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JÜLICH FORSCHUNGSZENTRUM

Magnetic Resonance Imaging

Introduction to MRI

Ezequiel Alejandro Farrher

Outline

- Introduction
  - Magnetic Resonance Imaging
  - Some Examples
- MR Scanner Components
- Physical Introduction
  - Spin ½ in B_0
  - Larmor Precession
  - Resonance (excitation and signal reception)
  - Relaxation
  - FID, Echoes and Fourier Transform
  - Basic Idea of MR Imaging
- Basic Safety Issues

Magnetic Resonance Imaging

MRI is a tomography method but it is very different from CT (Computer Tomography)

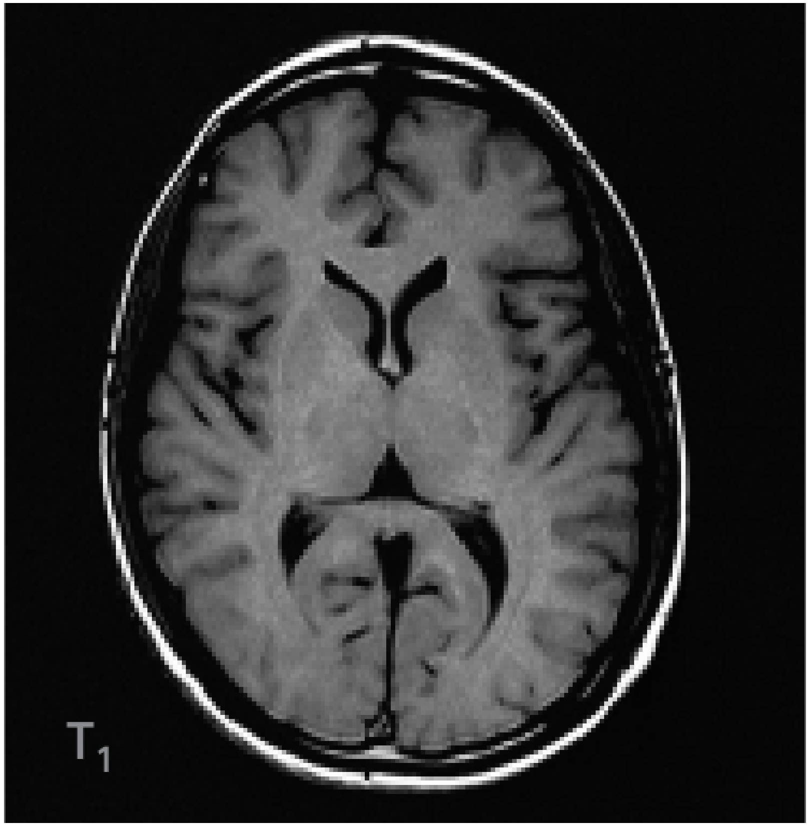
Some positive characteristics of MRI:

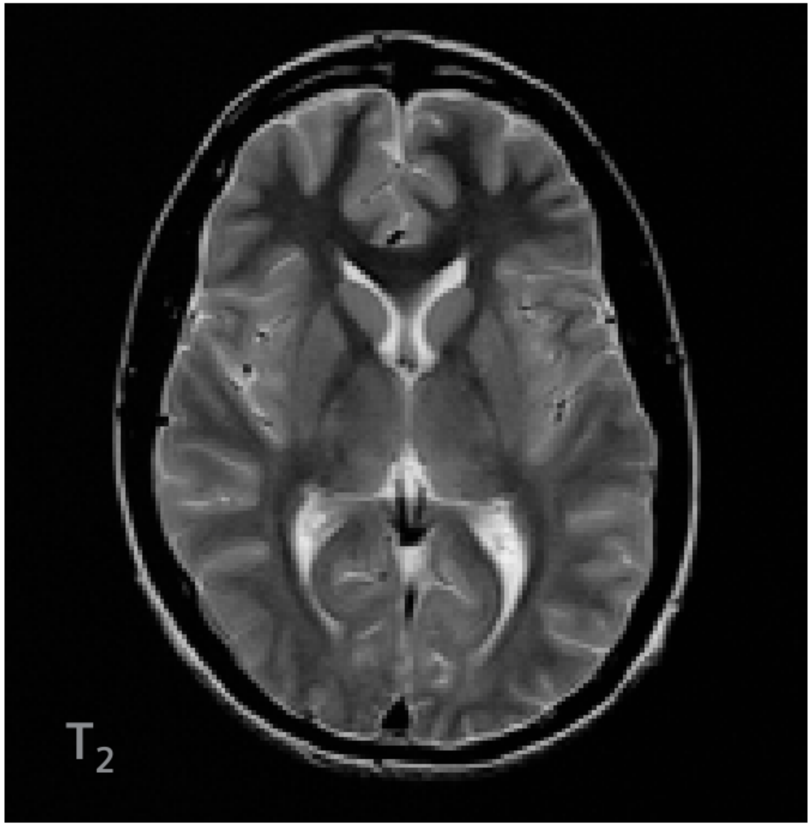
Non-ionising	*Using radio-waves, not X-rays*
Non-invasive	*No contrast agents required*
Soft-tissue sensitive	*MRI signal ~ Proton density ρ ~ H_2O*
Quantitative	*MRI signal ~ Magnetisation = $f(\rho, T_1, T_2, T_2^*, D, \alpha, \ldots)$* *➔ density, relaxometry, diffusivity, perfusion, …*
Multi-contrast	*Various imaging sequences/ parameters*
Multi-purpose/modal	*Anatomy, activity, connectivity, vessels, …*
Oblique slices	*Flexible spatial encoding with arbitrary image slice orientation.*

<u>MRI weakness</u>:

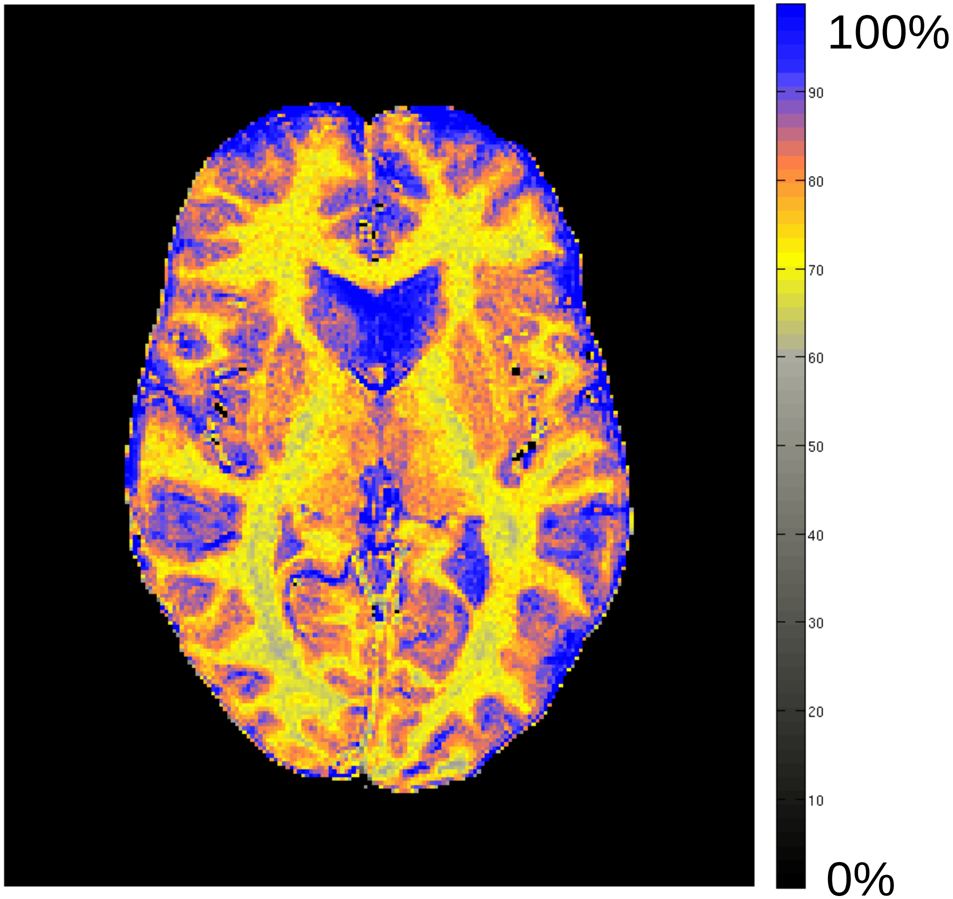
low signal-to-noise ratio *and* (conventional) MRI not usable for materials with little water content

