = h \nu. \tag{2}
\]
wherein Planck's constant is given by $h$ [1].

**Table 1:** Gyromagnetic ratio in units of MHz/T and the relative sensitivity for different nuclei. The relative sensitivity applies at constant field and for equal number of nuclei [6,7].

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Gyromagnetic ratio $\gamma$ (MHz/T)</th>
<th>Relative Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>42.58</td>
<td>1.00</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>3.076</td>
<td>$1.01 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$^{23}$Na</td>
<td>11.42</td>
<td>$9.25 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td>4.172</td>
<td>$4.70 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

In an NMR experiment it is the second oscillating magnetic field $B_1$ which is used to emit energy to the sample of interest. The bunch of atoms in a sample can absorb this energy and the different atoms make transitions. This results in a change in direction of their magnetic moment with respect to $B_0$. From a macroscopic point of view, all these magnetic moment vectors of the atoms add up to a net magnetization $M$. So, the application of $B_1$ induce a change in direction of $M$. Without an external $B_1$-field, the net magnetization vector lies along $B_0$ and is called the equilibrium magnetization $M_0$. $M_0$ and $B_0$ are pointing in the $z$-direction by convention. This alignment can be understood from a more detailed microscopic point of view. The precession movement of the magnetization vectors of the individual atoms is random in alignment with the external static field. Adding up all those vectors cancels the $xy$-components and keeps a net $z$-component along the field, resulting in a net magnetization $M_0$ in the same direction as $B_0$ [8]. The $z$-component of $M$ is called the longitudinal component $M_z$, the $xy$-component is called the transverse magnetization component $M_{xy}$.

The $B_1$-pulse is generated by a coil which is placed around the $x$-axis. When an alternating current passes through the coil for a certain time at the Larmor frequency, it creates an oscillating magnetic field pulse along its axis which will cause the net equilibrium magnetization $M_0$ to spiral down about the $z$-axis at the same Larmor frequency. Because this frequency is typically within the radiofrequency (RF) range, one talks sometimes about an RF-coil which creates an RF-pulse. The length of time $\tau$ (pulse time) that the pulsed field $B_1$ is on, determines the rotation angle $\theta$ of $M_0$ about the $x$-axis [1]:

$$\theta = 2\pi \gamma \tau B_1. \quad (3)$$

After the pulse, the magnetization vector keeps precessing about the $z$-axis, spiraling up to recover its equilibrium position in alignment with the $z$-axis. The precessing motion introduces a changing magnetic flux $\varphi$ in the RF-coil which induces an alternating voltage $V$ across it, according to Faraday's law [4,9,10]:

$$V = -N \frac{d\varphi}{dt}. \quad (4)$$

The number of windings of the RF-coil is given by $N$. 

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In this way, the voltage creates an alternating current in the solenoid. Plotting the current as a function of time provides the time signal in pulsed NMR measurements. It is important to notice that only the transverse component of the net magnetization contributes to the changing flux because the longitudinal component is always perpendicular to the direction of the coil. So only the transverse component can be measured. From this picture, it is easy to see that the largest signal can be obtained if \( M \) precesses in the \( xy \)-plane. This is the reason why 90° pulses are used. During the relaxation process, the transverse component starts to decay with time constant \( T_2^{*} \) \([1,2]\), resulting in a smaller changing flux through the solenoid and leading to less signal. The signal is called a free induction decay or FID and is depicted in figure 2.

![Figure 2: The measured time signal (FID) as a consequence of the precessing motion of the transverse magnetization component. The decay is described by the \( T_2^{*} \) time constant.](image)

Notice the decaying amplitude as a consequence of \( T_2^{*} \) in this picture. The FID is a decaying sine wave characterized by the frequency of the precessing nuclei. By performing a Fourier transform, one is able to create an NMR frequency spectrum, showing the frequencies the time signal contains.

### 2.2 Relaxation

The recovery of the equilibrium magnetization is called relaxation. One considers two relaxation times. The first is the spin-lattice relaxation time or \( T_1 \). It is described as the time constant that indicates how the longitudinal component \( M_z \) returns to its equilibrium value according to:

\[
M_z = M_0 \left( 1 - \exp \left( -\frac{t}{T_1} \right) \right),
\]

wherein \( t \) represents the time after the 90° pulse \([1,11]\).

\( T_1 \) relaxation is a consequence of energy exchanges between excited nuclei and the lattice. The transfer of energy results from the interaction between an excited nucleus and the
oscillating lattice field created by the surrounding magnetic nuclei. As a result of the interaction, the atomic nuclei line up with the static field and \( M_z \) equals \( M_0 \) again. For interaction to occur, the nearby lattice field must fluctuate at the Larmor frequency of the excited nucleus \([2,11]\). Since the Larmor frequency is proportional to \( B_1 \), \( T_1 \) will therefore vary as a function of magnetic field strength \([1]\). In a sample of atoms there is a distribution of field frequencies because of molecular motion. The better these frequencies encloses the Larmor frequency, the higher the efficiency of energy transfer and the shorter the spin-lattice relaxation time. Because of the dependence on molecular motion, the frequency distribution is influenced by the size of the molecules and the physical state of the sample. To give an example, \( T_1 \) values of solids are rather high because the vibrational frequencies present in a solid lattice are typically far higher than normal Larmor frequencies \([2]\). Other characteristics that determine the spin-spin relaxation time are viscosity and temperature. \( T_1 \) relaxation can be measured with the saturated recovery pulse sequence and will be explained in section 2.5.3.

The second relaxation time is the spin-spin relaxation time or \( T_2 \). To explain this, consider that one emits a pulse causing \( M \) to deviate from its equilibrium position. After the applied pulse \( M \) starts to precess about the \( B_0 \)-field at the Larmor frequency. Because of some inevitable fixed inhomogeneities in the \( B_0 \)-field, the rotating motion causes the net magnetization to dephase; the different spins in a sample experience a slightly different \( B_0 \)-field and thus rotates at their own Larmor frequency according to formula (1). The longer the elapsed time, the greater the phase difference. At the end, all nuclei precess at random and complete decay of the transverse component has occurred. The exponential decay of \( M_{xy} \) as function of the parameter \( T_2 \) is given by \([1,12]\):

\[
M_{xy} = M_{xy0} \cdot \exp\left( -\frac{t}{T_2} \right).
\]  

(6)

\( M_{xy0} \) is the initial transverse component, the variable \( t \) represents the time after the 90° pulse.

\( T_2 \) is not only a result of the fixed inhomogeneities of \( B_0 \). Interactions between spins have a contribution as well. There are two kinds of spin-spin interactions. The first, spin-spin coupling or J-coupling, create random local magnetic field variations which, in turn, cause fluctuations in the precessional frequency of the individual nuclei. The ability of a sample to maintain the local field variations determines \( T_2 \). Molecular size and physical state play an important role. For example, solids and large molecules are characterized by relatively short \( T_2 \) values since the fixed molecular structure is effective in maintaining the magnetic field fluctuations. In contrast, small molecules in liquids can move through the sample tending the local magnetic field variations to average, resulting in rather long \( T_2 \) relaxation times \([2]\). The other spin-spin interaction is called spin exchange. Two spins can exchange energy, changing their spin orientation with respect to \( B_0 \). \( T_2 \) will be affected because phase coherence of the transverse magnetization is lost during exchange. The exponential decay of \( M_{xy} \) caused by all these contributions is characterized by the effective transverse relaxation time or \( T_{2*} \), as summarized in formula (7) \([1]\):

\[
M_{xy} = M_{xy0} \cdot \exp\left( -\frac{t}{T_{2*}} \right).
\]  

(7)
\[
\frac{1}{T_2^*} = \frac{1}{T_{2\text{, inhomogeneous}}} + \frac{1}{T_{2\text{, J-coupling}}} + \frac{1}{T_{2\text{, spin exchange}}}.
\]

The \( T_2 \) relaxation that results from spin-spin interactions can be measured with the CPMG recovery pulse sequence and will be explained in section 2.5.2.

In a sample of atoms both processes, \( T_1 \) and \( T_2 \) relaxation, occurs at the same time. The transverse component spirals down to zero and the longitudinal magnetization grows until \( M_z \) equals \( M_0 \). Remember that \( T_2 \) is less than or equal to \( T_1 \).

## 2.3 Pulse sequences

There are many kinds of pulse sequences to obtain an NMR time signal. A pulse sequence is a series of RF-pulses applied to the sample. Each sequence has its own characteristics from which some features of the sample can be deduced. In this section the four pulse sequences that are relevant for the rest of this report are described.

### 2.3.1 Hahn spin echo

The Hahn spin echo is build up of a 90° pulse, followed by a 180° pulse. The first pulse rotates \( M_{xy} \) down into the \( xy \)-plane where it starts to dephase. After a while the second pulse is applied and the magnetization rotates by 180° about the \( x \)-axis. The spins that where first leading in the dephasing magnetization are now falling behind. As a consequence, these faster spins will catch up the slower spins, resulting in a rephasing of \( M_{xy} \). This produces a signal called an echo. Figure 3 illustrates the timing diagram [1,13].

