2 Excitation and detection in NMR

2.1 RF pulses in NMR

To probe the nuclear magnetisation, magnetic pulses are applied to excite transitions between the Zeeman energy levels. These magnetic fields are conventionally known as B_1 and are not static (like B_o) but are oscillating at frequency ω_1 (which must be close to the Larmor frequency). For protons at 1T the Larmor frequency is 42.57 MHz, which is in the RF range. Therefore this excitation B_1 field is often known as the RF field. The B1 field typically points along the x or y direction, but we shall see shortly that this field is effectively circularly polarized, (ie rotating in the xy plane).

A special coil (antenna) is used to produce the RF field; the coil is tuned to the appropriate resonant frequency.

<u>The rotating frame</u>

It is usually think of RF pulses in rotating frame. The lab frame is defined to have coordinates x, y & z. In the lab frame the B_1 field is rotating.

Now imagine standing on a record player that is rotating at the the frequency of the RF pulse ω_1. Define a new rotating frame of reference on the record (x^1 y^1 z^1). In this frame the B_1 field is stationary (ie not rotating). The lab frame and rotating frame are related by:

- $z^1 = z$
- x^1 rotating at frequency ω_1 with respect to x.
- y^1 rotating at frequency ω_1 with respect to y.

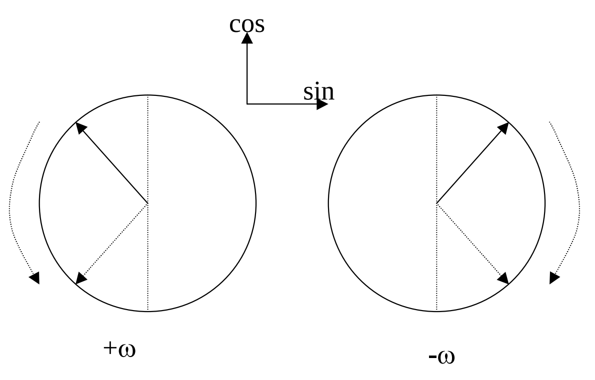

Fig. 1 A sinusoidally varying field can be decomposed into two counter-rotating circularly polarized fields.

<u>What happens to the NMR in the the rotating frame?</u>

To transform the spins into the rotating frame a fictitious field of amplitude ω_1/γ must be applied (to cancel their rotation). If ω_1 is close to the Larmor frequency, then the up shot of this is that B_o transforms to (approximately) zero in the rotating frame (this makes sense as spins aren't precessing about z in that frame).

<u>Circular Polarization</u>

An RF magnetic field pointing along x axis and varying sinusoidally in amplitude is equivalent to 2 circulating polarised magnetic fields rotating at ± ω_1. This is because the cos components reinforce each other whilst the sin components cancel each other (fig 1). Therefore the RF field corresponds to 2 rotating magnetic fields at + ω_1 and $-\omega_1$

The component at $+\omega_1$ appears stationary in rotating frame

The component at $-\omega_1$ seems to be rotating at $-2\omega_1$ and can be ignored

In the rotating frame, the only field acting is now the RF field (which is usually called B_1) (the static field B_o has transformed to zero). The magnetisation will now precess around B_1, and so the bulk magnetisation rotates in y^1 z^1 plane.

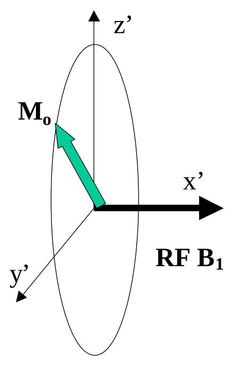

Fig. 2 Magnetisation tipped by an RF pulse in the rotating frame.

Therefore the duration (τ) and strength (B_1) of the RF pulse determines tip/flip angle (α) of an RF pulse (that is the angle through which the bulk magnetisation is rotated by the pulse).

$$\alpha = \gamma B_1 \tau$$

- A 180 ^{o} pulse will flip the magnetisation to –z and it is said that the magnetisation is inverted. We will see that this pulse can also refocus magnetisation.
- A 90^o pulse will flip the magnetisation to the xy plane and it is said that the magnetisation is excited or saturated.
- More generally a θ^o pulse acting on equilibrium magnetisation will reduce M_z from M_o to $M_o\cos(\theta)$, and increase M_{xy} to $M_o\sin(\theta)$

The NMR signal is an RF signal, and so is the excitation pulse. However the excitation pulse is enormous compared to the signal. Therefore the RF pulse could saturate or even damage the receiver, so during the application of an RF pulse the receiver is gated off.

