Allgemeines

- MRI = Magnetic resonance imaging (MRT = Magnetresonanztomographie)
- bildgebendes Verfahren, vor allem für die Medizin genutzt
- **Funktionsweise:** Resonanzfrequenz proportional zum Magnetfeld
$\Longrightarrow$ durch Änderung des Magnetfeldes (linear in einer Achse) ändert sich auch die Resonanzfrequenz linear zur Position auf der Achse (solches lineare Feld auch Gradientenfeld genannt)
- MRI meist 3 Greadientenspulen für jede Achse, oft nur einige Milisekunden $\Longrightarrow$ wird als gepulst bezeichnet
- B_0 is the main magnetic field 1.5T
- das Gradientenfeld besitzt oft nur $10bis40mT/m$, welches klein ist im vergleich zu B_0
- area under spectrum tells the amount of magnetisation after prepolarising pulse
- it is also possible to do measurements not in kartesien coordinates but in a radial component and azimuth compenent → filtered back projection (fourier transform in polar manner)(artifacts in image accour probably because of small off resonant signal)

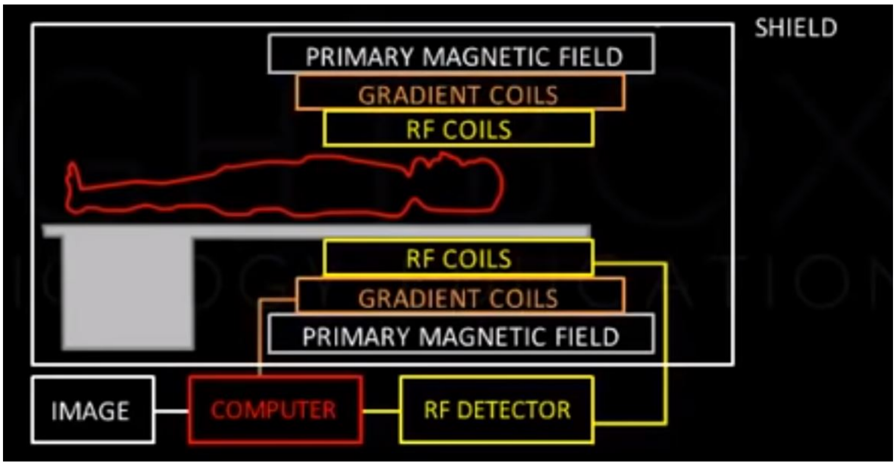


Figure 1: Theoretical construction of a MRI `https://www.youtube.com/watch?v=Ok9ILIYzmaY`

1.)Kernspin, magnetisches Moment, gyromagnetisches Verhältnis

- spin is an intrinsic form of angular momentum carried by elementary particles, composite particles (hadrons), and atomic nuclei.

- spin is like a vector quantity: it has a definite magnitude, and it has a direction.

- Spin quantum number $\frac{1}{2} \leq I$ ($I = \sum_{i=1}^{A}(\overline{s_i} + \overline{l_i})$). In this experiment only $I = \frac{1}{2}$, because it is easier. (^{2}3Na is spin $\frac{3}{2} \longrightarrow$ multiple quantum coherence)

- Number of discrete orientations (with ext. field): $2I + 1$ ($m = -I, ..., I$)

- with $I = \frac{1}{2}$ two possible orientations ($\pm\frac{1}{2}$; spin up prefered $\longrightarrow$ lower energy) $=> E_m = -\gamma\hbar m B_0$ γ is gyromagentic ratio (ratio of its magnetic moment to its angular momentum)

- Protons, neutrons, and many nuclei carry nuclear spin, which gives rise to a gyromagnetic ratio $\gamma = \frac{e}{2m_p} g_n = g_n \frac{\mu_N}{\hbar}$; μ_N is the nuclear magneton, and g_n is the g-factor of the nucleon or nucleus in question. The ratio of $\frac{\gamma_n}{2\pi g_n}$, equal to $\frac{\mu_N}{h} = 7\,622593285 \frac{MHz}{T}$

- The gyromagnetic ratio of a nucleus plays a role in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). These procedures rely on the fact that bulk magnetization due to nuclear spins precess in a magnetic field at a rate called the Larmor frequency, which is simply the product of the gyromagnetic ratio with the magnetic field strength. With this phenomenon, the sign of γ determines the sense (clockwise vs counterclockwise $\gamma \leq 0$) of precession. ^{1}H $\frac{\gamma_n}{2\pi} = 42\,577478518 \frac{MHz}{T}$

- Boltzmann statistic (distribution of spin up and down)): $\frac{P_{\frac{1}{2}}}{P_{-\frac{1}{2}}} = exp\left(\frac{\gamma\hbar B_0}{k_B T}\right)$; wihtout thermal movement $\rightarrow$ spin up; population differences results in bulk magnetisation (linearized with $k_B T$ way bigger then $\gamma\hbar m B_0$; $M = \frac{N\gamma^2\hbar^2 I(I+1)B_0}{3k_B T}$) parallel to the ext. mg. field

2.)Kern-Zeeman-Effekt, Energiedifferenz der Zustände, Vergleich mit anderen Anregungszuständen im Atom

- Zeeman effect: effect of splitting of a spectral line into several components in the presence of a static magnetic field; Zeeman sub-levels is a function of magnetic field strength