![Figure 3: Timing diagram of the Hahn spin echo. A 90° pulse is followed by a 180° pulse producing an echo at the echo time.](image)

The rephasing behavior is indicated by the rising amplitude of the echo. It is a result of \( T_2^* \). The maximum corresponds with the moment that all spins are rotating in phase. This means that a 180° pulse is able to remove the effect of the fixed inhomogeneities in the field [2,14]. The subsequent decay of amplitude is also a result of \( T_2^* \) relaxation.
A pulse sequence can be repeated several times in a row (number of averages) to obtain a better signal-to-noise ratio (SNR). This is because noise signal is random in time. Adding up the different measurements cancels the noise, and amplifies the signal. The SNR is proportional to the number of averages $N$ according to [1]:

$$\text{SNR} \propto \sqrt{N}.$$ 

(8)

Notice that one average implies two measurements to get rid of the offset signal of the amplifier which is built in to amplify the weak NMR signals. The different averages are separated by the repetition time. Its chosen to be greater than four times $T_1$ so $M_z$ can recover completely before performing the next measurement.

By executing several Hahn spin echo sequences after each other with an increasing echo time and under a fixed gradient, it is possible to measure the diffusion coefficient. The echo time is described as the time from the beginning of the $90^\circ$ pulse till the center of the echo. The longer the echo time, the smaller the maximum amplitude of the measured echoes. This is due to relaxation, but also to diffusion. The main idea is that the Brownian motion makes it possible for spins to end up with a different rotational frequency after the $180^\circ$ pulse than before, cancelling out each other and so, reducing the signal. By applying a gradient field $G$, the effect of diffusion becomes more noticeable since it creates an extra contribution to the fixed inhomogeneities in the $B_0$-field. The relation between the diffusion coefficient $D$ and the decaying signal amplitude $S$ is given by [13]:

$$S \propto M_0 \exp\left( -\frac{\gamma^2 G^2 D \tau^3}{12} \right) \exp\left( -\frac{\tau}{T_2} \right).$$ 

(9)

$\tau$ is the varying echo time, $\gamma$ the gyromagnetic ratio and $M_0$ the net magnetization. To see how much the signal decay depends on diffusion, different measurements with varying gradient fields are executed.

2.3.2 CPMG

The Carr-Purcell-Meiboom-Gill (CPMG) sequence consists of a $90^\circ$ pulse, followed by a series of $180^\circ$ pulses. The different pulses are represented in the timing diagram of figure 4 [13].
Figure 4: Timing diagram of the CPMG. A 90° pulse is followed by a series of 180° pulses. Every 180° pulse creates an echo signal.

A CPMG measures the $T_2$ relaxation time. Every 180° pulse is followed by an echo. The signal amplitude decays because of $T_2$ relaxation and diffusion. To minimize the effect of diffusion, the echo time is kept small. Plotting the signal amplitude $S$ as a function of the different echo times $TE$, results in a plot according to formula (10) [1]:

$$S = S_0 \left( 1 - \exp \left( - \frac{TR}{T_1} \right) \right) \cdot \exp \left( - \frac{TE}{T_2} \right) \quad (10)$$

$S_0$ is the signal amplitude when the equilibrium magnetization is rotated into the $xy$-plane. The repetition time $TR$ is chosen to be greater than or equal to four times $T_1$, to obtain a small contribution of the second term between brackets.

2.3.3 Saturation recovery

The saturation recovery sequence can be used to measure the $T_1$ relaxation time of a sample. The sequence starts with emitting some random pulses to disturb the equilibrium net magnetization, followed by a spin echo. The timing diagram for one sequence is illustrated in figure 5.

Figure 5: Timing diagram of the saturated recovery sequence. It starts with some random pulses, followed by a spin echo. This sequence is repeated several times with an increasing long delay time.

This sequence is repeated several times, while the recovery time is gradually increased. The random pulses make it possible to start every measurement with the same initial magnetization. Every 90°-180° pulse combination results in an echo. The subsequent echoes rise in maximum signal amplitude. This can be explained since a longer repetition time permits a better $T_1$ recovery of the signal. The 90° pulse of the next measurement will always rotate a net magnetization vector into the $xy$-plane with a greater magnitude than the previous one. The signal intensity can be plot as a function of repetition time. The plot should correspond to [1]:

\[ \text{Signal Intensity} = \text{Function of Repetition Time} \]
\[ S = S_0 \left(1 - \exp\left(-\frac{TR}{T_1}\right)\right). \]

### 2.3.4 Spectroscopy

A 90-FID sequence is applied for spectroscopy purposes. It emits a 90° RF-pulse to the sample. The recorded signal is a FID. Figure 6 depicts the timing diagram of the free induction decay [13].

![Figure 6: Timing diagram of the free induction decay. By application of a 90° pulse, one can record an FID signal because of the recovery phenomenon of the spins.](image)

Spectroscopy is possible if the \( B_1 \)-field is homogeneous. The resolution increases by a large window width and a high sample frequency. The spectroscopy spectrum is the Fourier spectrum of the FID. Characteristics of the nuclei can be extracted from it. For example, the number of peaks in the spectrum depends on the chemical environment of the nuclei. Also magnetic properties can be measured. The higher the frequency resolution, the more detailed the spectrum is.

To explain the spectroscopy spectrum, it is necessary to understand the term 'chemical shift'. An atom is surrounded by electrons which form a shield for the nucleus. This affects the \( B_0 \)-field experienced by the nucleus. In a molecule, the shielding depends on the electron density around each nucleus. As a consequence, two atoms of the same type in the molecule can feel a different strength of \( B_0 \) and thus resonate at other frequencies. This is the chemical shift phenomenon. In NMR it is convenient to express the resonance frequencies with respect to a reference frequency. This quantity is named chemical shift \( \delta \) and is reported in parts per million (ppm), according to formula 12 [1]:

\[ \delta = \left(\frac{v_{\text{resonance}} - v_{\text{reference}}}{v_{\text{reference}}}\right) \times 10^6. \]
The chemical shift is a very precise metric of the chemical environment around a nucleus. It provides also a convenient description for comparing NMR spectra which are measured with different field strengths.

The different peaks in the spectroscopy spectrum are caused by spin-spin coupling. If the distance between two nuclei with a different chemical shift is less than or equal to three bond lengths, this magnetic interaction can occur [1]. It is easiest to explain this with an example. Consider two different spin 1/2 nuclei A and B. Without spin-spin coupling, they each precess with their own Larmor frequency resulting in two peaks in the frequency spectrum. If the nuclei meet the above condition of spin-spin coupling, four energy configurations are possible, based on the different spin combinations of A and B with respect to $B_0$. Only transitions between energy states where one of the two spins changes direction are allowed [1]. This makes that there are two absorption frequencies for both A and B, resulting in 4 absorption lines in the NMR frequency spectrum. The A absorption lines are centered on $\delta_A$, the B absorption lines on $\delta_B$. It means that spin-spin coupling results in a splitting of the absorption lines associated with electron shielding, creating doublet states centered on the chemical shifts. Other advanced structures like a coupling between three spin 1/2 nuclei result in triplet state structures. The distance between two absorption lines of a nucleus is called the J-coupling constant and is a measure of the magnetic interaction between two nuclei. The height of the peak gives information about the number of transitions that are possible and how many nuclei of a certain type there are interacting [1].
3. LC circuit

This section describes the different components of an RF-circuit and how it is build up. The theory behind the circuit and a description of the corresponding features are also worked out. A more detailed overview of the calculation is given in Appendix A.

3.1 Setup

An LC circuit is build up of an inductor and a capacitor. The former is a $N$-winding solenoid coil, made of copper wire. The inductance $L$ and the capacitor $C_1$ are connected in series, like illustrated in the boxed area of figure 7 [15].

![Figure 7: L, C₁ and C₂ form the RF-circuit. The series LC circuit is build up of an N-winding solenoid and C₁, like in the boxed area. R represents the total resistance in this circuit. C₂ is connected in parallel with the LC setup.](image)

The resistance $R$ in this figure is added for completeness because every circuit suffers from losses. The LC circuit is connected in parallel with another capacitor $C_2$. This second capacitor is needed to match the impedance of the spectrometer to the one of the LC circuit. That's why it is sometimes called the coupling capacitor. In most of the setups which will be discussed in section 4, the spectrometer is connected to point A and point B is grounded. All connections are made with copper wire. The whole setup is build in a small box of copper with a semi rigid coax connection for the spectrometer.

3.2 Characteristics

3.2.1 Resonance frequency

Suppose that one connect an AC source with frequency $\omega$ across the terminals A and B of the circuit as depicted in figure 4. The impedance $Z$ of the setup determines the amplitude of the current $I$ that appears in the circuit. $Z$ can be calculated from the impedances of the resistance $R$, the inductor $L$ and both capacitors $C_1$ and $C_2$. These are respectively $R$, $jL\omega$ and $1/jC\omega$ with $C$ equal to $C_1$ or $C_2$ [15,16]. The calculation is worked out in appendix A1, resulting in formula (13) [15]:
This means that for a certain value of \( \omega \), \( Z \) is minimum resulting in a maximum current amplitude. This specific value of frequency is called the resonance angular frequency of the circuit, denoted as \( \omega_0 \) \[17\]. Demanding that the imaginary part equals zero causes \( Z \) to be minimum. Calculating this as it is done in the rest of appendix A1, the following formula (14) arises:

\[
\left(L^2 C_1^2 C_2 \omega_0^4 + \left(R^2 C_2 C_1^2 + L C_1^2 - 2 C_2 L C_1\right)\omega_0^2 + \left(C_1 + C_2\right)\right) = 0.
\]  

From this condition, it is possible to calculate \( \omega_0 \). The circuit is always tuned at the Larmor frequency of the nuclei of interest. In this way, the measured alternating current in the RF-coil, induced by the rotating motion of the net magnetization during relaxation, will be maximum. For this project, one uses a 4.7 tesla super-cooled magnet. From formula (1) and the gyromagnetic ratios given in table 1, the Larmor frequencies can be determined.