Examples: Multi-Contrast (T1/T2-weighting)

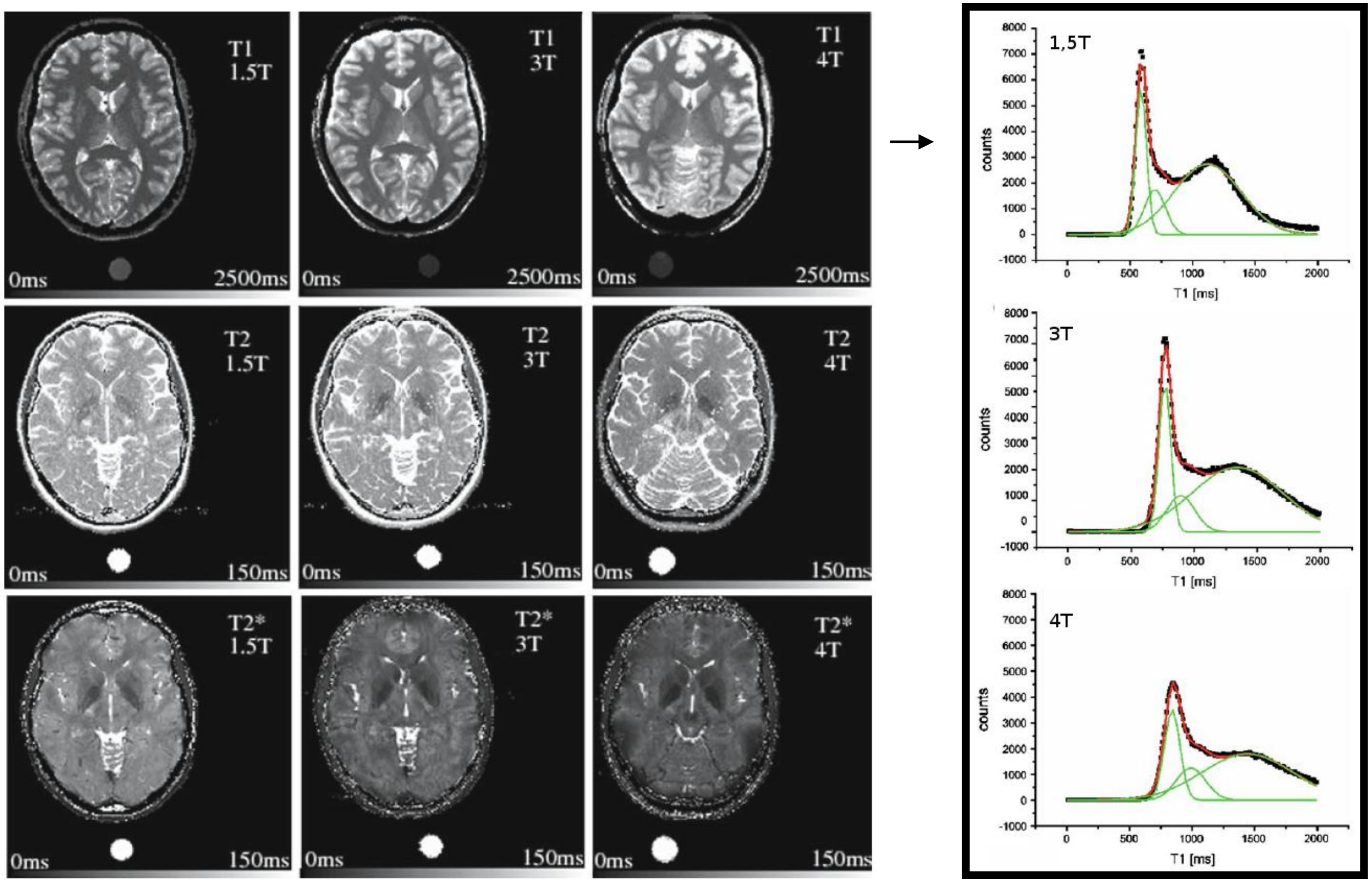




Examples: Quantitative – Watermap



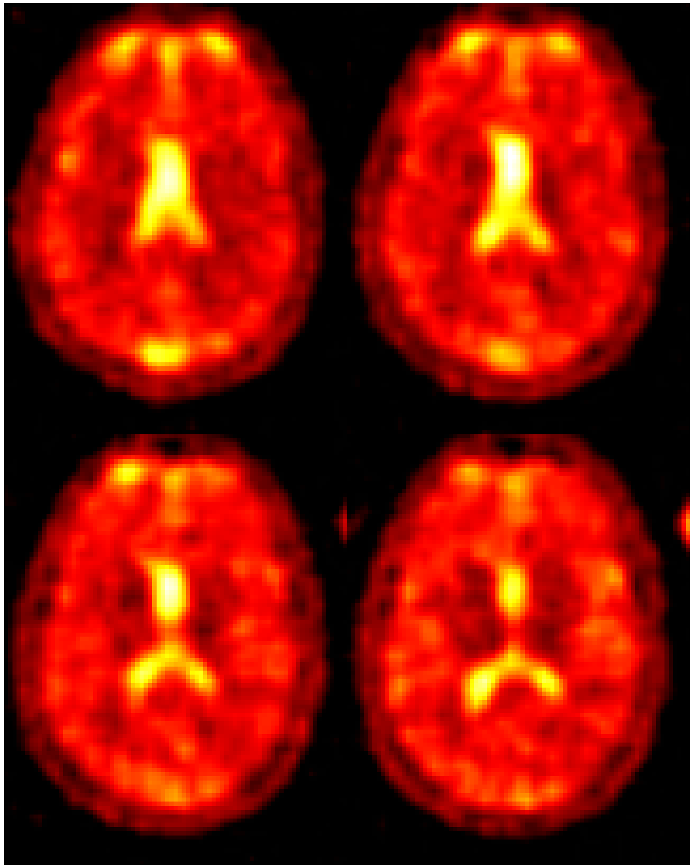
Examples: Quantitative – Relaxometry



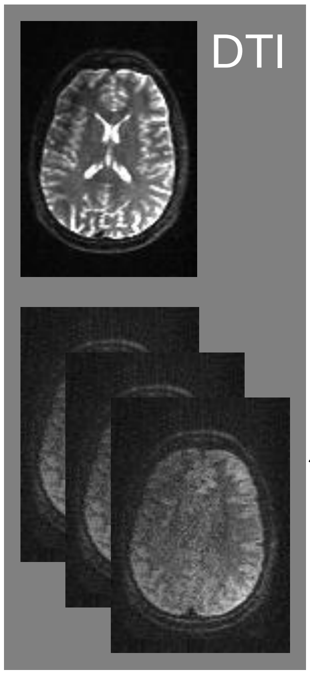
Oros-Peusquens AM, Laurila M, Shah NJ. Magnetic field dependence of the distribution of NMR relaxation times in the living human brain. Magn Reson Mater Phy. 2008;21:131-147.