- $\Delta E = \gamma \Delta m \hbar B_0$

- NMR usually for us $\Delta m = 1$

3.)Drehimpuls, B_0, B_1, Drehmoment, Präzession, Larmor-Frequenz

- angular momentum $L = r \times p$

- torque, rotation force $\tau = r \times F$

- with the torque the angular momentum can be reduced or raised and the rotation axis of the body can be changed
- B_0 is the external Magnetic field; the lowest energie level is, when the magnetic moments are parallel to B_0
- angular momentum: $|I| = \hbar\sqrt{I(I+1)}$
- I do not actuall know what it is ment by B_0 and B_1, but might be the coils in the experiment. B_1 coil (also gradient coil) is called the innerst coil (use: excite and detect precession) and with B_0 is probably ment the ext. field (Measurements about EFNMR $B_0 = B_E$ of the earth)
- lamor frequency $\omega_L = \gamma B_0$
- on other atoms, there is an angular momentum, which causes the precession(Lamor frequency) because of the angular momentum preservation
- Precession is the change in the orientation of the rotation axis
- if you get the item out of the angular axis(with force), the body rotates around another axis, because of the anguar momentum.
- lamor frequency $f_{Lamor} = \frac{2\gamma}{2\pi}B$; $\omega_{Lamor} = 2\pi f_{Lamor} = \gamma B = g_j \frac{q}{2m} B$
- B_1 is the magnetic field which is detected in the B_1 coil (is the most inner coil in the set up). This coil is used to detect the Signal with a LCR-circuit; B_1 is the magnetic field, which gets generated, if the magnetic mometum occure in the x-y axis

4.)Rotierendes Koordinatensystem (Zerlegung von linear polar. B_1 in 2 gegenläufig zirkular polarisierte Komponenten, die um z-Achse rotieren), $_0$ verschwindet in Resonanz

5.) 90°- bzw. $\frac{\pi}{2}$- und 180°- bzw. π -Puls

- in conventional NMR B_0 is high so that ω_L is radio frequency (RF puls)
- also known under the word „Gradient echoes“

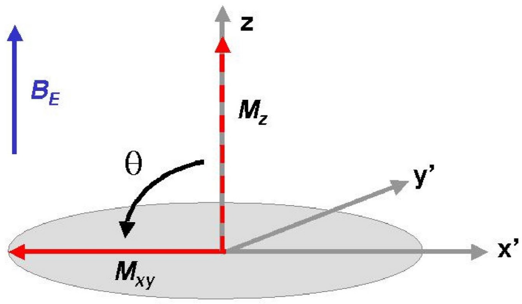


Figure 2: usually the spin is in the direction of the earths field B_E or in case B_0 is applied in the direction of B_0. In our experiment we try to manipulate this direction. We produce a RF puls so the spin flips to M_{xy} with the tip angle θ. The greyed circle shows the precession (longitudinal and transversal component; phase is random, thats why the net transversal components cancel $\rightarrow$ net magnetisation along longitudinal axis). WE DETECT ONLY THE TRANSVERSAL COMPONENT thats why with a tip angle of $\theta = 90°$ we get the best output. At $\theta = 180°$ there is now output at all (under best conditions)

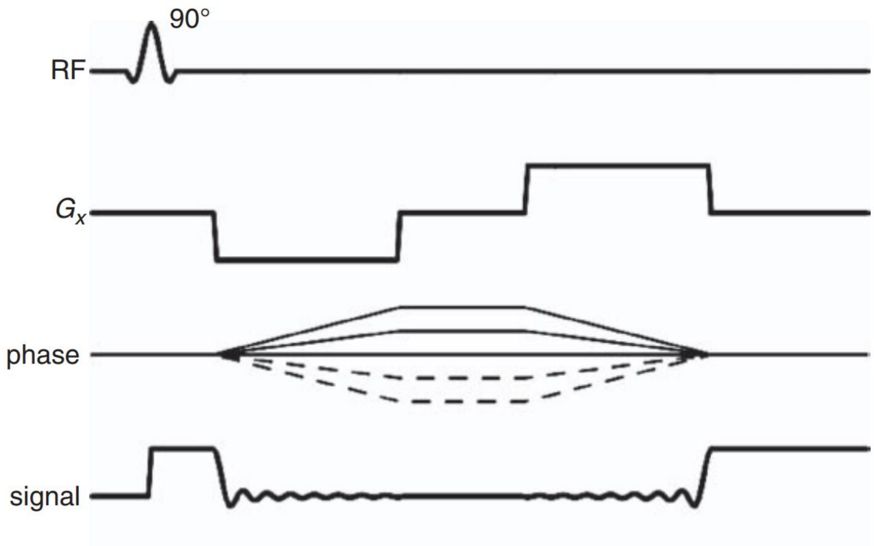


Figure 3: RF-Pulse with 90°

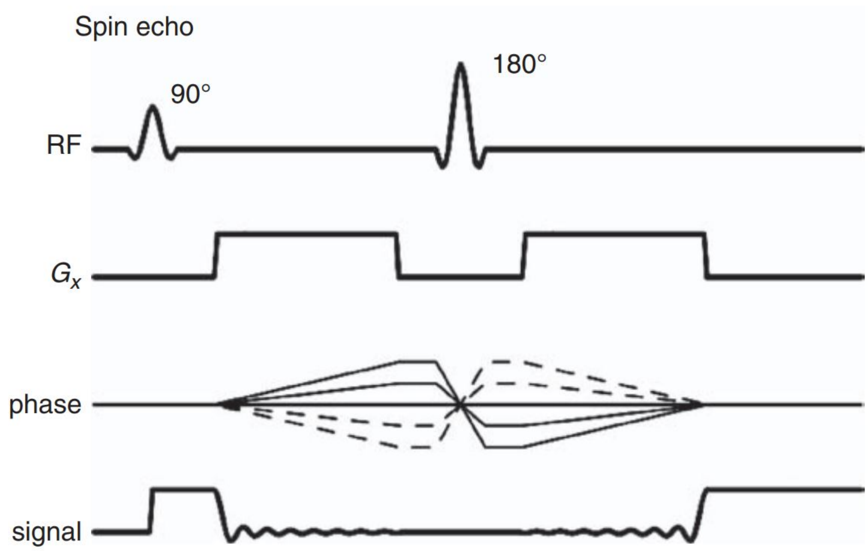


Figure 4: RF-Pulse first with 90° and then 180°

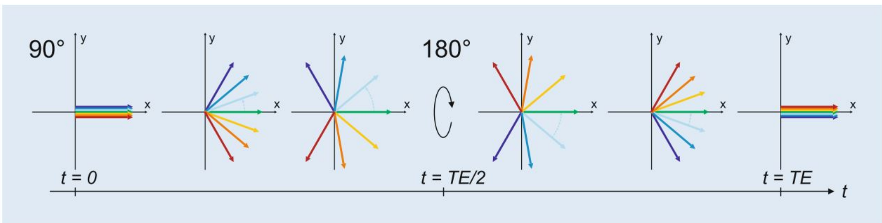


Abb. 3 ▲ Erzeugung eines Spinechos (SE) durch Refokussierung der Transversalmagnetisierungsvektoren: Nach der Anregung durch einen 90°-Puls laufen die Vektoren auseinander. Der 180°-Puls spiegelt die Vektoren an der x-Achse, sodass sie bis zum Echozeitpunkt *TE* refokussiert sind und das SE bilden