To create a circuit that resonates at the Larmor frequency, the corresponding capacitances of \( C_1 \) and \( C_2 \) must be chosen carefully. The capacitor \( C_1 \) is called the tuning capacitor and its value determines \( \omega_0 \). In most setups, it is a variable capacitor which makes it more easy to trim the circuit afterwards. \( C_2 \) is also a variable capacitor, except in the cases of low resonance frequencies. To have an indication of which values are needed for \( C_1 \) and \( C_2 \), formula (14) can be used. \( C_1 \) is chosen and \( C_2 \) is determined. The resistance \( R \) is estimated by the length of the solenoid, the thickness of the wire and the resistivity of copper, as illustrated in appendix A2. Other sources of resistance like connecting wires, conducting samples and electrical influences from outside the circuit [15] are not taken into account. Another influencing factor for the frequency is the inductance \( L \). For a single layer round solenoid coil with \( N \) turns, a radius \( r \) (in cm) and a length \( x \) when winded (in cm), the inductance (\( \mu \)H) is represented by formula (15) [18]:

\[
L = \frac{0.4 N^2 r^2}{9 r + 10 x}
\]  

A low inductance is required for measuring high Larmor frequencies. For a given sample tube, this means that the RF-coil counts a small number of windings. Since the solenoid doesn't has an infinite length, the magnetic field distribution tends towards an heterogeneous distribution [15] which means that \( B_1 \) is nonuniform, with the intensities decreasing as the distance from the center of the coil increases. A homogeneous field is required to obtain a low distribution of rotation angles of the spins since the rotation angle depends on \( B_1 \). A homogeneous field leads to a high signal.
3.2.2 Reflected power
Before the net magnetization starts to induce a current in the RF-coil, it has to disturbed from its equilibrium position by application of an RF-pulse. The pulse is emitted with a certain amount of power, called the forward power. Of course, one hopes that all power emitted will reach the sample. In practice, this is not the case since the RF-setup is characterized by an amount of reflected power. The reflected power is defined as the amount of forward power, not accepted by the solenoid [1]. To measure this fraction, a network analyzer can be used. It shows a visual representation of the reflected power as a function of frequency, like in figure 8.

![Diagram of reflected power as a function of frequency](image)

Figure 8: Reflected power as a function of frequency. $\omega_0$ is the resonance frequency of the RF-setup and $\Delta\omega$ is the full width at half maximum. Their ratio equals the Q factor.

The spectrum belongs to the hydrogen-sodium double coil setup (section 4.2.3) to measure hydrogen. It has a dip centered at the resonance frequency. It is an important feature that the resonance frequency of the RF-system is characterized by the minimum in reflected power. This means that almost all forward power is used to excite the nuclei of interest. The dip can be minimized further by adjusting the matching capacitor. A perfect matching of the impedances of both the resonance circuit and the spectrometer results in the ideal case of zero reflected power [18]. As an illustrative analogy, think of the solenoid as balancing between a glass mode and a mirror mode for the forward power. The former mode is the preferred one.

3.2.3 Q factor
The Q factor or quality factor is an important characteristic of the electric circuit. Two interpretations need to be distinguished; both play a role in the pulsing process of the NMR experiment. The first characterizes the reflected power. It says that $Q$ equals $\omega_0/\Delta\omega_0$ [15,18] with $\Delta\omega_0$ the full width at half maximum of the dip illustrated in figure 8. It is best to make a circuit where $\Delta\omega_0$ is as small as possible. In this way, the forward power is better concentrated at one frequency which means that the risk of losing energy to other frequencies is reduced. As a consequence, less power is needed to create e.g. a 90° pulse. Sometimes, this
interpretation is given as $2\pi$ times the energy stored in the solenoid divided by the energy dissipated per cycle [15].

The first interpretation holds when the RF-coil is able to accept all delivered power. In fact, it takes an amount of time to achieve this situation. The forward power can't be fully accepted immediately after application to the sample. Interpretation two states that the time it takes to accept the maximum delivered power is determined by $Q$. In this interpretation, $Q$ equals the number of rotations needed to accept the maximum power. To be more specific, an RF-pulse cause the net magnetization to spiral down at the Larmor frequency. During the time before the maximum power can be absorbed, the magnetization has rotated a number of times. This number equals $Q$. For a given frequency, when $Q$ is low, less time is needed to deliver the maximum power and the pulse time for a 90° pulse can be shortened.

Both interpretations of $Q$ are contradictory. The first requires $Q$ to be high while the second prefers $Q$ to be low. The value of $Q$ is an instinctively based choice. For a weak power source it is better to enlarge $Q$. In case of a low resonance frequency one tries to keep $Q$ low.

From the second version of the first interpretation it follows that energy losses causes $Q$ to change. At high frequencies, the circuit can behave like an antenna, resulting in a decrease of $Q$. The copper box where the whole construction is build in, works as a shield against these distortions from outside. Other sources of losses like long connecting wires inducing stray inductance and resistances like the ones specified in section 3.2.1 are also better reduced [15,18]. In cases where a lowering of $Q$ is needed, an additional resistance could be placed in series with the inductor.
4. Measurements with practical designs

Different RF-circuits where made. Hydrogen, chloride, nitrogen and sodium can be measured using several practical designs. Two different types of RF-coils are available: single coils and double coils. Both types have setups with capillary tubes (with an inner diameter of 1mm) and larger sample tubes (with an inner diameter of 6.6mm). Images of the different coils can be viewed in appendix B. The values of the setup components of each RF-circuit are noted in this section. Furthermore, the results of the noise measurements, the relaxation measurements and some diffusion calculations are also exposed for every design. A noise signal is measured several times for different values of the number of averages. For this, a Hahn spin echo is used. The $T_1$ relaxation measurement is executed using the saturation recovery pulse sequence. For the $T_2$ relaxation measurement, a CPMG has been applied. The data for the diffusion calculation has been obtained from a Hahn spin echo.

4.1 Single coils

Figure 9 is a sketched representation of a single coil design. The length of the coil when wound $x$, the number of windings $N$ and the radius $r$ are indicated. Four setups are available: three for measuring hydrogen and one for chloride.

4.1.1 Hydrogen

4.1.1.1 Setup characteristics

The single hydrogen RF-circuit is designed for sample tubes with a diameter of 0.68cm. A copper wire of thickness 1mm surrounds the tube with 5 windings. The length $x$, as illustrated in figure 9, equals 3cm. The $C_1$ capacitor like in figure 7, is a tuning capacitor with a range from 5 to 30pF. $C_2$ is also a tuning capacitor with a value from 1 to 30pF. An additional capacitor of 2.2pF is connected in parallel with it. The circuit is characterized by a Q factor of 66 and an amplitude of -30dB for the reflected power at the resonance frequency.

4.1.1.2 Measurements

The first measurement is a noise measurement. The noise signal is measured by applying several Hahn spin echoes without pulse for different averages. Afterwards, another Hahn spin echo with pulse is executed to obtain a useful NMR signal. Both signals are log-log plotted as a function of the number of averages, represented by figure 10. The noise is fitted with a straight line. Its slope can be compared with formula 8: by taking the logarithm of both sides of the formula, and rearranging in such a way that one obtains an expression for the logarithm of the noise signal as a function of the logarithm of the number of averages, a proportionality
constant of $-1/2$ can be found. This means that the slope of the fitted curve should correspond to $-1/2$. For this hydrogen coil, the slope equals $-0.52$. The point from where the noise starts to stagnate gives an indication about the maximum number of averages that are useful to measure a NMR signal. The number of averages equals 512. Both results are noted in table 2.

Figure 10: Signal and noise measurement of the single hydrogen coil. Both are log-log-plotted as a function of the number of averages.

A T1 measurement is represented in figure 11. It depicts a plot of the signal as a function of the recovery time. By performing an exponential fit, the $T_1$ value is determined and equals ... .

Figure 11: $T_1$ relaxation measurement of hydrogen with the single hydrogen coil. The signal is plotted as a function of the recovery time. The measured sample is $H_2O$. 
To obtain the $T_2$ relaxation time, the decaying signal amplitude as a function of the rising echo time is plotted like in figure 12. The exponential fit gives a $T_2$ value of ... . Both $T_1$ and $T_2$ measurements are obtained from a H$_2$O sample. The tube was completely filled what corresponds with a volume of approximately 10ml H$_2$O.

Figure 12: $T_2$ relaxation measurement of hydrogen with the single hydrogen coil. The signal is log-plotted as a function of the echo time. The measured sample is H$_2$O.