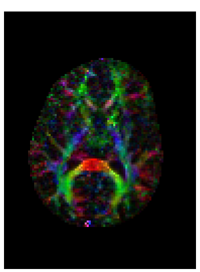
Examples: Vessels (Angiography)

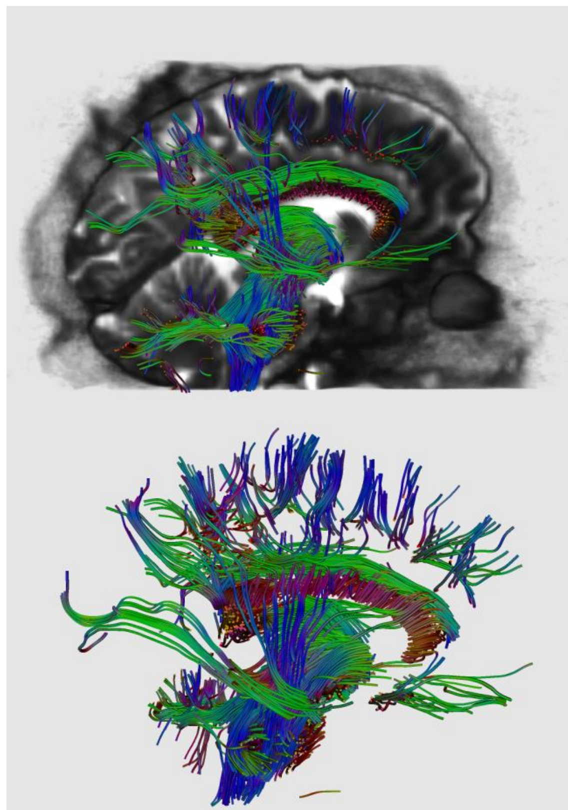
Examples: Metabolism (^{23}Na-Imaging)

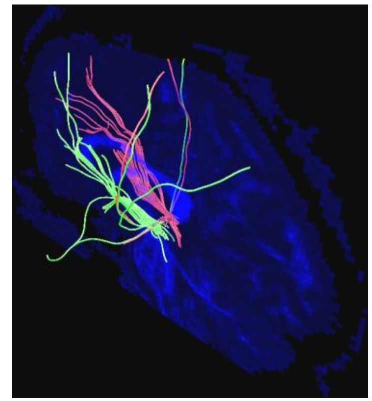


Examples: Structural connectivity / DTI









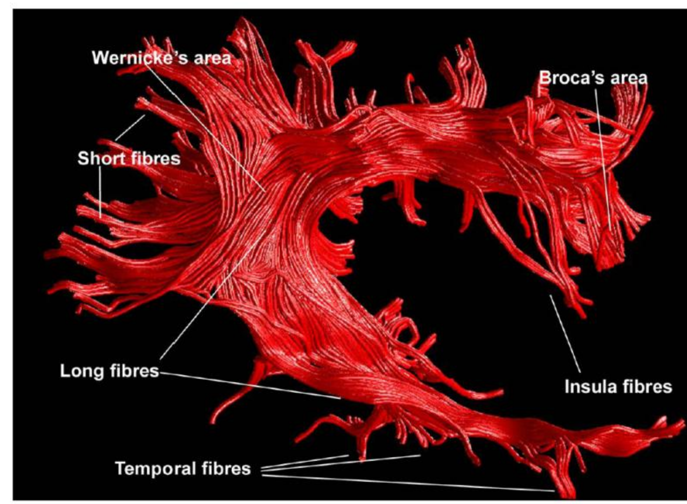
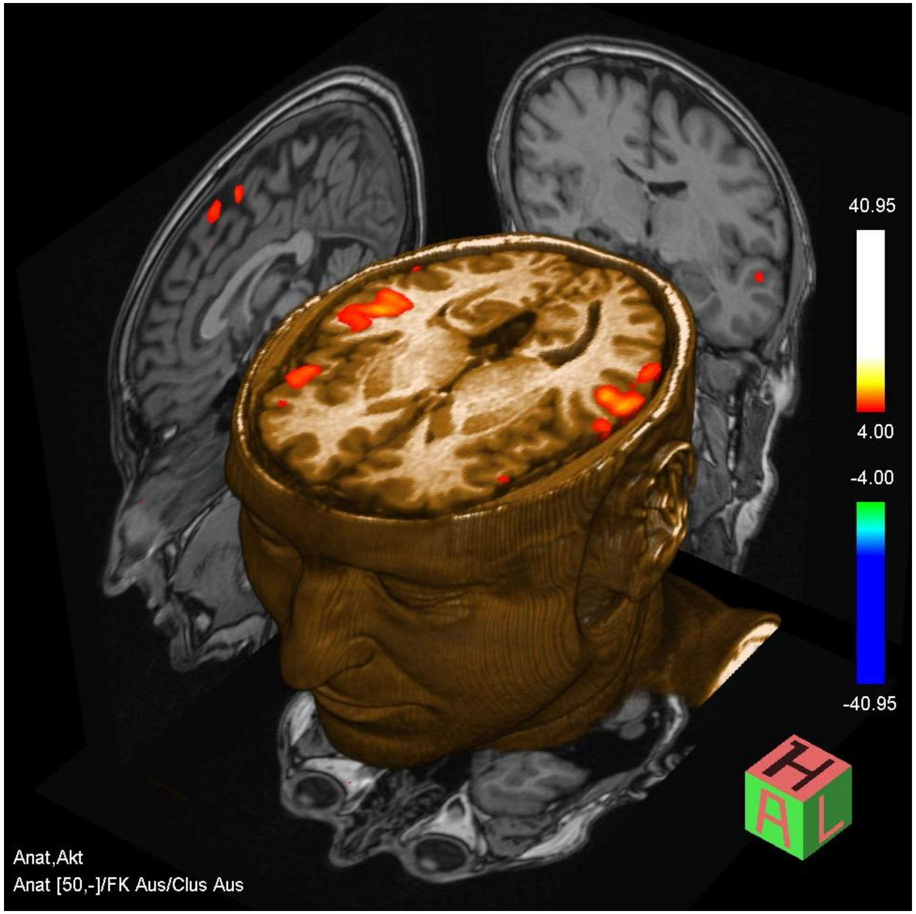


Figure 1. Streamline reconstruction of the superior longitudinal fasciculus (image courtesy Derek Jones).

Examples: Function / Activity (fMRI)



http://www.radiologie.ruhr-uni-bochum.de/imperia/md/images/institut/mrt/fmri.jpg

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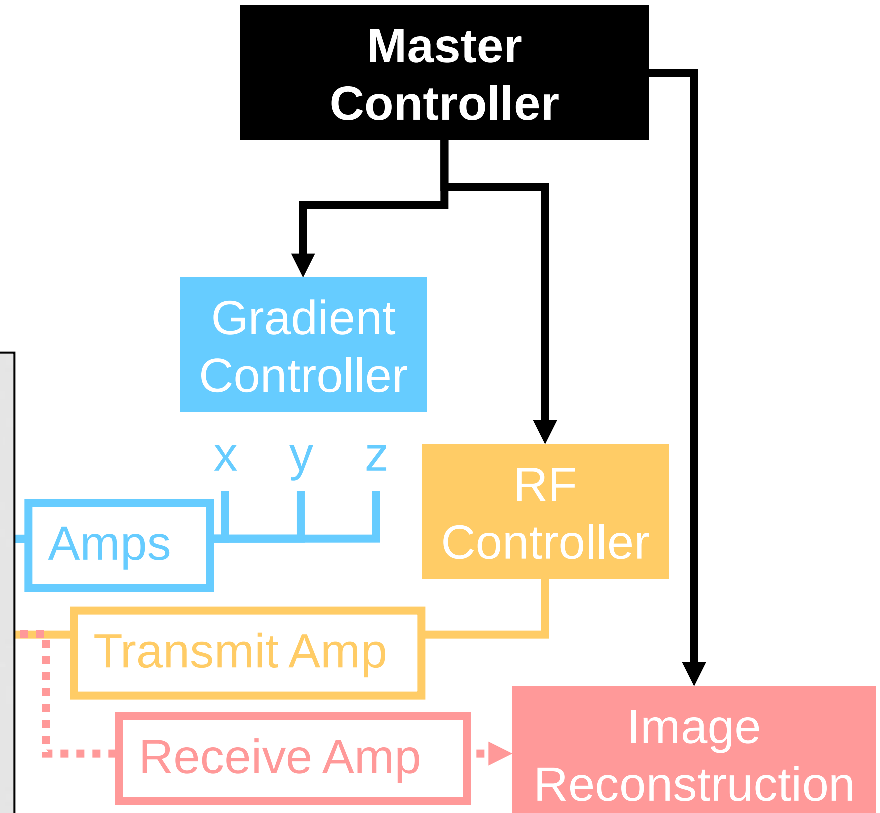
MR Scanner Components (simplified)

3 Types of magnetic fields:

1. Static field ($B_0 \parallel z$)
2. Dynamic gradients ($G_i = dB_z/dr_i$)
3. Radio-frequency ($B_1 \perp z$)



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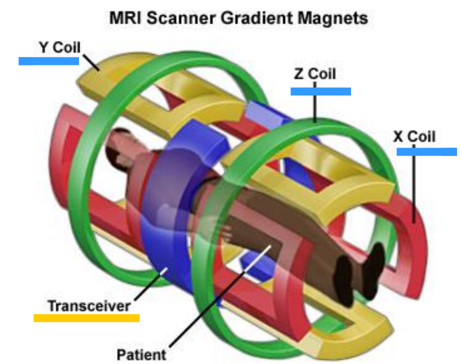