Figure 5: Veranschaulichung des Gradientenechos

6.)Fourier-Transformation: Beispiele im Zeit- und Frequenzraum (Sinus (un-)endlicher Dauer, Rechteck-Puls und sinc-Funktion, exponentielles Abklingen, Voigt-Profil, Schwebung). Hier ist ein grundlegendes Verständnis der Zusammenhänge wichtig, nicht so sehr die Mathematik dahinter: wie wirken sich Änderungen im Signal auf das Spektrum aus und umgekehrt. Time Domain Filters [5.3.2]

7.)Bloch-Gleichungen, Free Induktion Decay FID

- the bloch-equation is a macroscopic equation to calculate the nuclear magnetisation $M = (M_x, M_y, M_z)$ as a function of the ralaxation time T_1 and T_2 (empirical research)(also known as equation of motion of nuclear magnetization)

- bloch-equation are for liquid and in some cases are also for solid states

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{H}_a - \vec{e}_x\frac{M_x}{T_2} - \vec{e}_y\frac{M_y}{T_2} - \vec{e}_z\frac{M_z - M_0}{T_1} \tag{1}$$

$$\gamma\vec{M} \times \vec{H}_a = \text{is themagnetisation in the magnetic field} \tag{2}$$

- FID was first measured 1946 from Felix Bloch
- FID fourie transform nuclear magnetic resonance spectroscopy; observable NMR signal, which is generated by non-equilibrium nuclear spin; this signal gets measured in the detection coil, caused by the induction; Throughout the measuring process there is no high frequency exchange field, so this is called a „free“degeneration; this degeneration is an exponential decay; the magnetisation can be produced by applying a short pulsed radio frequency close to the Lamor frequency of the nuclear spin; the spin is precessing, so that the induced potential in the coil is oscillating; the measured data is then often digitised and then Fourier transformed to get an NMR frequency spectrum
- the enveloping S(t) from the amplitudes is described in the following

$$S(t) = S(0)exp\left(\frac{-t}{T_2}\right) \tag{3}$$

- often the amplitude decays much faster, because of T_2^*

8.)Longitudinale Spin-Gitter- sowie transversale Spin-Spin-Relaxation, T1[3.3], T2, $T2^*$**[4.3]**

- measure the time until the equilibrium state (GG-Lage)
- measure in 2 directions, T_1 & T_2
- T_1: longitudinal; parallel to B_0(in the z-Axis): time until the thermal equilibrium state (spin lettuce relaxation); describes from the magnetisation $M_{x,y}$to the M_0 state and as a result an longitudinal magnetisation M_z; T1 depends on the current state and the thermal equilibrium state, molecular dynamics and the strength of the magnetic field; exponentially process;the time when 63% of the magnetisation reached M_0 is called as the T_1-relaxation time

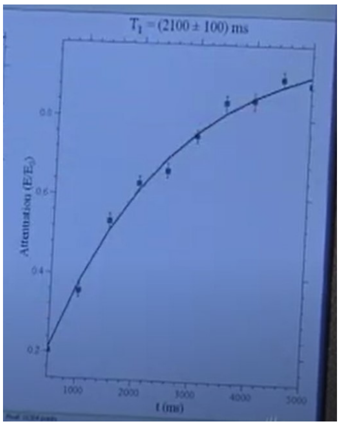


Figure 6: area under spectrum (tells the amount of MAGNETISATION after prepolarising pulse) against the DURATION of polarising pulse. Plateau value exists. single exp. fit → decay constant (T1)

$$M_z(t) = M_p(1 - exp(-t/T_1)) \tag{4}$$
$$\textbf{in the earth magnetic field} \tag{5}$$
$$M_z(0)\text{equal to}M_p \tag{6}$$
$$M_z(t) = M_p exp(-t/T_1) \tag{7}$$

- T_2: transverse (transversale Spin-Spin-Relaxation); perpendicular to B_0(in the x-y plane)
- T2 is one factor of the phase coherence loss, spin-spin relaxation
- spin-spin-relaxation: caused by magnetic dipole coupling between the two neighbour-spins (in homogeneous fields, this is the main reason for phase coherence loss)

$$S(t) = S_0 exp(-t/T_2) \tag{8}$$
$$S_0 = \text{initial magnitude at } t = 0 \tag{9}$$

for water the T2 time constant is in the order of couple seconds

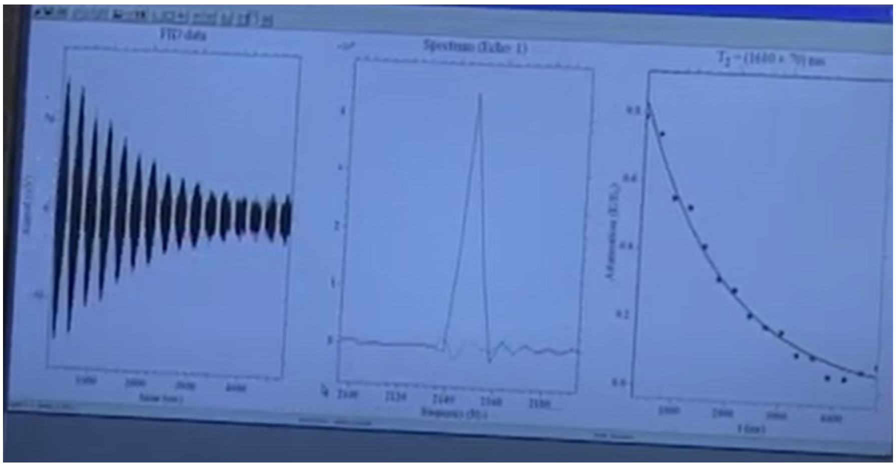


Figure 7: each echo is fourier transformed. area under spectrum (tells the size of each individual echo) at different echo times against the time. single exp. fit → decay constant (T2)