Also a diffusion measurement has been applied. The natural logarithm of the signal intensity is plotted in figure 13 as a function of echo time. Based on formula (9), the diffusion coefficient can be calculated from these data, as showed in appendix C. The result is a value of ....

Figure 13: Diffusion measurement of water, measured with the single hydrogen coil. The natural logarithm of the signal intensity is plotted as a function of the echo time. By fitting the data points with a polynomial fit, the diffusion coefficient can be calculated.
The results of the relaxation and diffusion measurements are summarized in table 2. Also the parameters where the measurements are applied with are given. These are the frequency of the transmitted power \( xmit \), the value of \( xmit \), the pulse time \( p90 \), the window width \( ww \), the echo time and the gradient. More specific information for each measurement is noticed as well.

**Table 2:** Different parameters are summarized for the hydrogen single coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, \( T_1 \), \( T_2 \) and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: H(_2)O</th>
<th>Single H (capillary): H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>NO DATA</td>
</tr>
<tr>
<td>( xmit ) (dB)</td>
<td></td>
</tr>
<tr>
<td>( p90 ) (( \mu )s)</td>
<td></td>
</tr>
<tr>
<td>( \text{gradx} ) (T/m)</td>
<td></td>
</tr>
<tr>
<td>( ww ) (( \mu )s)</td>
<td></td>
</tr>
<tr>
<td>( \text{TE} ) (( \mu )s)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>( T_1 )</th>
<th>( T_2 )</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW (kHz)</td>
<td>1000</td>
<td>( \text{Ld}_{\text{begin}} ) (( \mu )s)</td>
<td># Echoes</td>
</tr>
<tr>
<td># Averages</td>
<td>512</td>
<td>( \text{Ld}_{\text{end}} ) (( \mu )s)</td>
<td># Echoes</td>
</tr>
<tr>
<td>RF gain</td>
<td>30</td>
<td>Steps</td>
<td>Steps</td>
</tr>
<tr>
<td>Slope = -0.53</td>
<td>( T_1 = )</td>
<td>( T_2 = )</td>
<td>D =</td>
</tr>
</tbody>
</table>

### 4.1.2 Hydrogen capillary tube

**4.1.2.1 Setup characteristics**

The length of this single hydrogen coil when wound is 0.5cm. The used copper wire has a thickness of 1/4mm and it is wound around a capillary tube of 1.6mm with 15 turns. Both \( C_1 \) and \( C_2 \) are tuning capacitors with a range from 1 to 30pF. The value of the matching capacitor is raised by placing two additional capacitors with it in parallel; one has a value of 2.2pF, the other is a 82pF capacitor. The Q factor of this RF-circuit equals 53. The amplitude of the reflected power at the Larmor frequency is - 30dB.

**4.1.2.2 Measurements**

This RF-circuit allows 512 maximum useful averages, as can be seen in figure 14. The fitted curve of the noise signal has a slope of -0.52.
Figure 14: Signal and noise measurement of the single hydrogen coil with capillary tube. Both are log-log-plotted as a function of the number of averages.

The relaxation measurements are applied using a H$_2$O sample. Based on the measurements, the $T_1$ relaxation time equals 3422 ms. For $T_2$, it seems there are two $T_2$ relaxation times: one of 76 ms, another of 20 ms. Both measurements are depicted in figure 15 and 16 respectively.

Figure 15: $T_1$ relaxation measurement of hydrogen with the single hydrogen coil with capillary tube. The signal is plotted as a function of the recovery time. The measured sample is H$_2$O.
Figure 16: $T_2$ relaxation measurement of hydrogen with the single hydrogen coil with capillary tube. The signal is log-plotted as a function of the echo time. The measured sample is H$_2$O. There are two $T_2$ times present as indicated by (1) and (2) in the picture.

The diffusion calculation (according to appendix C) resulted in a diffusion coefficient with value $4.6 \times 10^{-10} \text{m}^2/\text{s}$. The measurement is imaged in figure 17.

Figure 17: Diffusion measurement of water with the hydrogen coil (capillary tube). The natural logarithm of the signal intensity is plotted as a function of the echo time.

Table 3 summarizes the obtained results and the used parameters during the measurements.
Table 3: Different parameters are summarized for the hydrogen single coil (capillary tube). The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: H$_2$O</th>
<th>Single H (capillary): H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>199.873</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>16</td>
</tr>
<tr>
<td>$p90$ (μs)</td>
<td>5</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.068</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>800 (ww equals 1000 for the noise measurement)</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>1000 (TE equals 800 for the noise measurement)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>SW (kHz)</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000</td>
<td>10</td>
<td>2048</td>
<td>1000</td>
</tr>
<tr>
<td># Averages</td>
<td>512</td>
<td></td>
<td></td>
<td>34000</td>
</tr>
<tr>
<td>RF gain</td>
<td>30</td>
<td>30000</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Steps</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$T_1 = 3422$ms  
$T_2 (1) = 64$ms  
$T_2 (2) = 24$ms  
$D = 4.6 \cdot 10^{-10}$m$^2$/s

4.1.2.3 Spectrum of ethanol

A spectroscopy measurement has also been done using this setup. The frequency spectrum of the ethanol molecule is depicted in figure 18. The chemical shifts are clearly visible.

**Figure 17:** The frequency spectrum of the ethanol molecule (CH$_3$CH$_2$OH). The left peak corresponds with the CH$_3$ group, the middle one with the CH$_2$ group, the right peak is due to the OH group.

The parameters where the measurement has been applied with are tabulated in table 4.
Table 4: different parameters used for the spectroscopy measurement of ethanol are summarized.

<table>
<thead>
<tr>
<th>Solution: CH₃CH₂OH</th>
<th>Single H (capillary): H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>199.871</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>10</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>5</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.068</td>
</tr>
<tr>
<td>wW (μs)</td>
<td>50000</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>800</td>
</tr>
</tbody>
</table>

4.1.3 Chloride

4.1.3.1 Setup characteristics
The single chloride coil is a 30 turn solenoid, wound on a sample tube of diameter 0.78cm over a length x of 2cm. Copper wire of thickness 1/2mm is used. C₁ is a tuning capacitor with a value from 1 to 30pF. C₂ equals 390pF. The Q factor is 28, the amplitude of the reflected power has a value of -21dB at the resonance frequency.

4.1.3.2 Measurements
The noise measurement is depicted in figure 18. The slope of the fitted curve equals -0.51. The maximum number of useful averages is 32.

![Figure 18](image)

Figure 18: Signal and noise measurement of the single chloride coil. Both are log-log-plotted as a function of the number of averages.

The $T_1$ and $T_2$ measurements are done with a NaCl solution of 3M. According to the exponential fit, illustrated in figure 19, $T_1$ equals 62ms.
Figure 19: $T_1$ relaxation measurement of chloride with the single chloride coil. The signal is plotted as a function of the recovery time. The measured sample is 3M NaCl solution.

Figure 20 shows the $T_2$ measurement. The exponential fit gives a value of 21ms for the $T_2$ relaxation time.

Figure 20: $T_2$ relaxation measurement of chloride with the single chloride coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl solution.

The diffusion measurement is plotted in figure 21. Based on the calculations as showed in appendix C, a value of $8.38 \cdot 10^{-8}$ m$^2$/s for the diffusion coefficient is obtained.
Figure 21: Diffusion measurement of chloride in 3M NaCl solution, obtained with the single chloride coil. The natural logarithm of the signal intensity is plotted as a function of the echo time.

The calculated results together with the parameters to obtain the measurements are summarized in table 5.

Table 5: Different parameters are summarized for the chloride single coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, T₁, T₂ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Single Cl coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>19.583</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>22</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>30</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.068</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>500</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>600</td>
</tr>
<tr>
<td>SNR</td>
<td>T₁</td>
</tr>
<tr>
<td>SW (kHz)</td>
<td>100</td>
</tr>
<tr>
<td># Averages</td>
<td>32</td>
</tr>
<tr>
<td>RF gain</td>
<td>35</td>
</tr>
<tr>
<td>Slope = -0.51</td>
<td>T₁ = 62ms</td>
</tr>
</tbody>
</table>

4.1.4 Temperature controlled
With the temperature controlled single hydrogen coil, a noise measurement, $T_2$ relaxation measurement and diffusion calculations are done for different temperatures. $T_1$ relaxation measurements were not executed. The measured sample is H$_2$O in a larger sample tube.

The result of the noise measurement for a temperature at 40°C is showed in figure 22. The slope of the fitted straight line equals -0.47. 256 useful averages can be reached. Noise measurements at other temperatures can be found in appendix D.

![Figure 22: Signal and noise measurement of the single temperature controlled hydrogen coil at a temperature of 40°C.](image)

The data obtained from the $T_2$ measurement at 40°C are plotted in figure 23. The exponential fit gives a $T_2$ relaxation time of 18ms for water. Appendix D contains an additional $T_2$ measurement for a temperature of 60°C.

![Figure 23: Signal intensity over echo time for $T_2$ relaxation measurement at 40°C.](image)
**Figure 23:** $T_2$ relaxation measurement of hydrogen with the temperature controlled single hydrogen coil for a temperature of 40°C. The signal is log-plotted as a function of the echo time. The measured sample is H$_2$O.