2.2 Signal detection

As explained above, after a 90^o pulse the bulk magnetisation has been tipped into the x-y plane (all the spins are in phase with no net population difference between the up and down states).

Once the RF pulse is switched off, we can see that the xy magnetisation created by a pulse, will now precess about the main field B_o so that it rotates at the Larmor frequency.

This rotating magnetisation induces an oscillating e.m.f. in a pick-up coil that is tuned to RF frequencies (this is frequently the same coil that was used to produce the RF field to excite the magnetisation. The e.m.f. is detected via a phase sensitive detector, which is described below.

2.2.1 Phase sensitive detection (PSD)

As we shall see later, it is important to know the exact frequency of the received signal as this is used to encode images, as well as to perform spectroscopy in analytical NMR.

However it is difficult and unnecessary to handle signals that are oscillating at RF frequencies. Instead the signal is compared to some reference frequency, so that only the difference in frequency between the signal and reference frequency (usually in the audio range) is digitised and stored. This comparison is achieved by phase sensitive detection.

Let be the oscillator frequency, which determines the frequency of the transmitter and receiver, and which is in general set to be equal to the mean Larmor frequency of the sample. In practice the Larmor frequency varies across whole sample, as the local static field varies across the sample.

The signal from the scanner (v_i) is compared to a reference signal (v_r), which is oscillating at the same frequency as the transmitter.

$$v_i = v_{io} \cos \omega_i t$$
$$v_r = v_{ro} \cos \omega_o t$$

These signals are multiplied together so that the detected signal is given by

$v_d = v_{io} v_{ro} \cos \omega_i t \ \cos \omega_r t = ½\, v_{io} v_{ro} (\cos (\omega_1 - \omega_r)t + \cos (\omega_1 + \omega_r)t$

The detected signal is passed through a low pass filter so that the $(\omega_1 + \omega_r)$ term is filtered out, and the final detected signal oscillates at difference in frequency between the input signal and the oscillator, as required.

2.2.2 Quadrature phase sensitive detection

This makes it possible to distinguish between positive and negative differences in frequency (e.g. how can you distinguish 49 from 51Hz?).

Quadrature detection uses 2 PSDs with 90^o phase shifts between the reference signals.

$v_d^{re} = ½\, v_{io} v_{ro} \cos (\omega_1 - \omega_r)t$

$v_d^{im} = ½\, v_{io} v_{ro} \cos ((\omega_1 - \omega_r)t + 90) = ½\, v_{io} v_{ro} \sin (\omega_1 - \omega_r)t$

By comparing these two signals you can detect the circular motion of the magnetisation (compare with fig. 1). The resulting signal is usually considered to be complex, hence the labels ‘re’ and ‘im’.

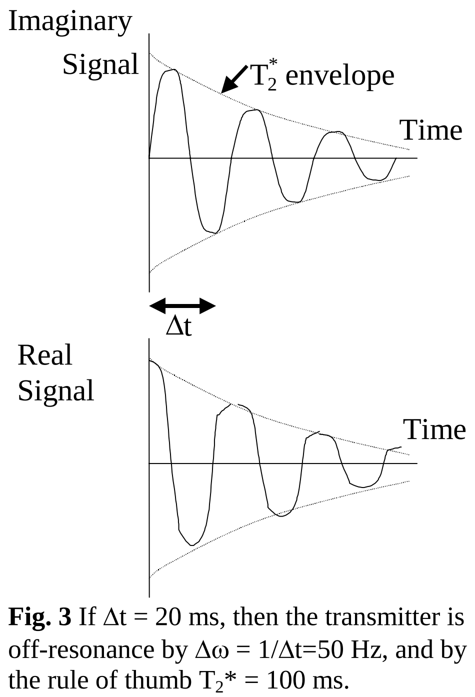

Fig. 3 If Δt = 20 ms, then the transmitter is off-resonance by $\Delta\omega = 1/\Delta t$=50 Hz, and by the rule of thumb T_2^* = 100 ms.

2.3 FID: free induction decay

This is the basic form of the signal detected in NMR. In general the signal from the sample is not at the same frequency as the oscillator reference frequency ω_o, so that after the PSD the signal oscillates at $(\omega_o - \omega_s) = \Delta\omega$. Furthermore the signal decays exponentially with a decay time T_2^* so that the typical signal from slice off resonance by 50Hz from the transmitter would look like that in the figure 3. (As a rule of thumb, the signal decays to nothing in a time equal to $5T_2^*$).