- in reality, the phase coherence losses come from spin-spin relaxation and the homogeneity of the magnetic field. Local homogeneity $\Longrightarrow$ a range of Larmor frequency. each nucleus has to the position associated frequency; the overall phase cohrence depends of all nuclei precessing at thesame frequency; frequency dispersion $\Longrightarrow$ loss of phase coherence and hence signal decay(weakens)
- $T2^*$ = T2 relaxation + field inhomogeneities

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma \Delta B_0 \tag{10}$$

$$T_2^* = \text{combined relaxation effect time} \tag{11}$$

$$S(t) = S_0 exp(-t/T_2^{ast}) \tag{12}$$

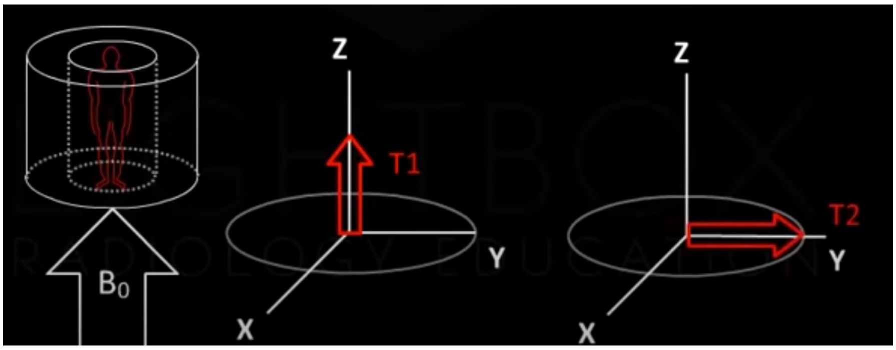


Figure 8: Visualisation of the T_1 and T_2 equibrilium state

9.)Relaxationskontrast; Einfluss paramagnetischer Ionen auf T1 und T2 [6.3]

- Der Kontrast zwischen einzelnen Gewebetypen (Muskeln, Bänder, Fett- und Bindegewebe) spielt in der klinischen Bildgebung eine große Rolle. Da die 1H-Konzentration überall nahezu gleich ist, muss der Kontrast über die Unterschiede in den Relaxationszeiten T1 und T2 generiert werden. Die Unterschiede beruhen einerseits auf der Struktur der Gewebetypen, können jedoch auch durch die Einnahme von Kontrastmitteln verstärkt werden.

10.)Hahn bzw. Spin-Echo, Carr-Purcell- und CPMG-Pulsfolge, 180°**x,** 180°**y, Phase**

- spin echo trick: produce inhomogenious field → different ω_L. At certain time flip spins over (turn magnetisation vectors (slow spins at the front and fast spins in the back)) using transvers oscilliating magnetic field → at the startpoint they are at the same place again. ; start with 90° pulse and wait till the magnetisation decay away (spins are out of phase again) then aply 180° pulse

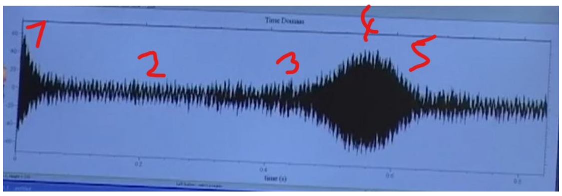


Figure 9: spin echo trick: point 1 (1ms) 90° pulse. Fast decay due to inhomogenious magnetic field. At point 2 180° pulse (this is the point when the spin flips and get in sync again). at point 3 the spins (slow and fast) have different precession frequencies. At point 4 (echo) both spins are back in step. At point 5 the fast ones are at the front and the slow in the back → out of phase again.

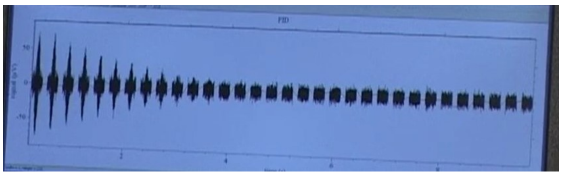


Figure 10: (Carr-Purcell) CPMG: This spin echo trick can produced several times (more 180° pulses (Gaps: because have to turn off the reciever). Amplitude dies away with time (T2 relaxation; irreversible effect); T1 is the relaxation into thermal equilibrium

11.) Resonanzbedingung im LCR-Schwingkreis (Empfang des NMR-Signals) [1.3.2]

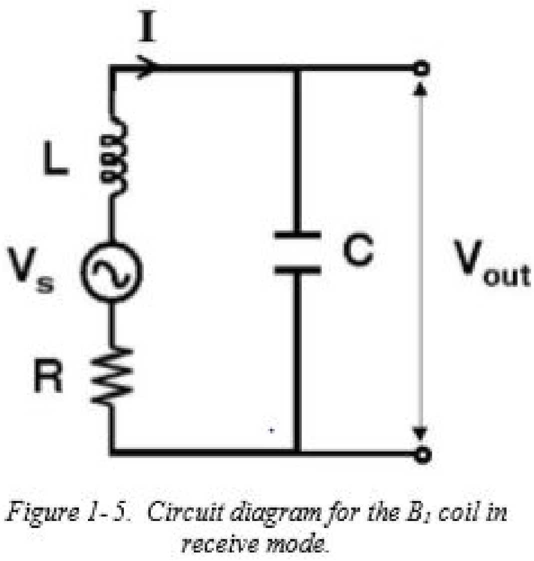


Figure 11: The structural setup for the measuring method

- A LCR-circuit is the measure methode in the inner cooil of the set up
- B_1 coil an inductor with inductance L, and internal resistance R; connected to a fixed capacitance C in spectrometer
- resonate frequency $\omega_0 = \frac{1}{\sqrt{LC}}$
- V_s is the induced voltage through the B_1 magnetic field, because of the precessing nuclear magnetism of the sample;