For measurements at 22°C, 40°C and 60°C, the diffusion data are plotted in figure 24. The calculated diffusion coefficients are respectively $1.38 \cdot 10^{-9}$ m$^2$/s, $2.12 \cdot 10^{-9}$ m$^2$/s and $2.76 \cdot 10^{-9}$ m$^2$/s. As expected, an increasing temperature results in an increasing temperature.

**Figure 24:** Diffusion measurement of water for different temperatures, obtained with the single hydrogen temperature controlled design. The natural logarithm of the signal intensity is plotted as a function of the echo time.

The parameters used for these temperature controlled measurements are given in table 6. The results of the measurements at other temperatures are also noted.

**Table 6:** Different parameters where the measurements are applied with are summarized for the temperature controlled hydrogen coil. Underneath, the specifications for the noise, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: H$_2$O</th>
<th>Temperature controlled single H coil: H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>199.888</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>24</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>10</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.17</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>100</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>T$_2$</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW (kHz)</td>
<td># Echoes</td>
<td>TE$_{begin}$ (μs)</td>
</tr>
<tr>
<td></td>
<td>1024</td>
<td>TE$_{end}$ (μs)</td>
</tr>
<tr>
<td></td>
<td>256</td>
<td>Steps</td>
</tr>
<tr>
<td># Averages (22°C)</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td># Averages (40°C)</td>
<td>256</td>
<td></td>
</tr>
</tbody>
</table>
### Averages (60°C)

- # Averages (60°C) 512
- RF gain 15
- Slope 22°C -0.74
  - 40°C -0.47
  - 60°C -0.55
  - 80°C -0.51

### Averages (80°C)

- # Averages (80°C) 1024

<table>
<thead>
<tr>
<th>Slope (°C)</th>
<th>22°C</th>
<th>T &lt;sub&gt;2&lt;/sub&gt;</th>
<th>40°C</th>
<th>18ms</th>
<th>D</th>
<th>22°C</th>
<th>1.38 ∙ 10&lt;sup&gt;-9&lt;/sup&gt; m&lt;sup&gt;3&lt;/sup&gt;/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>0.74</td>
<td>40°C 60°C</td>
<td>22°C</td>
<td>40°C 60°C</td>
<td>2.76 ∙ 10&lt;sup&gt;-9&lt;/sup&gt; m&lt;sup&gt;3&lt;/sup&gt;/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40°C</td>
<td>0.47</td>
<td>22°C 60°C</td>
<td>40°C</td>
<td>2.12 ∙ 10&lt;sup&gt;-9&lt;/sup&gt; m&lt;sup&gt;3&lt;/sup&gt;/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60°C</td>
<td>0.55</td>
<td>60°C 60°C</td>
<td>60°C</td>
<td>2.76 ∙ 10&lt;sup&gt;-9&lt;/sup&gt; m&lt;sup&gt;3&lt;/sup&gt;/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.2 Double coils

The structure of the double coil is schematically depicted in figure 25. The length of the coil when winded \(x\), the number of windings \(N\) and the radius \(r\) are indicated for the inner coil. The inner coil is separated with Teflon and a glass tube from the outer coil. In every design, it is the outer coil that measures hydrogen. The inner coil can measure chloride, nitrogen or sodium.

![Figure 25: Schematic picture of the structure of a double coil. The length \(x\), the number of windings \(N\) and the radius \(r\) are indicated for the inner coil.](image)

Both the inner and outer coil are part of an RF-circuit. This means that there are 4 capacitors for each double coil design.

#### 4.2.1 Hydrogen-chloride

##### 4.2.1.1 Setup characteristics hydrogen

The hydrogen coil is a copper wire of thickness 1/2mm, winded with 5 turns around the inner coil with a diameter of 1.175cm. The length \(x\), as illustrated in figure 10, is 2cm. The capacitor \(C_2\) is a tuning capacitor with a range from 1 to 30pF. \(C_1\) is a tuning capacitor with the same range, but connected in series with a parallel combination of two 2.2pF capacitors. This combination results in a Q factor of 19.6 and an amplitude of -40dB for the reflected power at the resonance frequency.

##### 4.2.1.2 Measurements hydrogen

The slope of the fitted straight line through the noise measurement is -0.41. The measured signal and noise as a function of the number of averages are plotted in figure 26. The hydrogen coil permits 8192 averages.
Figure 26: Signal and noise measurement of the hydrogen coil. Both are log-log-plotted as a function of the number of averages.

The relaxation measurements were applied on a 3M NaCl solution. The obtained $T_1$-value equals 3277ms. The measurement is plotted in figure 27.

Figure 27: $T_1$ relaxation measurement of hydrogen with the hydrogen coil. The signal is plotted as a function of the recovery time. The measured sample is 3M NaCl solution.

Figure 28 shows the result of the $T_2$ measurement. According to the fit, hydrogen has a $T_2$ relaxation time of 24ms.
Figure 28: $T_2$ relaxation measurement of hydrogen with the hydrogen coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl solution.

The diffusion calculation resulted in a diffusion coefficient of $3.30 \cdot 10^{-9} \text{m}^2/\text{s}$ for hydrogen. Figure 29 depicts the plotted diffusion data.

Figure 29: Diffusion measurement of water with the hydrogen coil. The natural logarithm of the signal intensity is plotted as a function of the echo time.

Table 7 summarizes the used measurement parameters. The results are also noted.
**Table 7:** Different parameters are summarized for the hydrogen coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Double coil H + Cl: H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>frequency (MHz)</strong></td>
<td>199.908</td>
</tr>
<tr>
<td><strong>xmit (dB)</strong></td>
<td>17 (xmit equals 30 for the noise measurement)</td>
</tr>
<tr>
<td><strong>p90 (μs)</strong></td>
<td>25</td>
</tr>
<tr>
<td><strong>gradx (T/m)</strong></td>
<td>0.068</td>
</tr>
<tr>
<td><strong>ww (μs)</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>TE (μs)</strong></td>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SW (kHz)</strong></td>
<td>1000</td>
<td>$L_d_{begin}$ (μs)</td>
<td>10</td>
</tr>
<tr>
<td><strong># Averages</strong></td>
<td>8192</td>
<td>$L_d_{end}$ (μs)</td>
<td>40000</td>
</tr>
<tr>
<td><strong>RF gain</strong></td>
<td>30</td>
<td>Steps</td>
<td>32</td>
</tr>
<tr>
<td><strong>Slope = -0.41</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**4.2.1.3 Setup characteristics chloride**
The chloride coil is wounded with 30 turns around the sample tube with a diameter of 0.78cm. Copper wire with thickness 1/2mm is used. The length $x$ equals 2cm. $C_1$ is a tuning capacitor with a range from 1 to 30pF. $C_2$ has a value of 480pF. This RF-setup is characterized by a Q factor of 31 and an amplitude of -33dB for the reflected power at the resonance frequency.

**4.2.1.4 Measurements chloride**
From the noise measurement of chloride, a slope of -0.51 has been obtained. The number of averages according to this slope equals 4096. The noise data and fitted curve are plotted in figure 30.

**Figure 30:** Signal and noise measurement of the chloride coil. Both are log-log-plotted as a function of the number of averages.
The $T_1$ measurement results in a 37ms relaxation time. Figure 31 visualizes the measurement.

\[\text{Figure 31: } T_1 \text{ relaxation measurement of chloride with the chloride coil. The signal is plotted as a function of the recovery time. The measured sample is 3M NaCl solution.}\]

Obtained from the $T_2$ measurement, chloride has a 20ms spin-spin relaxation time. The exponential fit and data are represented in figure 32. Both the $T_1$ and $T_2$ measurement are done with a 3M NaCl solution.

\[\text{Figure 32: } T_2 \text{ relaxation measurement of chloride with the chloride coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl solution.}\]

Figure 33 represents the diffusion measurement. The diffusion coefficient for chloride can be calculated and equals $6.4 \cdot 10^{-7} \text{ m}^2/\text{s}$. 
Figure 33: Diffusion measurement of chloride for 3M NaCl solution. The natural logarithm of the signal intensity is plotted as a function of the echo time.

The slope, $T_1$ and $T_2$ values and the diffusion coefficient are summed up in table 8. Also the measurement settings are noted.

Table 8: Different parameters are summarized for the chloride coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Double coil H + Cl: Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>19.59</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>23</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>40</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.068</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>220</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>300</td>
</tr>
<tr>
<td>SNR</td>
<td></td>
</tr>
<tr>
<td>SW (kHz)</td>
<td>200</td>
</tr>
<tr>
<td># Averages</td>
<td>4096</td>
</tr>
<tr>
<td>RF gain</td>
<td>30</td>
</tr>
<tr>
<td>Slope = -0.51</td>
<td></td>
</tr>
<tr>
<td>T$_1$</td>
<td>37 ms</td>
</tr>
<tr>
<td>T$_2$</td>
<td>20 ms</td>
</tr>
<tr>
<td>Diffusion</td>
<td></td>
</tr>
<tr>
<td>D = $6.4 \cdot 10^{-7}$ m$^2$/s</td>
<td></td>
</tr>
</tbody>
</table>

4.2.2 Hydrogen-nitrogen

4.2.2.1 Setup characteristics hydrogen
The hydrogen coil has a length $x$ of 2cm. 5 windings of copper wire are winded around an outer glass tube of 1.175cm. The thickness of the wire is 1/2mm. $C_1$ and $C_2$ are tuning
capacitors with a range from 1 to 30pF. $C_f$ is lowered by connecting a parallel coupled capacitor pair of both 2.2pF in series with it. The Q factor is 53 and the amplitude equals -42dB for the reflected power.