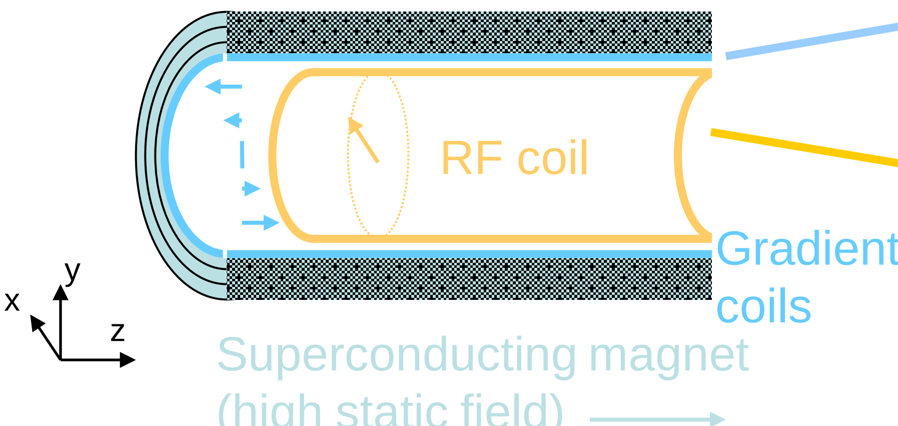

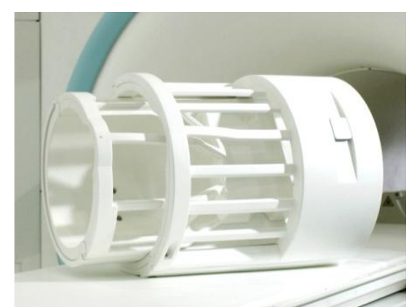

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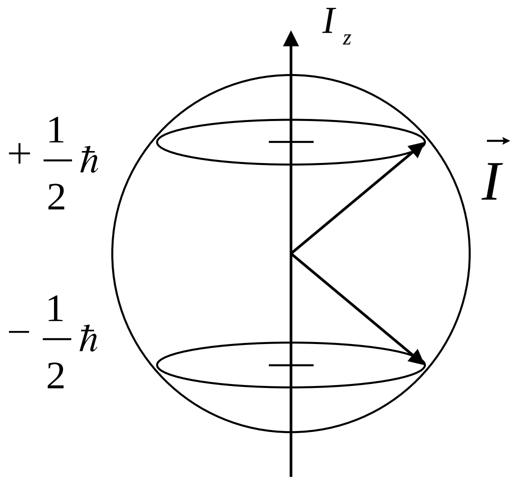
Nuclear Spin – Basic overview

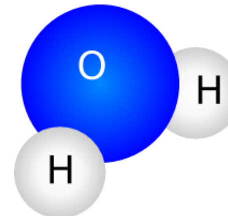
- Atomic nuclei are composed of *protons* and *neutrons* that have the quantum mechanical property: ***spin***.
- The overall spin of the composed nucleus is called ***nuclear spin****.*
- The possible values of the spins' *z*-component are <u>quant</u>ized in integer steps.



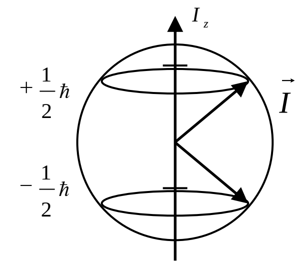
Spin ½ example

$2\pi\hbar = h$ = Planck's constant ≈ 6.626068·10^{-34} J s

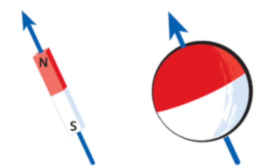
The Proton and Spin 1/2



- The most simple atom is Hydrogen, H
- The human body consists of approx. 70% water
- Hydrogen's nucleus is only one proton.
  Its nuclear spin quantum number is *S*=½, i.e. $I_z = \pm \frac{1}{2}\hbar$



- Associated to every nuclear spin is a **nuclear magnetic moment**, $\vec{\mu} = \gamma \vec{I}$
- γ is called the ***gyromagnetic ratio*** and is nucleus-specific.
  For hydrogen, γ = 267.513·10^6 rad/(s·T).

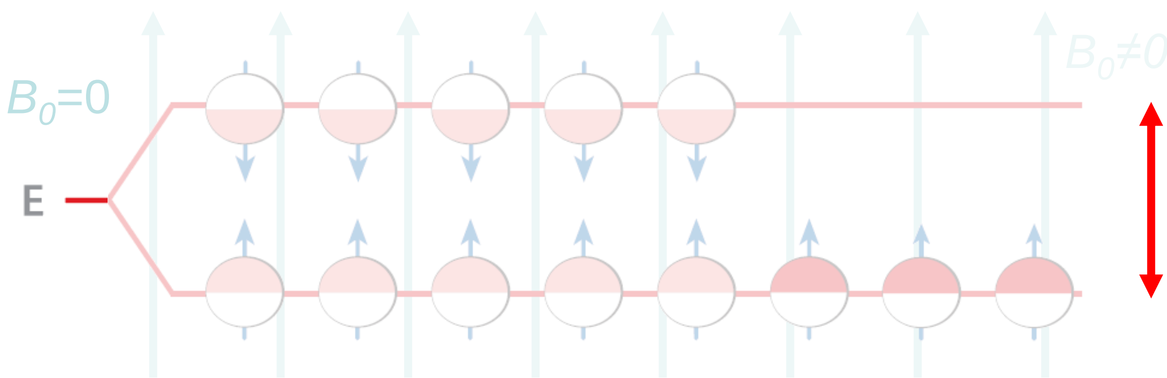


$\gamma / 2\pi \approx$ 42.6 MHz/T

Nuclear Zeeman Effect

- Exposed to a static external magnetic field, B_0, the z-components of the nuclear magnetic moments align with B_0.
- Two possible orientations of the magnetic moments: parallel and anti-parallel with energies

$$E_{\uparrow,\downarrow} = \mu_{z\uparrow,\downarrow} B_0 = \mp \frac{1}{2} \hbar \gamma B_0$$

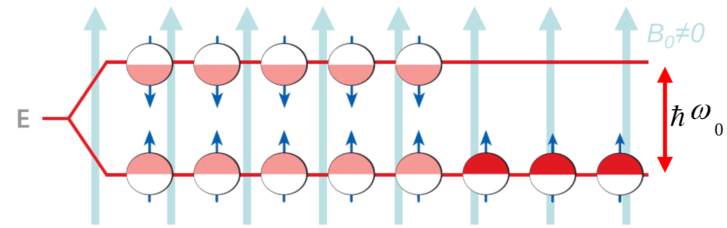


Zeeman splitting

$$\Delta E = \hbar \gamma \underline{B_0} = \hbar \omega_0$$

Larmor frequency

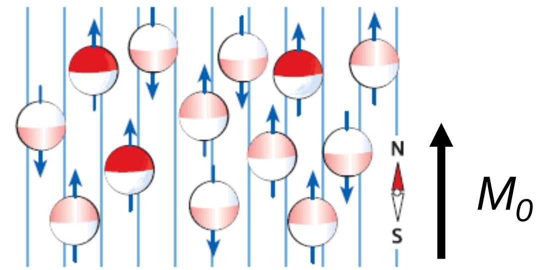
Equilibrium Magnetisation



- There is a small excess of spins in the lower energy states.

- However, the small excess amounts in a **measurable macroscopic magnetisation**, *M*, which is the ensemble average of the nuclear magnetic moments.