$$Z_{eq} = Z_R + Z_L + Z_C = R + i(\omega L - \frac{1}{\omega C)} \tag{13}$$

$$I = \frac{V_s}{Z_{eq}} = \frac{V_s}{R + i(\omega L - \frac{1}{\omega C)}} \tag{14}$$

$$\xrightarrow{\omega_0 = \frac{1}{\sqrt{LC}}} I = \frac{V_s}{RS} \tag{15}$$

therefore the output voltage V_{out} at resonance of ω_0 ist

$$|V_{out} = |IZ_C| = \frac{|V_s|}{R\omega_0 C} = \frac{|V_s|\omega_0 L}{R} = |V_s|Q \tag{16}$$

where Q is the quality factor$\Longrightarrow$ the LCR circuit amplifies the input/signal voltage with the factor Q.

$$Q = \frac{f_0}{\Delta f} = \frac{\omega_0}{\Delta \omega} \tag{17}$$
$$= \frac{\omega_0 L}{R} \tag{18}$$

Q factor describes the width of the resonance peak
higher Q $\longrightarrow$ narrower the peak $\longrightarrow$ bigger the amplification of the LCR

- in the NMR the signal to ratio(Verhältnis vom Signal zum Rauschen) is often more interesting than the signal level. The reason for this is, that beside the fact, that the signal is getting tuned by Q, also the noise gets tuned by the LCR. (Only the case by resonance).
  At other frequency there is a attenuation and therefore the signal to noise ratio is boosted, of the detected signal(important: detection bandwidth is bigger than linewidth NMR)

12.)Aufbau der Terranova-Spule(n) [1.2]; Kompensation von Magnetfeldinhomogenitäten: Shimming; Gradientenfelder [7.3]

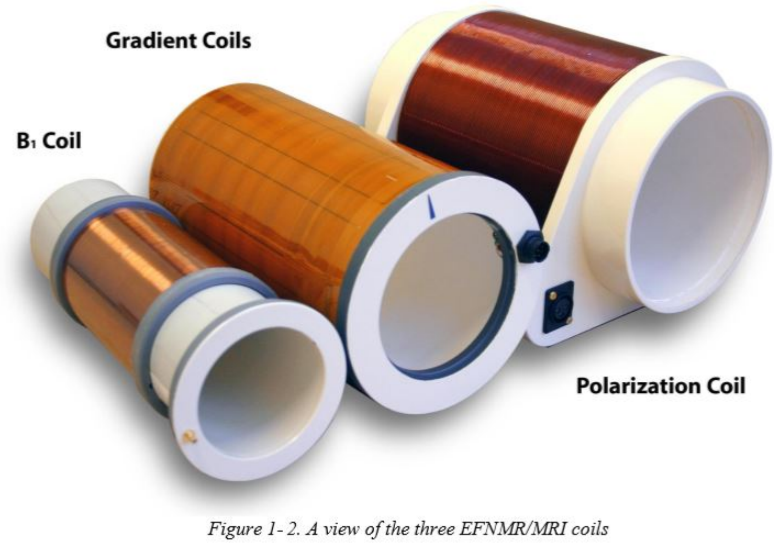


Figure 12: This is the set up for the experiment. There are three solenoids, but in the experiment they are in the biggest coil with the sample

- Gradientenfelder (WICHTIG: ein Gradient in x-,y-,z-Richtung bedeutet, dass der Betrag von B0 bei Bewegung parallel zur x-, y- oder z-Achse linear variiert, nicht aber, dass B_0 zusätzliche Anteile in diese Richtung erhält! B0 zeigt immer in dieselbe Richtung. Gradient Gi = dBz/di , i = x, y, z)

- 2 coaxial solenoids(Magnetspulen) and a third tube, which are 4 coils to generate a x,y,z gradients.(there are 2 x-coils, one for imaging an shimming; one for pulsed gradient NMR)
- the biggest coil has got a high current; which provides a B_p polarising magnetic field, where the nuclear magnetisation from the sample is established(in the experiment, this magnetisation is 350times bigger than the earth magnetic field, so the signal is also 350times bigger than in the earth magnetic field) It' s activatet fora few seconds, so thematerial gets a magnetisation and after turning of, there is still a magnetisation, which can be measured;the middle/gradient coil makes an linear magnetic field gradient(two important factors: 1.) correct the earth magnetic field by applying a small current(inhomogenity occurs by metal in the room...), 2.)by variing the magnetic field with the coil, it is possible to produce a Lamor frequency, which depends from the pales of the nuclei, ; the inner coil is used to excite and detect the precessing magnetisation
- shimming: adjust current in gradient coil to improve homgenity of magnetic field (narrower peak in the spectrum)

13.)Erdmagnetfeld: Dipolfeld, Flussdichte, Orientierung; Ausrichtung der Terrranova-Spule im Erdmagnetfeld [1.4]

- earth magnetic field 50mT $\Longrightarrow$ leads to a Lamor frequency of a few kilo Hertz for the Hydrogen atom

14.) Besonderheiten EFNMR: Vorpolarisierung (pre-polarisation) [2.3.2], Empfindlichkeit, Probenvolumen

15.) MRI – Magnetic Resonance Imaging, Magnetresonanz-Bildgebung [7.3]

- Variiert das Magnetfeld Bz linear entlang der x-Achse, so hängt die Larmor-Frequenz jedes 1H-Atoms von dessen Position entlang der x-Achse ab. Jedem Frequenzwert im Spektrum kann deshalb eine x-Position zugeordnet werden. Das Spektrum zeigt dann das Profil der 1H-Verteilung entlang der x-Achse.