### 4.2.2.2 Measurements hydrogen

The noise measurement can be seen in figure 34. The slope has a value of -0.50. The maximum number of useful averages is 512, as written down in table 9.

![Figure 34: Signal and noise measurement of the hydrogen coil. Both are log-log-plotted as a function of the number of averages.](image)

For the $T_1$ and $T_2$ measurement, a solution of NH$_3$ is used (28-30% solution). This results in a $T_1$ relaxation time of 3981ms, and a $T_2$ value of 52ms for hydrogen. The measurements are represented in figures 35 and 36 respectively.

![Figure 35: $T_1$ relaxation measurement of hydrogen with the hydrogen coil. The signal is plotted as a function of the recovery time. The measured sample is NH$_3$ solution (28-30%).](image)
Figure 36: $T_2$ relaxation measurement of hydrogen with the hydrogen coil. The signal is log-plotted as a function of the echo time. The measured sample is NH$_3$ solution (28-30%).

From the diffusion calculation, a value of $5.12 \cdot 10^{-9}$ m$^2$/s for the diffusion coefficient arises. The data are plotted in figure 37.

Figure 37: Diffusion measurement of hydrogen for NH$_3$ solution (28-30%). The natural logarithm of the signal intensity is plotted as a function of the echo time.

Table 9 contains all data for the different measurements.
Table 9: Different parameters are summarized for the hydrogen coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: NH$_3$ (28-30%)</th>
<th>Double coil H + N: H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>199.94</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>20 (xmit equals 18.5 for the noise measurement)</td>
</tr>
<tr>
<td>$p90$ (µs)</td>
<td>25</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.17 (gradient equals 0 for the noise measurement)</td>
</tr>
<tr>
<td>ww (µs)</td>
<td>100 (ww equals 160 for the noise measurement)</td>
</tr>
<tr>
<td>TE (µs)</td>
<td>200</td>
</tr>
<tr>
<td><strong>SNR</strong></td>
<td><strong>T$_1$</strong></td>
</tr>
<tr>
<td>SW (kHz)</td>
<td>1000</td>
</tr>
<tr>
<td># Averages</td>
<td>512</td>
</tr>
<tr>
<td>RF gain</td>
<td>35</td>
</tr>
<tr>
<td>Slope = -0.50</td>
<td>$T_1 = 3981$ms</td>
</tr>
</tbody>
</table>

4.2.2.3 Setup characteristics nitrogen

The nitrogen coil is a 38 turn solenoid, winded on a sample tube of diameter 0.78cm over a length $x$ of 2.5cm. Copper wire of thickness 1/2mm is used. $C_1$ is a tuning capacitor with a value from 1 to 30pF. It is connected in parallel with an additional 8.2pF capacitor. $C_2$ equals 820pF. The Q factor is 33, the amplitude of the reflected power has a value of -40dB around the resonance frequency.

4.2.2.4 Measurements nitrogen

The noise signal is visualized in figure 38. The number of useful averages equals 4096. The slope of the fitted straight line is -0.52.

![Figure 38: Signal and noise measurement of the nitrogen coil. Both are log-log-plotted as a function of the number of averages.](image-url)
From the $T_1$ relaxation time measurement, 2ms for $T_1$ was obtained. The measurement is represented in figure 39 and was executed with NH$_3$ solution (28-30%).

**Figure 39:** $T_1$ relaxation measurement of nitrogen with the nitrogen coil. The signal is plotted as a function of the recovery time. The measured sample is NH$_3$ solution (28-30%).

The $T_2$ relaxation time measurement is also done with NH$_3$ solution (28-30%). The result is a $T_2$ time of 2ms. The measurement can be seen in figure 40.

**Figure 40:** $T_2$ relaxation measurement of nitrogen with the nitrogen coil. The signal is log-plotted as a function of the echo time. The measured sample is NH$_3$ solution (28-30%).

The diffusion calculation resulted in a value of $7.13 \cdot 10^{-6}$ m$^2$/s for the diffusion coefficient of nitrogen. The fitted data are represented in figure 41.
Figure 41: Diffusion measurement of nitrogen for NH$_3$ solution (28-30%). The natural logarithm of the signal intensity is plotted as a function of the echo time.

Table 10 gives an overview of the used measurement parameters and results.

**Table 10:** Different parameters are summarized for the nitrogen coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, T$_1$, T$_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: NH$_3$ (28-30%)</th>
<th>Double coil H + N: N</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>14.444</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>20 (xmit equals 21 for the noise measurement)</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>60 (p90 equals 40 for the noise measurement)</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.068 (gradient equals 0.272 for the noise measurement)</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>300</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>400</td>
</tr>
<tr>
<td>SNR</td>
<td>T$_1$</td>
</tr>
<tr>
<td>SW (kHz)</td>
<td>150</td>
</tr>
<tr>
<td># Averages</td>
<td>4096</td>
</tr>
<tr>
<td>RF gain</td>
<td>30</td>
</tr>
<tr>
<td>Slope = -0.52</td>
<td>T$_1$ = 2ms</td>
</tr>
</tbody>
</table>

4.2.3 Hydrogen-sodium

4.2.3.1 Setup characteristics hydrogen
A 3 turn copper wire solenoid is winded over a length of 1cm around a glass tube with diameter 1.175cm. The thickness of the used copper wire is 0.5mm. $C_1$ and $C_2$ are both tuning
capacitors with a range from 1 to 30pF. The Q factor of the circuit is 36, the amplitude of the reflected power at the Larmor frequency equals -30dB.

4.2.3.2 Measurements hydrogen
The slope of the fitted straight line through the noise measurement is -0.48. The measured signal and noise as a function of the number of averages are plotted in figure 42. The hydrogen coil permits 2048 averages.

![Signal and noise measurement of the hydrogen coil](image)

**Figure 42:** Signal and noise measurement of the hydrogen coil. Both are log-log-plotted as a function of the number of averages.

The relaxation measurements were applied on a 3M NaCl solution. The obtained $T_1$-value equals 3005ms. The measurement is plotted in figure 43.

![T₁ relaxation measurement of hydrogen with the hydrogen coil](image)

**Figure 43:** $T_1$ relaxation measurement of hydrogen with the hydrogen coil. The signal is plotted as a function of the recovery time. The measured sample is 3M NaCl solution.
Figure 44 shows the result of the $T_2$ measurement. According to the fit, hydrogen has a $T_2$ relaxation time of 30ms.

![Figure 44: $T_2$ relaxation measurement of hydrogen with the hydrogen coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl solution.](image)

The diffusion calculation resulted in a diffusion coefficient of $9.98 \cdot 10^{-10}$ m$^2$/s for hydrogen. Figure 45 depicts the plotted diffusion data.

![Figure 45: Diffusion measurement of water. The natural logarithm of the signal intensity is plotted as a function of the echo time.](image)

Table 11 summarizes the used measurement parameters. The results are also noted.
Table 11: Different parameters are summarized for the hydrogen coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Double coil H + Na: H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>199.903</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>18.5</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>20</td>
</tr>
<tr>
<td>gradx $T_2$ (T/m)</td>
<td>0.068 (gradient equals 0.102 for the $T_1$ measurement)</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>160</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>200</td>
</tr>
<tr>
<td><strong>SNR</strong></td>
<td><strong>T_1</strong></td>
</tr>
<tr>
<td>SW (kHz)</td>
<td>N.D.</td>
</tr>
<tr>
<td># Averages</td>
<td>2048</td>
</tr>
<tr>
<td>RF gain</td>
<td>N.D.</td>
</tr>
<tr>
<td>Slope = -0.48</td>
<td>$T_1 = 3005$ms</td>
</tr>
</tbody>
</table>

4.2.3.3 Setup characteristics sodium

The sodium solenoid is wound with 20 turns over a length of 2cm. 0.5mm copper wire was used and wound around a sample tube of 0.75cm diameter. The $C_1$ capacitor is a tuning capacitor with a range from 1 to 30pF. $C_2$ is a parallel combination of a tuning capacitor with the same range and a capacitor with a value of 150pF. Q equals 24, the amplitude of the reflected power is -42dB.

4.2.3.4 Measurements sodium

From the noise measurement of sodium, a slope of -0.51 has been obtained. The number of averages according to this slope equals 4096. The noise data and fitted curve are plotted in figure 46.

![Figure 46: Signal and noise measurement of the sodium coil. Both are log-log-plotted as a function of the number of averages.](image)
The $T_1$ measurement results in a 59ms relaxation time. Figure 47 visualizes the measurement.

![Figure 47](image_url)

**Figure 47:** $T_1$ relaxation measurement of sodium with the sodium coil. The signal is plotted as a function of the recovery time. The measured sample is 3M NaCl solution.

Obtained from the $T_2$ measurement, sodium has a 48ms spin-spin relaxation time. The exponential fit and data are represented in figure 48. Both the $T_1$ and $T_2$ measurement are done with a 3M NaCl solution.