- The equilibrium magnetisation for *N* atoms with nuclear spin quantum number, *S*, is given by Curie's law:



$$M_0 = N \frac{\gamma^2 \hbar^2 S(S+1)}{3 k_B T} B_0$$

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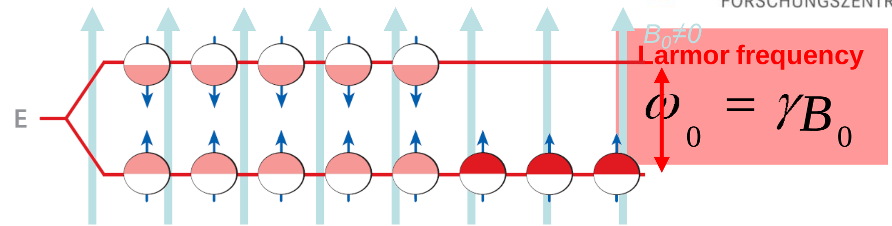
k_B = Boltzmann constant ≈ $1.381 \cdot 10^{-23}$ J / K

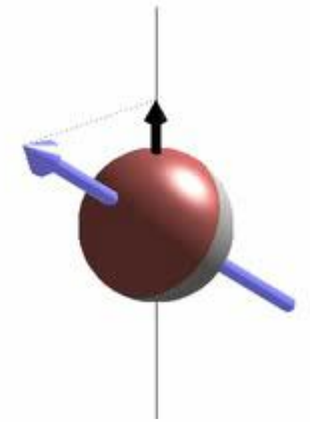
Larmor Precession



- In equilibrium only the spin's *z*-components are aligned with B_0

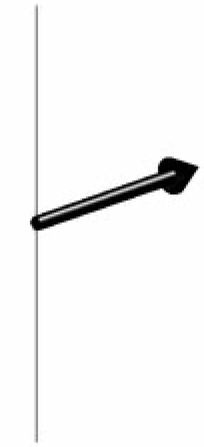
➔ All **spins precess about B_0 with the Larmor frequency, ω_0**

➔ But the resulting **magnetisation is static and aligned with B_0**



- If one excites the spins, i.e., deflect them from their equilibrium alignment,

➔ **the magnetisation precesses about B_0 with the Larmor frequency, ω_0**



Larmor Precession – Example

$$\gamma = 267.5 \cdot 10^6\ {}^{\mathrm{rad}}/_{\mathrm{sT}} \text{ and } \omega_0 = \gamma B_0$$

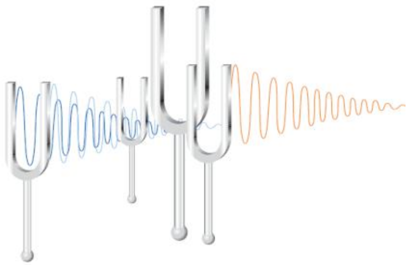
- At B_0=1.5T clinical field strength the Larmor frequency (angular frequency) is

$$\begin{aligned} \omega_0(B_0 = 1.5\,\mathrm{T}) &= 267.5 \cdot 10^6\ {}^{\mathrm{rad}}/_{\mathrm{sT}} \cdot 1.5\,\mathrm{T} \\ &= \underline{\underline{401.25 \cdot 10^6\ {}^{\mathrm{rad}}/_{\mathrm{s}}}} \end{aligned}$$

- In ordinary frequencies, this corresponds to **f_0=63.9MHz**.

- For 9.4T human research scanner: f_0=400MHz

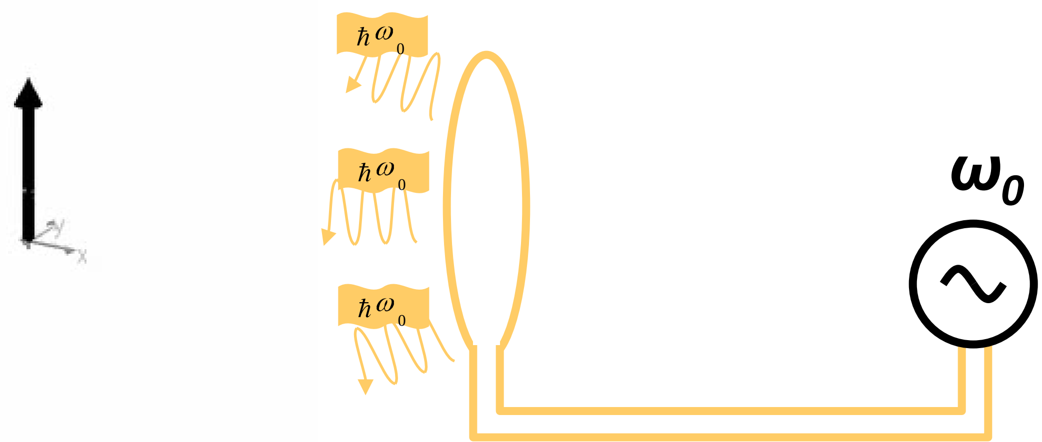
Excitation



- Principle of reciprocity:

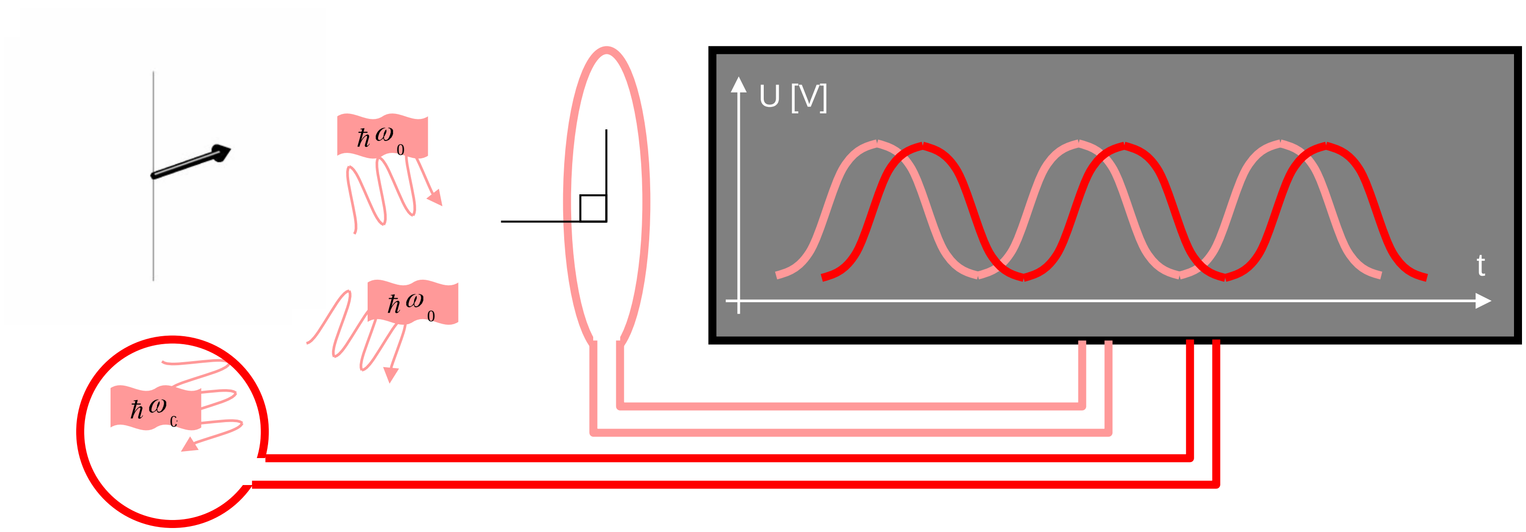
➔ Apply a **resonant radiofrequency (RF) pulse** to excite all spins, i.e. excite the magnetisation from its equilibrium.

➔ **Resonance** ↔ frequency of RF pulse = Larmor frequency $\boldsymbol{\omega_0}$.