16.) k-Raum, Fouriertransformation in den realen Raum [7.3.2]

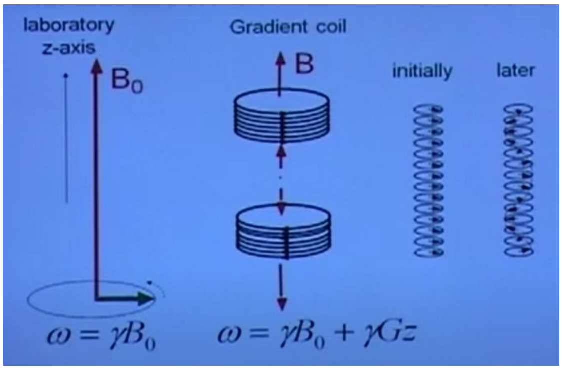


Figure 13: Additional el. mg. field to B_0, therefore $\omega_L = \gamma B_0 + \gamma G z$. G units in $\frac{T}{m}$.$\gamma G z$ angular frequency. In 3 dimensions $G = \vec{G} = \Delta B$ and $z = \vec{r}$; simply write all with vectors

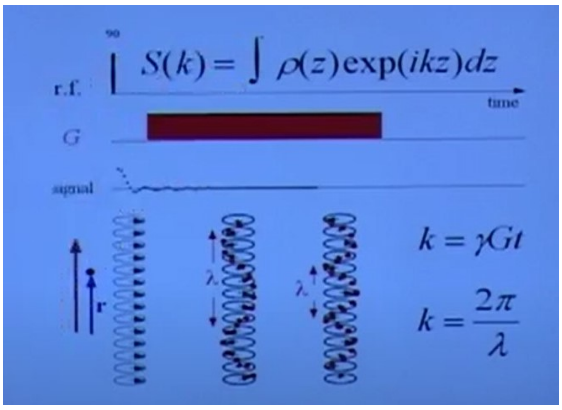


Figure 14: MRI k-space. λ gets smaller by time and k gets bigger. $\rho(z)$ says how many nuclei are at position z. $S(k)$ is the signal. 3 dimensions simply write vectors everywhere

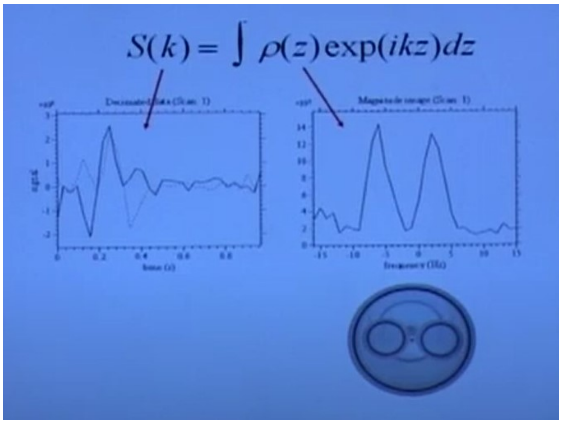


Figure 15: Relation between $S(k)$ and the fourier transformed (MRI image for 2 water-tubes).

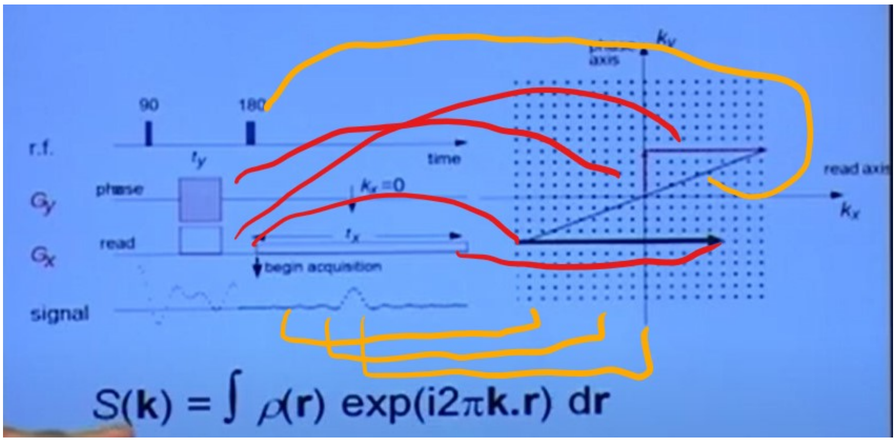
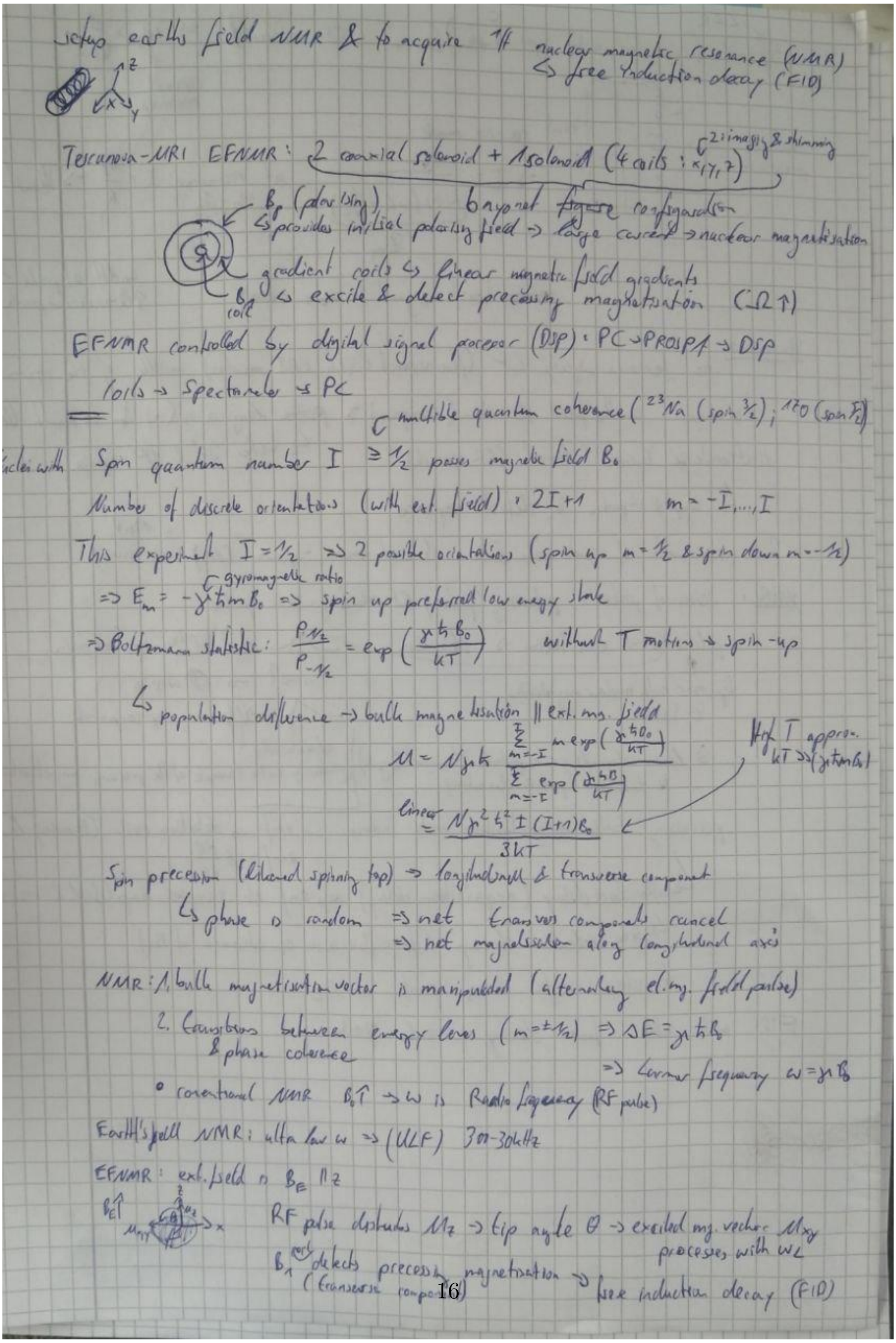