![Figure 48](image_url)

**Figure 48:** $T_2$ relaxation measurement of sodium with the sodium coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl solution.

Figure 49 represents the diffusion measurement. The diffusion coefficient for sodium can be calculated and equals $2.27 \cdot 10^{-9}$m$^2$/s.
Figure 49: Diffusion measurement of sodium for 3M NaCl solution. The natural logarithm of the signal intensity is plotted as a function of the echo time.

The slope, $T_1$ and $T_2$ values and the diffusion coefficient are summed up in table 12. Also the measurement settings are noted.

Table 12: Different parameters are summarized for the sodium coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Double coil H + Na: Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>52.878</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>18.5</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>20</td>
</tr>
<tr>
<td>gradx $T_2$ (T/m)</td>
<td>0.068 (gradient equals 0.102 for the $T_1$ measurement, 0.238 for diffusion)</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>400 (ww equals 1000 for the noise measurement)</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>500 (TE equals 1100 for the noise measurement)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW (kHz)</td>
<td>Ld$_{\text{begin}}$ (μs)</td>
<td># Echoes</td>
<td># Averages</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>512</td>
<td>30000</td>
</tr>
<tr>
<td>4096</td>
<td>500</td>
<td>32</td>
<td>40</td>
</tr>
</tbody>
</table>

Slope = -0.51

$T_1 = 59\text{ ms}$

$T_2 = 48\text{ ms}$

$D = 2.27 \cdot 10^{-9}$ m$^2$/s

4.2.4 Hydrogen-sodium capillary tubes

4.2.4.1 Setup characteristics hydrogen
The hydrogen coil is a 6 turn solenoid, wound with a diameter of 2.8mm over a length $x$ of 0.4cm. Copper wire of thickness $1/4$ mm is used. $C_1$ and $C_2$ are tuning capacitors with a value from 1 to 30pF. The Q factor is 40, the amplitude of the reflected power has a value of -40dB at the resonance frequency.

### 4.2.4.2 Measurements hydrogen

The noise measurement can be seen in figure 50. The slope has a value of -0.50. The maximum number of useful averages is 512, as written down in table 13.

![Figure 50: Signal and noise measurement of the hydrogen coil. Both are log-log-plotted as a function of the number of averages.](image)

For the $T_1$ and $T_2$ measurement, 3M NaCl solution is used. This results in a $T_1$ relaxation time of 2761ms, and a $T_2$ value of 43ms for hydrogen. The measurements are represented in figures 51 and 52 respectively.

![Figure 51 and 52](image)
**Figure 51:** $T_1$ relaxation measurement of hydrogen with the hydrogen coil. The signal is plotted as a function of the recovery time. The measured sample is 3M NaCl.

**Figure 52:** $T_2$ relaxation measurement of hydrogen with the hydrogen coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl.

From the diffusion calculation, a value of $3.90 \times 10^{-9}$ m$^2$/s for the diffusion coefficient arises. The data are plotted in figure 53.

**Figure 53:** Diffusion measurement of hydrogen for 3M NaCl solution. The natural logarithm of the signal intensity is plotted as a function of the echo time.

Table 13 contains all data for the different measurements.
Table 13: Different parameters are summarized for the hydrogen coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, $T_1$, $T_2$ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Double coil H + Na (capillary): H</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>199.943</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>17</td>
</tr>
<tr>
<td>p90 (μs)</td>
<td>5</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.068 (gradient equals 0.17 for the $T_2$ measurement)</td>
</tr>
<tr>
<td>ww (μs)</td>
<td>300</td>
</tr>
<tr>
<td>TE (μs)</td>
<td>320</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>T&lt;sub&gt;1&lt;/sub&gt;</th>
<th>T&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>L&lt;sub&gt;begin&lt;/sub&gt; (μs) 10</td>
<td># Echoes 2048</td>
<td>TE&lt;sub&gt;begin&lt;/sub&gt; (μs) 400</td>
</tr>
<tr>
<td>512</td>
<td>L&lt;sub&gt;end&lt;/sub&gt; (μs) 40000</td>
<td>Steps 64</td>
<td>TE&lt;sub&gt;end&lt;/sub&gt; (μs) 100000</td>
</tr>
<tr>
<td>35</td>
<td>Steps 64</td>
<td>Steps 100</td>
<td></td>
</tr>
</tbody>
</table>

Slope = -0.5  
$T_1 = 2761$ms  
$T_2 = 43$ms  
$D = 3.90 \times 10^{-9}$m²/s

4.2.4.3 Setup characteristics sodium

The length of this (capillary) sodium hydrogen coil when winded is 0.4cm. The used copper wire has a thickness of 1/10mm and it is wounded around a capillary tube of 1.6mm with 42 turns. Both $C_1$ and $C_2$ are tuning capacitors with a range from 1 to 30pF. The value of the matching capacitor is raised by placing an additional 68pF capacitor with it in parallel. The Q factor of this RF-circuit equals 20. The amplitude of the reflected power at the Larmor frequency is -25dB.

4.2.4.4 Measurements sodium

The noise signal is visualized in figure 54. The number of useful averages equals 16384. The slope of the fitted straight line is -0.53.

![Figure 54: Signal and noise measurement of the sodium coil. Both are log-log-plotted as a function of the number of averages](image)

49
From the $T_1$ relaxation time measurement, 57 ms for $T_1$ was obtained. The measurement is represented in figure 55 and was executed with 3M NaCl solution.

![Figure 55: $T_1$ relaxation measurement of sodium with the sodium coil. The signal is plotted as a function of the recovery time. The measured sample is NaCl solution.](image)

The $T_2$ relaxation time measurement is also done with NaCl solution. The result is a $T_2$ time of 89 ms. The measurement can be seen in figure 56.

![Figure 56: $T_2$ relaxation measurement of sodium of the sodium coil. The signal is log-plotted as a function of the echo time. The measured sample is 3M NaCl solution.](image)

The diffusion calculation resulted in a value of $3.90 \cdot 10^{-9}$ m$^2$/s for the diffusion coefficient of nitrogen. The fitted data is represented in figure 57.
**Figure 57**: Diffusion measurement of sodium for 3M NaCl solution. The natural logarithm of the signal intensity is plotted as a function of the echo time.

Table 14 gives an overview of the used measurement parameters and results.

**Table 14**: Different parameters are summarized for the sodium coil. The parameters where the measurements are applied with are summed up. Underneath, the specifications for the noise, T₁, T₂ and diffusion measurement are given. The row at the bottom summarizes the end results.

<table>
<thead>
<tr>
<th>Solution: 3M NaCl</th>
<th>Double coil H + Na (capillary): Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>52.893</td>
</tr>
<tr>
<td>xmit (dB)</td>
<td>11</td>
</tr>
<tr>
<td>p90 (µs)</td>
<td>5</td>
</tr>
<tr>
<td>gradx (T/m)</td>
<td>0.238 (gradient equals 0.272 for the noise measurement)</td>
</tr>
<tr>
<td>ww (µs)</td>
<td>500</td>
</tr>
<tr>
<td>TE (µs)</td>
<td>23204 (?)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SNR</th>
<th>T₁</th>
<th>T₂</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW (kHz)</td>
<td>200</td>
<td>1</td>
<td>512</td>
</tr>
<tr>
<td># Averages</td>
<td>16384</td>
<td>500</td>
<td>TE&lt;sub&gt;begin&lt;/sub&gt; (µs) 550</td>
</tr>
<tr>
<td>RF gain</td>
<td>20</td>
<td>Steps</td>
<td>TE&lt;sub&gt;end&lt;/sub&gt; (µs) 10000</td>
</tr>
<tr>
<td>Slope = -0.53</td>
<td>T₁ = 57ms</td>
<td>T₂ = 89ms</td>
<td>D = 3.90·10⁻⁹ m²/s</td>
</tr>
</tbody>
</table>

*DEZE MOET OPNIEUW GEMETEN WORDEN*
5. Discussion and conclusion

Eight different RF-designs where developed during this project. Single and double coils where created to measure both larger sample tubes and capillary tubes. During their development, different challenges occurred.

First of all, the circuit calculations are indicative. In most cases, an adjustment of the calculated capacitor values is needed after building the RF-circuit. The deviation from the calculation is due to distortions in the circuit. For example the copper box where the circuit is build in, acts as a source of distortion. The calculations are also done without including a sample in the interior of the coil. The characteristics of the RF-circuit change if the coil surrounds a sample. So, it is best to adjust the capacitor values after the sample is inserted.

During the tuning of the double coil to measure hydrogen and sodium, a noteworthy situation occurred. An adjustment of the resonance frequency for the hydrogen coil to higher frequencies was needed. This was done by connecting an additional capacitor in series with the tuning capacitor $C_1$. It was remarkable that the resonance frequency strongly depended on the length of the connecting wires of the additional capacitor. One was not able to tune the circuit at the right frequency because the unwanted stray inductances controlled the resonant behavior. From this instructive situation, one can conclude that sometimes it is better to adjust the number of windings of the solenoid or increasing its length when winded, instead of adapting the capacitor values.