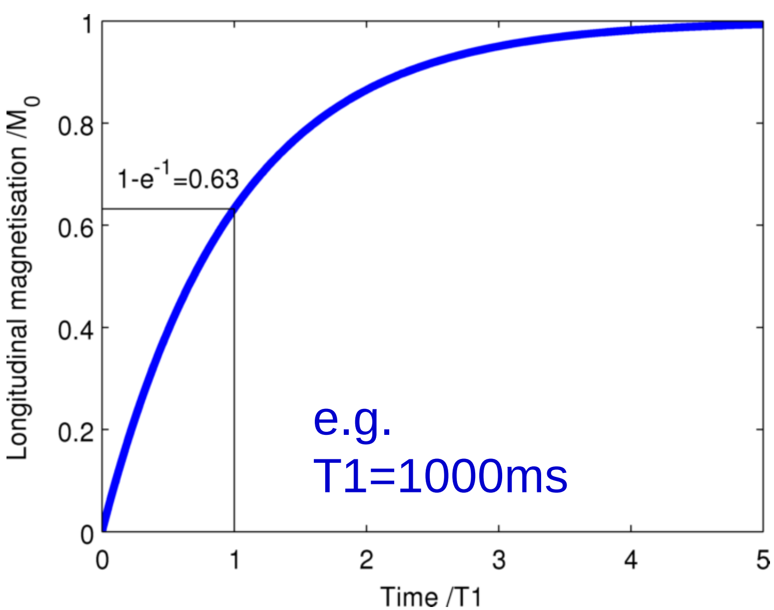
MR Signal Reception

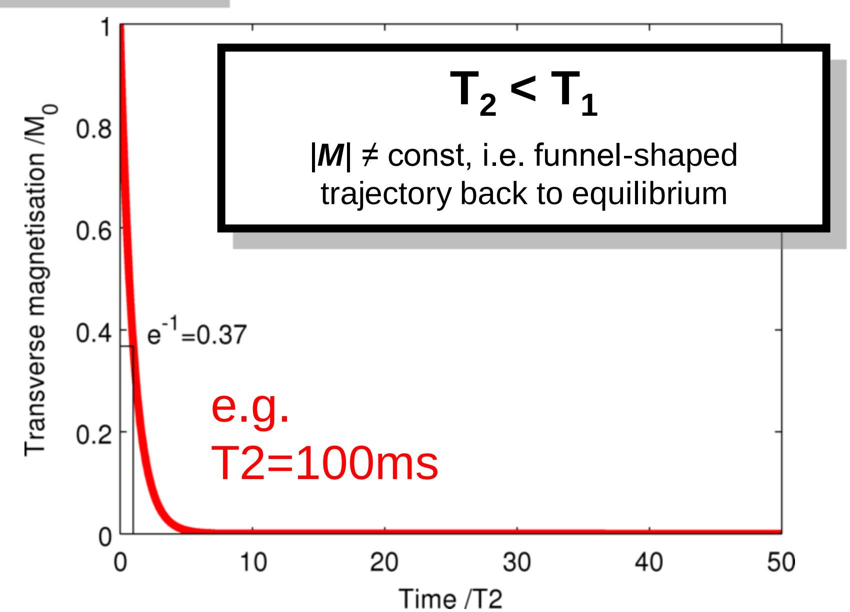
- Faraday's law:
  "A changing magnetic flux induces a voltage in a conductive loop."
  (electromotors, dynamos , …)



Relaxation

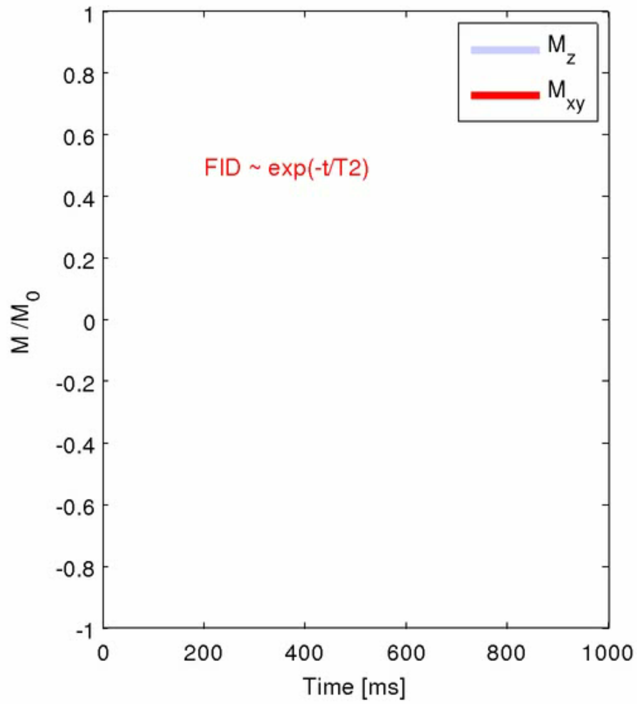
- It is intuitive that equilibrium-magnetisation must be regained somehow.
- Heuristically described by two relaxation times:
  - T_1 (longitudinal relaxation time) $\boxed{M_z = M_0 \left(1 - e^{-t/T_1}\right)}$
  - T_2 (transverse relaxation time) $\boxed{M_{xy} = M_0 e^{-t/T_2}}$





Free Induction Decay (FID)

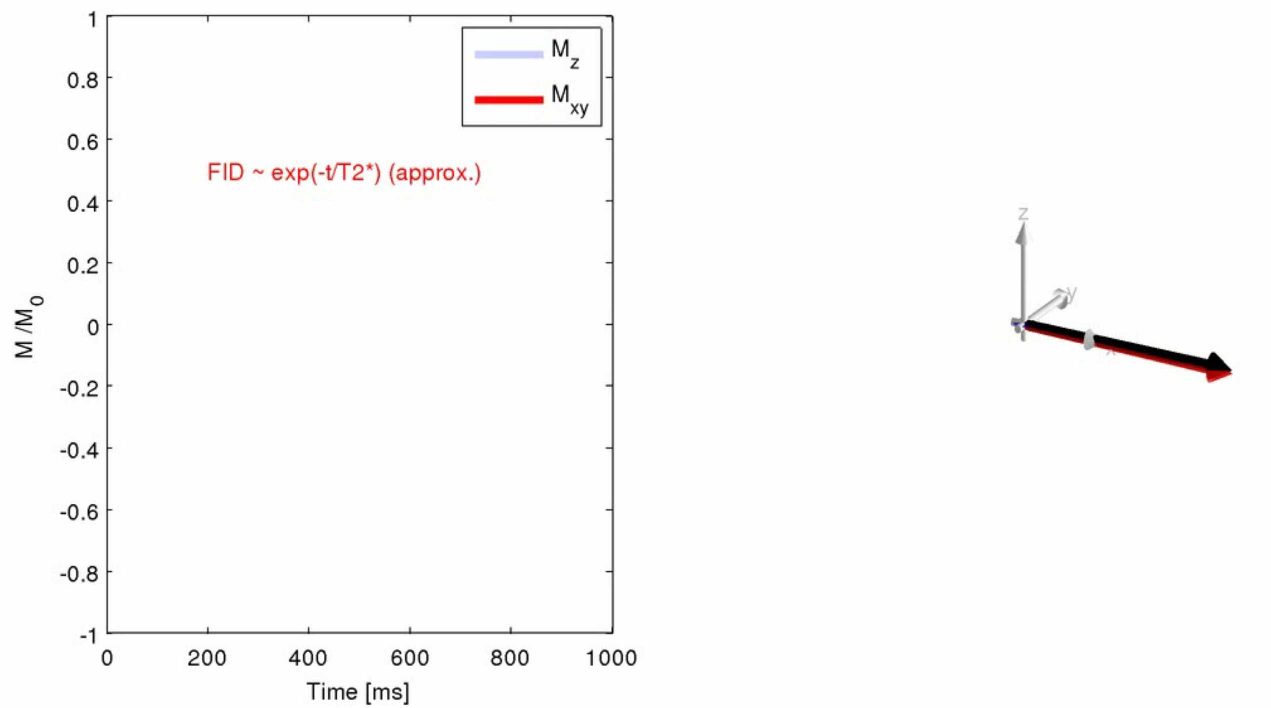
- The received MR signal decays exponentially with the time constant T_2.



Free Induction Decay (FID)