2.4 Outline of an NMR scanner

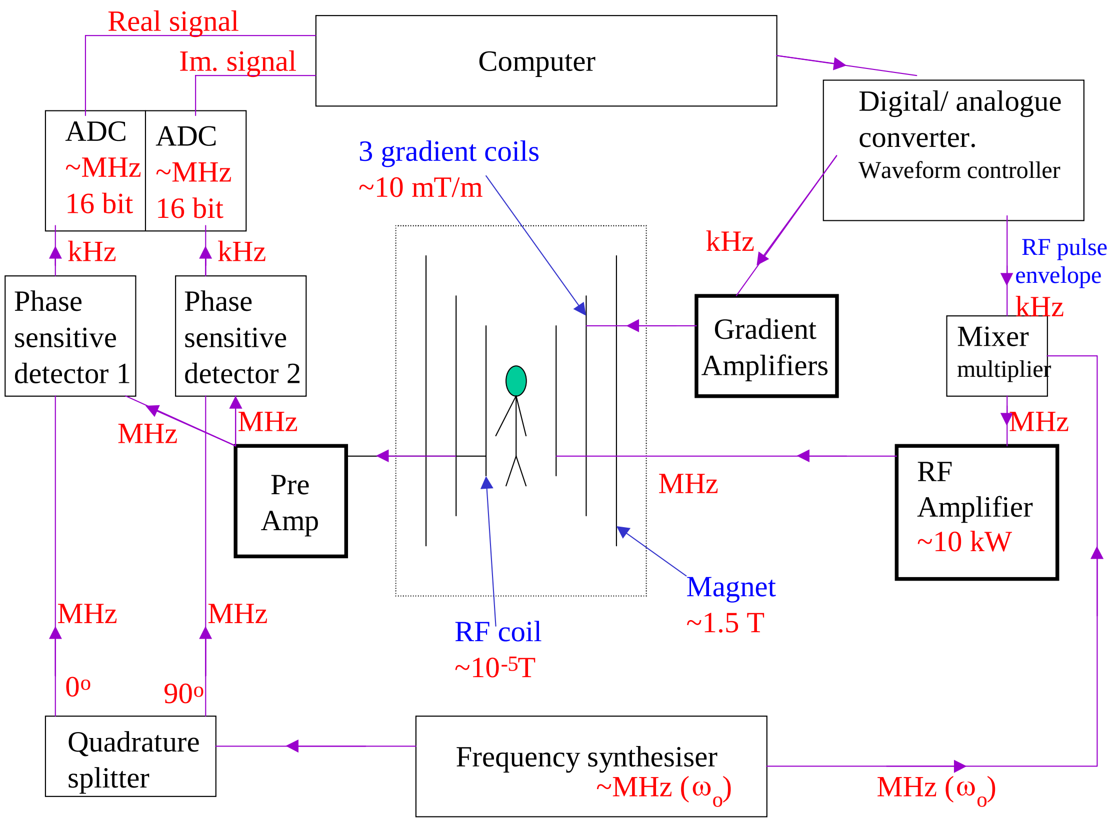

Fig. 4 Outline of an NMR imaging scanner. There is a **blank** version of this figure available on the website for you to practice filling in.

Producing an RF pulse: The computer sends the desired pulse (e.g. 90^{o}) to the waveform controller, which produces the appropriate analogue audiofrequency modulation, defining the shape of the RF pulse (see section 4). The frequency synthesiser produces the carrier RF frequency, which is set to be at the mean Larmor frequency of the whole sample. This is multiplied with the RF pulse envelope in the mixer, giving and RF modulated pulse. This is then passed to an RF amplifier before being sent to the RF coil.

Detecting Signal: The frequency synthesiser is also fundamental to signal detection. First the reference signal from the synthesiser (which is close to the Larmor frequency) is passed through a quadrature splitter, producing two reference signals that are 90^{o} out of phase with each other. The signal detected in the RF coil is first sent to a pre amp, to ensure that the final signal to noise ratio is dominated by the coil and sample, not the later electronics. It is mixed with the reference signals in the two quadrature (90^{o} out of phase) phase sensitive detectors (p.s.d.s). This demodulates the signals down to audio frequencies, and the signals are then sent to two analogue to digital converters, before being acquired by the computer where they are processed and stored.

Gradients: As we will see later, magnetic field gradients are used to encode image information. The Waveform controller also produces analogue gradient waveforms that are amplified by gradients amplifiers before being used to drive the gradient coils.