Also the system to position the coil in the magnet needs to be designed carefully. The first measurements where done with a positioning system that made use of a copper rod. The system was easy in use, but the rod caused strong inhomogeneities in the field. Another positioning system, made of plastic, was necessary. Furthermore, each design has its own shape. The setups of the double coils are larger than those with a single coil. As a consequence, the coils are not all fixed at the same height which makes that every box needs a slightly different position in the magnet. From this point of view, it was better to create designs where the coils are at the same height in each box, so that the position should be determined only once.

The coils of the circuits are packed in Teflon. This is done to avoid a stretching and contracting movement of the solenoid when a voltage is applied. This packaging of the coil is disadvantageous because the sample tube cannot be removed anymore. A possible solution is a design that makes use of a hollow cylinder with small slots in it in the shape of a helix. The wire of the solenoid can then be winded around the cylinder in these slots. In this way, the coil wire is fixed and the sample tube can move in and out the hollow cylinder.

The eight coils to measure hydrogen, nitrogen, chloride and sodium where all tested with a noise measurement. Also relaxation time and diffusion measurements where applied. Although there were small problems with the measuring equipment, all designs showed good
results and can be used to perform more experiments. Additionally, one gathered the knowledge to build coils for other nuclei that can be used in the future.
6. Literature

[8] *NMR topics*, "http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/Spectrpy/nmr/nmr2.htm"; 26/05/2013.
Appendix A: calculations of the LC circuit

Appendix A1: impedance and resonance condition
Consider figure 7. The impedance of the series circuit in the box, thus the connection between
the inductor, resistance and $C_1$, is called $Z_{\text{serie}}$. It is given as:

$$Z_{\text{serie}} = R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right). \quad (A1.1)$$

The impedance of $C_2$ is called $Z_{C_2}$ and equals:

$$Z_{C_2} = \frac{1}{j C_2 \omega}. \quad (A1.2)$$

The total impedance $Z$ of the circuit can be calculated as:

$$\frac{1}{Z} = \frac{1}{Z_{\text{serie}}} + \frac{1}{Z_{C_2}}. \quad (A1.3)$$

This implies the follow equation:

$$\frac{1}{Z} = \frac{1}{R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right)} + j C_2 \omega. \quad (A1.4)$$

Adding both terms and rearranging results in:

$$\frac{1}{Z} = \frac{1}{R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right)} + \frac{j C_2 \omega}{R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right)}, \quad (A1.5)$$

$$Z = \frac{R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right)}{\left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right) + j C_2 \omega R}. \quad (A1.6)$$

Multiplying and dividing by the complex conjugate of the denominator gives:

$$Z = \frac{R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right)}{\left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right) + j C_2 \omega R} \cdot \frac{\left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right) - j C_2 \omega R}{\left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right) + j C_2 \omega R}. \quad (A1.7)$$

After some calculations the total impedance can be obtained:

$$Z = \frac{R \left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right) + \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) C_2 \omega R + j \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right) - \left( \frac{C_2 \omega}{C_1 \omega} \right)^2}{\left( 1 - C_2 \omega \left( \frac{L \omega}{C_1 \omega} - \frac{1}{C_1 \omega} \right) \right)^2 + \left( C_2 \omega R \right)^2}. \quad (A1.8)$$
If the imaginary part equals zero, the resonance condition can be calculated:

\[
\left( L\omega_0 - \frac{1}{C_1\omega_0} \right) \left( 1 - C_2\omega_0 \left( L\omega_0 - \frac{1}{C_2\omega_0} \right) \right) - R^2 C_2\omega_0 = 0
\]  

(A1.9)

Notice that \( \omega \) has changed in \( \omega_0 \) to emphasize the resonance condition. Working this out and grouping certain terms carefully gives the end result:

\[
-L\omega_0^2 C_1^2 + L^2 \omega_0^4 C_1^2 C_2 - 2 C_2 L\omega_0^2 C_1 + R^2 C_2\omega_0^2 C_1^2 + C_1 + C_2 = 0
\]  

(A1.10)

\[
\left( L^2 C_1^2 C_2 \right) \omega_0^4 + \left( R^2 C_2 C_1^2 - L C_1^2 - 2 C_2 L C_1 \right) \omega_0^2 + \left( C_1 + C_2 \right) = 0
\]  

(A1.11)

**Appendix A2: resistance**

The resistance \( R \) of the RF-circuit in figure 7 is estimated by the resistance of the copper wire of the solenoid. First, the length \( l \) when the coil is not winded has to be known. If the coil is already winded, it can be calculated by the following formula:

\[
l = N \cdot 2 \cdot Pi \cdot r.
\]  

(A2.1)

\( N \) is the number of windings and \( r \) the radius of the solenoid. Also the area of the cross section of the coil has to be calculated:

\[
A = Pi \cdot r^2.
\]  

(A2.2)

Combining formula (A2.1) and (A2.2) results in an expression for the resistance \( R \):

\[
\frac{R}{A} = \frac{l \cdot \rho}{A}.
\]  

(A2.3)

\( \rho \) is the resistivity of copper. This value is known and equals \( 1.68 \cdot 10^{-8} \text{ Ohm} \cdot \text{m} \) [19].
Appendix B: images of the different RF-circuits

This appendix contains pictures from the inside of the RF-circuits.

Appendix B1: single coil designs

Figure B1.1: This picture shows the inside of the single hydrogen coil design. The matching capacitor $C_2$ is connected to the spectrometer. The capacitor in the left upper corner of the box is the tuning capacitor $C_1$.

Figure B1.2: This picture images the inside of the single hydrogen coil design with capillary tube. The left capacitor is $C_1$, the right one corresponds with $C_2$. 
**Figure B1.3:** This is an image of the inside of the single chloride coil design. The matching capacitor $C_2$ is connected to the spectrometer. The capacitor in the left upper corner of the box is $C_1$.

**Figure B1.4:** The temperature controlled single hydrogen coil. Before heating, the outside is covered with isolation material.
Appendix B2: double coil designs

Figure B2.1: In this picture one can see the double hydrogen-chloride coil design. Both capacitors on the left of the box belong to the chloride coil. The ones on the right side are for tuning the hydrogen circuit.

Figure B2.2: The double coil to measure hydrogen and nitrogen is depicted in this image. The left capacitors belong to the hydrogen coil. The capacitors on the right side tune the nitrogen coil.
**Figure B2.3:** The double coil design to measure hydrogen and sodium is depicted in this image. With the left capacitors, one is able to tune the hydrogen coil. The capacitors on the right side belong to the sodium RF-circuit.

**Figure B2.4:** This picture shows the inside of the double hydrogen-sodium coil design with capillary tube. With the two capacitors on top, the sodium coil can be tuned. The two capacitors underneath belong to the hydrogen coil.
Appendix C: calculating the diffusion coefficient

The diffusion coefficient can be calculated from formula (9), it is repeated here as formula (C1):

\[ S \propto M_0 \exp \left( -\frac{\gamma^2 G^2 D}{12} \tau^3 \right) \exp \left( -\frac{\tau}{T_2} \right). \]  

(C1)

\( \tau \) is the varying echo time, \( \gamma \) the gyromagnetic ratio, \( M_0 \) the net magnetization, \( G \) the gradient and \( D \) the diffusion coefficient.

By taking the natural logarithm of formula (C1), one obtains the following formula:

\[ \ln(S) = C + \left( -\frac{\gamma^2 G^2 D}{12} \right) \tau^3 + \left( -\frac{1}{T_2} \right) \tau. \]  

(C2)

The result is a third degree polynomial in which \( C \) is a proportionality constant. From this, one can see that a plot of the measured \( \ln(S) \) as a function of the echo time and fitting these data with a (third degree) cubic polynomial, leads to an estimate of the first term between brackets in the right hand side of formula (C2). Then the following equality holds:

\[ C_{fit} = \frac{\gamma^2 G^2 D}{12}, \]  

(C3)

wherein \( C_{fit} \) is the parameter obtained by the fit. It is expressed in units of \( 1/s^3 \). Rearranging this formula and isolating \( D \) results in:

\[ D = \frac{12 \cdot C_{fit}}{\gamma^2 G^2}. \]  

(C4)

The gyromagnetic ratio can be found in table 1. In this definition, \( \gamma \) needs to be expressed in units of \( \text{rad}/(\text{T} \cdot \text{s}) \). \( G \) is the gradient at which the measurement is done.
Appendix D: additional temperature controlled measurements

Noise measurements for the single hydrogen temperature controlled design at temperatures of 22°C, 60°C and 80°C are given below.

Figure D1: Signal and noise measurement for a temperature at 22°C. Both are log-log-plotted as a function of the number of averages. The maximum of useful averages is 512.

Figure D2: Signal and noise measurement for a temperature at 60°C. Both are log-log-plotted as a function of the number of averages. The maximum of useful averages is 2048.
Figure D3: Signal and noise measurement for a temperature at 80°C. Both are log-log-plotted as a function of the number of averages. The maximum of useful averages is 1024. An extra $T_2$ measurement at a temperature of 60°C has also been applied. Figure D4 gives the data. The $T_2$ time of water equals 22ms.

Figure D4: $T_2$ relaxation measurement of hydrogen with the single hydrogen coil, temperature controlled. The signal is log-plotted as a function of the echo time. The measured sample is H$_2$O.