Figure 16: Priciple of MRI. vary G_y so that very point at the grid is scanned. After fourier transform image is visible.
!Question: why do we need the invertation? Couldn't we apply negativ G_y and G_x ?!! $S(k)$ Signal looks like defraction pattern, only after fouriertransformation the image appears.

17.) J-Kopplung; Strukturanalyse; Spektrum von 2,2,2-Trifluorethanol (CAS 75-89-8) [12.3]

- Die Wechselwirkung der Kernspins benachbarter Atome ermöglicht es, die Struktur von Molekülen aufzuklären. Jedes magnetische Moment eines an der Wechselwirkung beteiligten Kerns mit Kernspin I beeinflusst das lokale Magnetfeld B0 des anderen Kerns derart, dass 2I+1 mögliche Flussdichten für 2I+1 mögliche Larmorfrequenzen sorgen. Im Spektrum, über alle Kerne integriert, erscheinen also 2I+1 Linien. Sind mehr als zwei Kerne an der Wechselwirkung beteiligt, ergeben sich zusätzliche Linien und die Linienintensitäten sind nicht mehr gleich

1 Usermanual zusammenfassung Seite 1-21 in der Pdf



setup earths field NMR & to acquire 1H nuclear magnetic resonance (NMR)
↳ free induction decay (FID)

Terranova-MRI EFNMR: 2 coaxial solenoid + 1 solenoid (4 coils: x, y, z) — 2: imaging & shimming
bayonet ~~figure~~ configuration

B_p (polarising) ↳ provides initial polarising field → large current → nuclear magnetisation
gradient coils ↳ linear magnetic field gradients
B_1 coil ↳ excite & detect precessing magnetisation ($\Omega\uparrow$)

EFNMR controlled by digital signal processor (DSP): PC → PROSPA → DSP
coils → Spectrometer → PC

multiple quantum coherence (^{23}Na (spin $\frac{3}{2}$); ^{17}O (spin $\frac{5}{2}$))

Nuclei with Spin quantum number $I \geq \frac{1}{2}$ posses magnetic field B_0

Number of discrete orientations (with ext. field): $2I+1$ $m = -I, \dots, I$

This experiment $I = \frac{1}{2}$ ⇒ 2 possible orientations (spin up $m = \frac{1}{2}$ & spin down $m = -\frac{1}{2}$)

⇒ $E_m = -\gamma \hbar m B_0$ (γ: gyromagnetic ratio) ⇒ spin up preferred low energy state

⇒ Boltzmann statistic: $\frac{P_{1/2}}{P_{-1/2}} = \exp\left(\frac{\gamma \hbar B_0}{kT}\right)$ without T motions → spin-up

↳ population difference → bulk magnetisation ∥ ext. mag. field

$$M = N \gamma \hbar \frac{\sum_{m=-I}^{I} m \exp\left(\frac{\gamma \hbar B_0}{kT}\right)}{\sum_{m=-I}^{I} \exp\left(\frac{\gamma \hbar B_0}{kT}\right)} \overset{\text{linear}}{=} \frac{N \gamma^2 \hbar^2 I (I+1) B_0}{3kT}$$

High T approx. $kT \gg |\gamma \hbar m B_0|$

Spin precession (like a spinning top) → longitudinal & transverse component
↳ phase is random ⇒ net transverse components cancel
⇒ net magnetisation along longitudinal axis

NMR: 1. bulk magnetisation vector is manipulated (alternating el.-mag. field pulse)
2. transitions between energy levels ($m = \pm\frac{1}{2}$) ⇒ $\Delta E = \gamma \hbar B_0$
& phase coherence
⇒ Larmor frequency $\omega = \gamma B_0$

- conventional NMR $B_0 \uparrow$ → ω is Radio frequency (RF pulse)

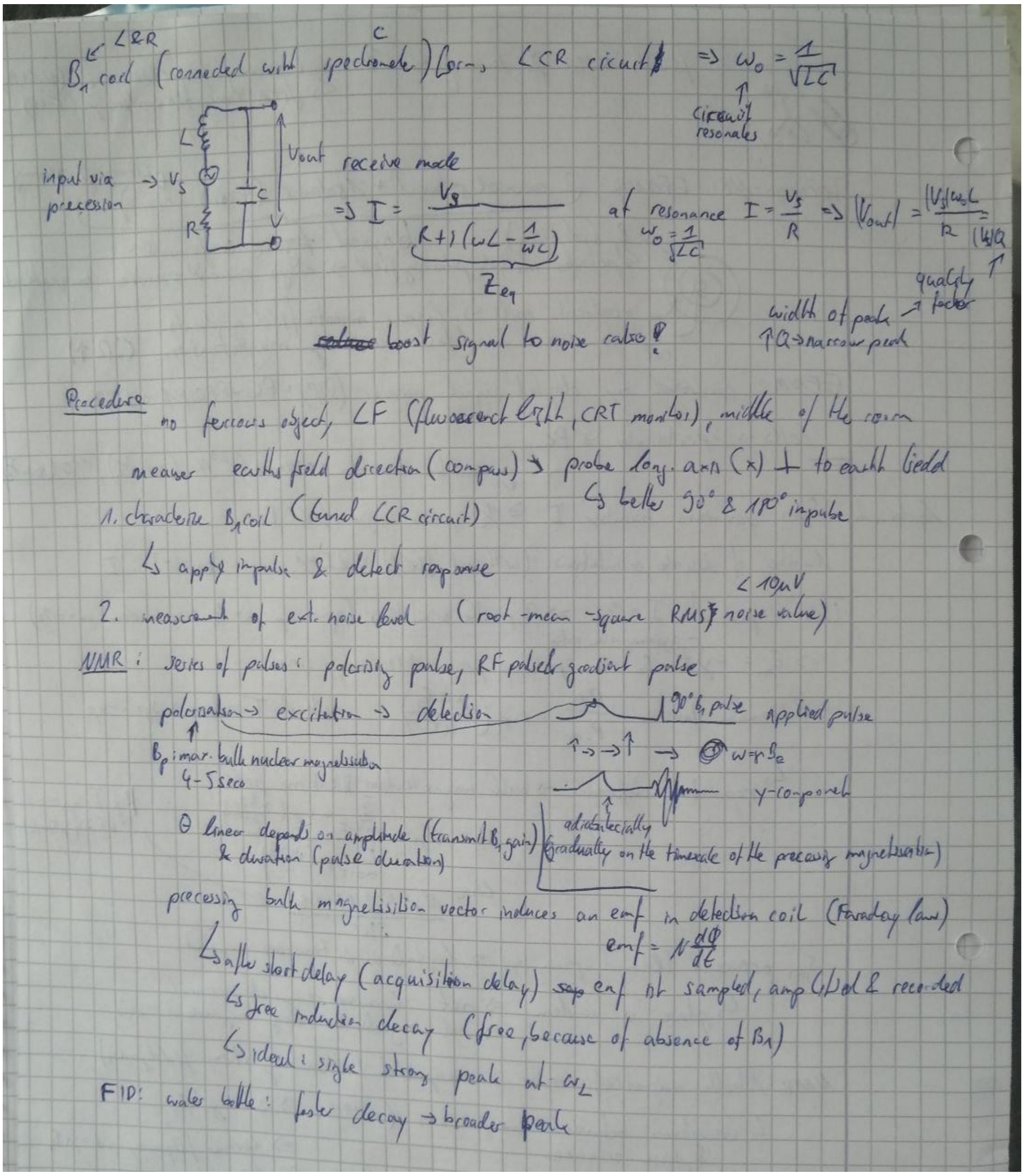
Earth's field NMR: ultra low ω → (ULF) 300-30kHz

EFNMR: ext. field is B_E ∥ z

RF pulse disturbs M_z → tip angle θ → excited mag. vector M_{xy} processes with ω_L

B_1 coil detects precessing magnetisation (transverse component) → free induction decay (FID)

Figure 17



B_1 coil (connected with spectrometer) forms LCR circuit $\Rightarrow \omega_0 = \frac{1}{\sqrt{LC}}$

circuit resonates

input via precession $\rightarrow V_S$

V_{out} receive mode

$\Rightarrow I = \frac{V_S}{\underbrace{R + i\left(\omega L - \frac{1}{\omega C}\right)}_{Z_{eq}}}$

at resonance $\omega_0 = \frac{1}{\sqrt{LC}}$: $I = \frac{V_S}{R} \Rightarrow |V_{out}| = \frac{|V_S|\omega_0 L}{R} = |V_S| Q$

quality factor

width of peak

$\uparrow Q \rightarrow$ narrow peak

~~[illegible]~~ boost signal to noise ratio!

Procedure

no ferrous object, LF (fluorescent light, CRT monitor), middle of the room

measure earths field direction (compass) $\rightarrow$ probe long. axis (x) $\perp$ to earth field

$\hookrightarrow$ better $90°$ & $180°$ impulse

1. characterize B_1 coil (tuned LCR circuit)

$\hookrightarrow$ apply impulse & detect response

2. measurement of ext. noise level (root-mean-square RMS noise value) $< 10\mu V$

NMR: series of pulses: polarising pulse, RF pulse & gradient pulse

polarisation $\rightarrow$ excitation $\rightarrow$ detection

$90°$ B_1 pulse applied pulse

B_p max. bulk nuclear magnetisation 4–5 secs

$\omega = \gamma B_e$

y-component

adiabatically (gradually on the timescale of the precessing magnetisation)

θ linear depends on amplitude (transmit B_1 gain) & duration (pulse duration)

precessing bulk magnetisation vector induces an emf in detection coil (Faraday law)

$emf = N\frac{d\Phi}{dt}$

$\hookrightarrow$ after short delay (acquisition delay) ~~sep~~ emf is sampled, amplified & recorded

$\hookrightarrow$ free induction decay (free, because of absence of B_1)

$\hookrightarrow$ ideal: single strong peak at ω_L

FID: water bottle: faster decay $\rightarrow$ broader peak

Figure 18