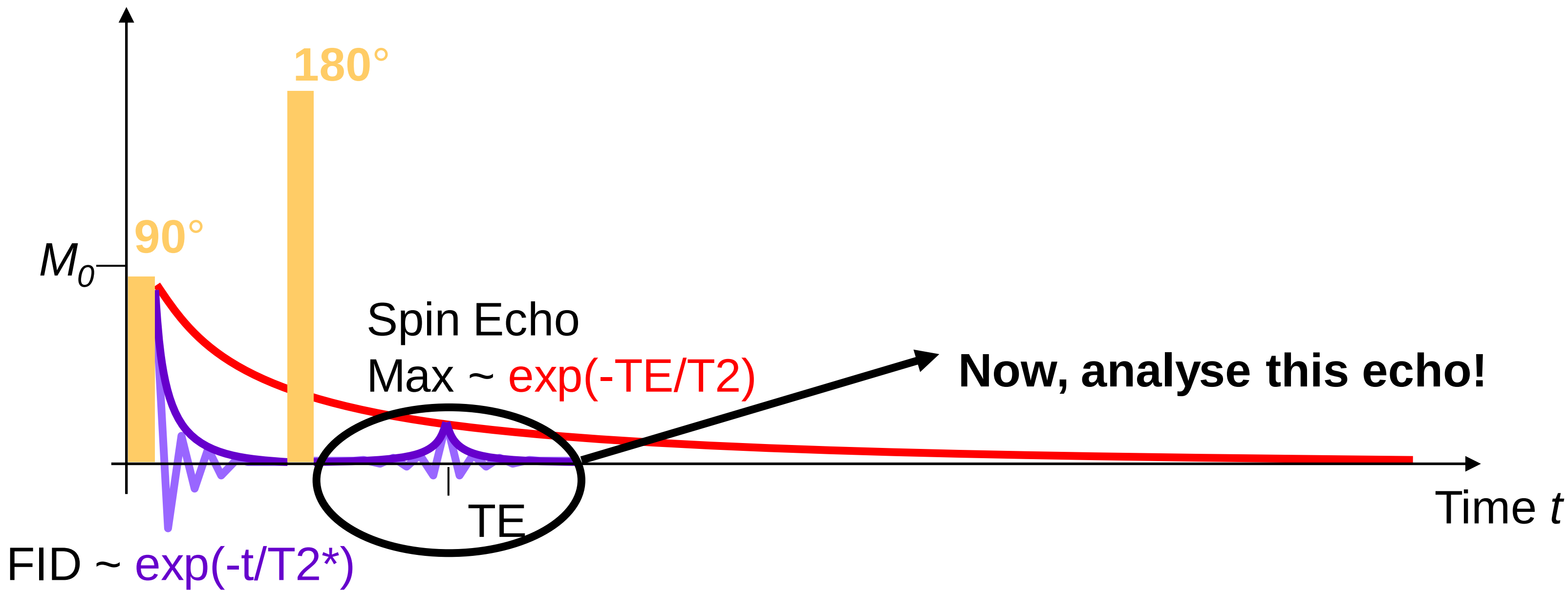
$T_2^* < T_2$

- The received MR signal decays exponentially with the time constant T_2.
- Local B_0 inhomogeneities cause an even ***shorter effective decay time, T_2**** (“T-two-star”).

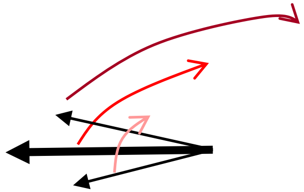


Spin Echo (SE)

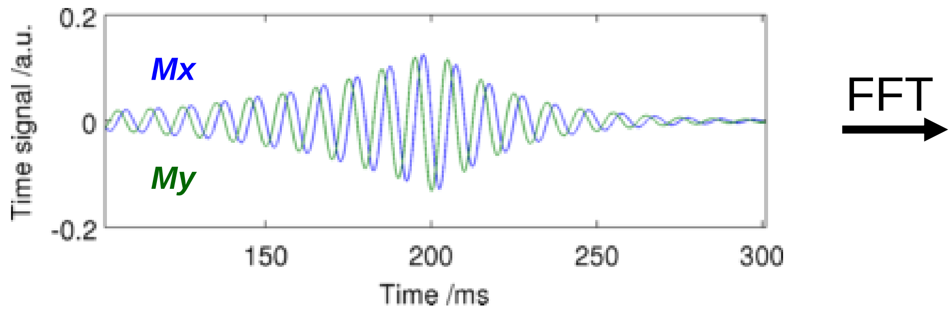
- Signal losses due to B_0 inhomogeneities is reversible
- Recall a ***spin echo*** by inversion of the spins using a 180° pulse.
- The individual spin's phase evolution due to the B_0 induced *frequency dispersion* (T_2*) is "rephased". But T_2 *decay is irreversible*.

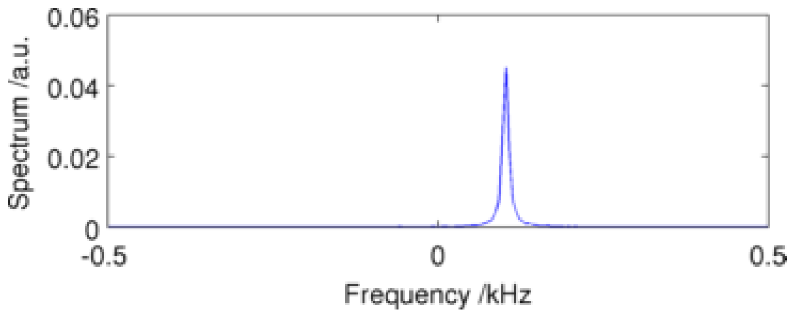


Fast Fourier Transformation (FFT)

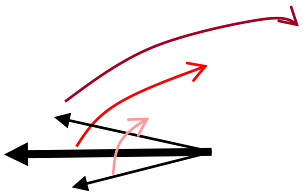


- We expect a frequency dispersion of subgroups of spins
- That means: most spins precess with the Larmor frequency but some are a little faster and some a little slower
- Obtain spectrum by a ***Fourier transform (FT)*** of the time signal, usually a Fast Fourier Transform



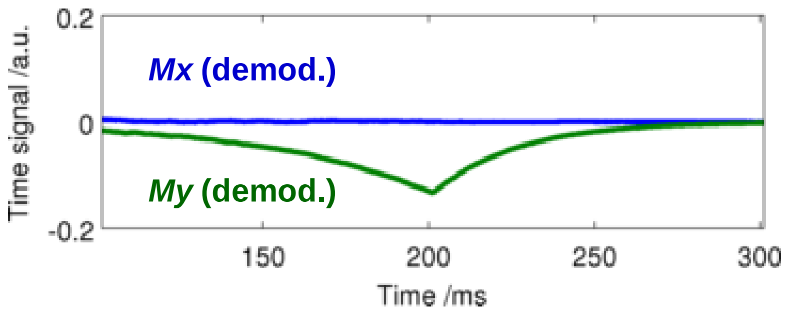


Fast Fourier Transformation (FFT)

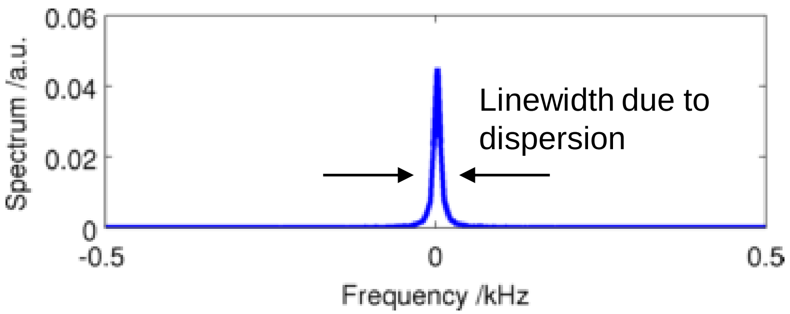


- The signal is always demodulated

- This demodulation corresponds to moving to another frame of reference, the “rotating frame”



FFT



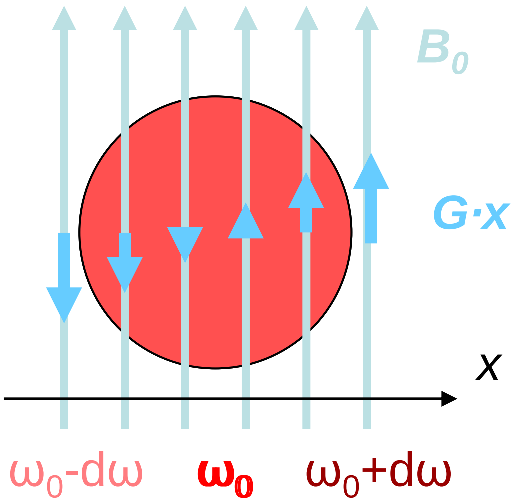
Spatial Encoding

- The basic idea of MRI:

  Make the precessional frequency a function of space

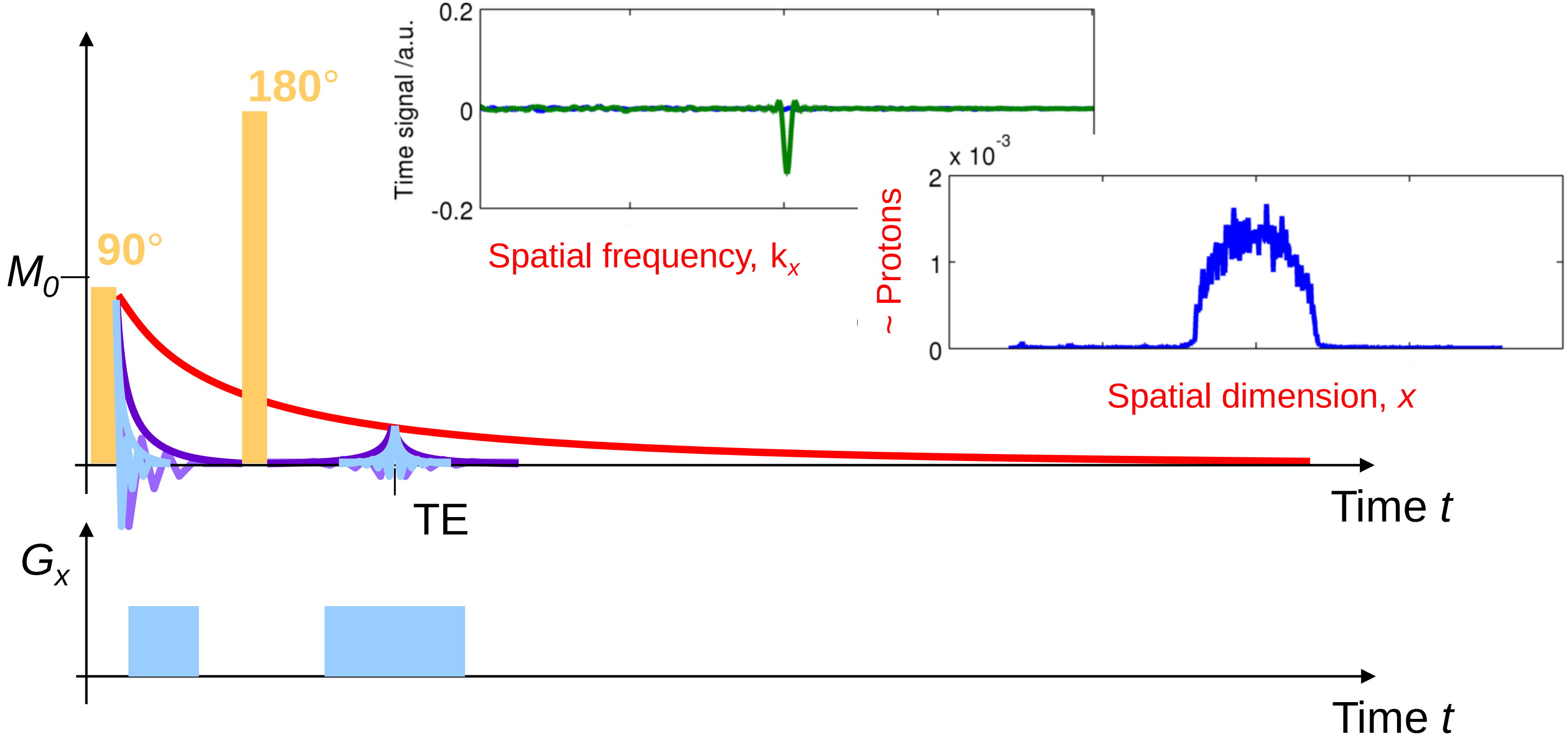
- The "spectrum" then reflects spatial distribution

- Linear field gradients of the B-field in z-direction, e.g. $G_x = dB_z/dx$



Spin Echo with Frequency Encoding

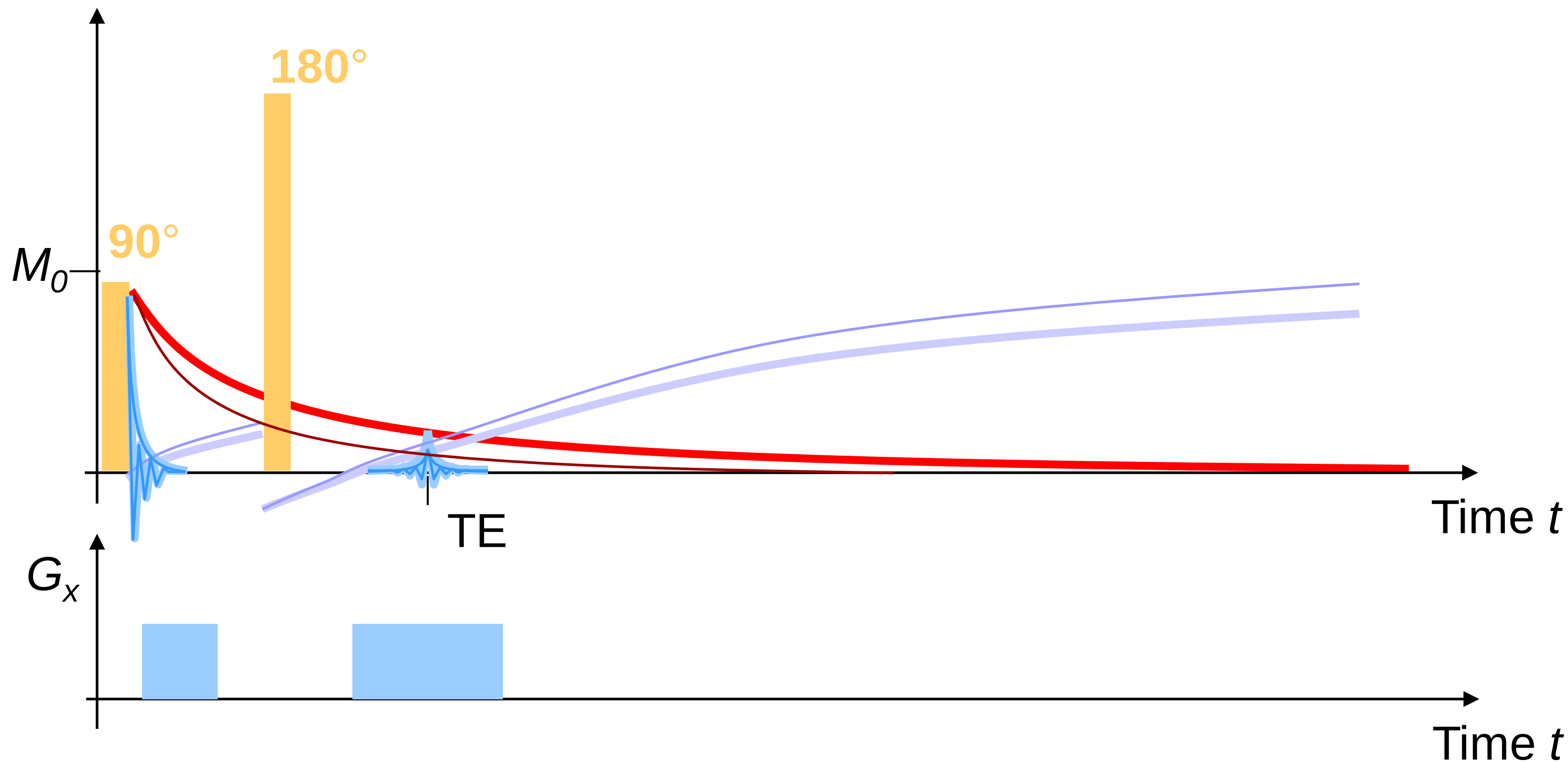
Take the spin echo and introduce gradients along *x*.



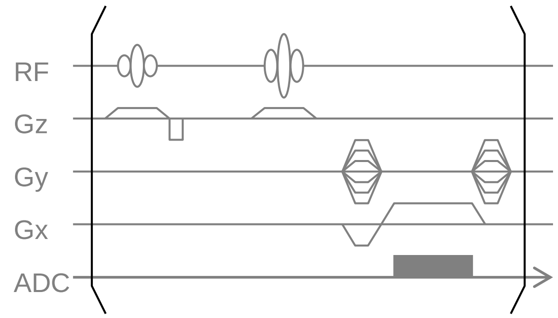
Contrast

Different tissues have different T1/T2 times

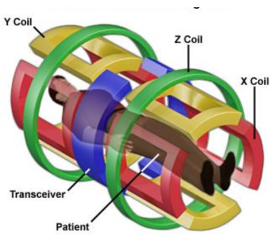
➔ Generate different contrasts through sequence timing parameters!



Imaging Sequences



- Gradient encoding must be applied in 3 dimensions for a complete spatial encoding.
  - During signal readout: *<u>frequency encoding</u>*
  - In a step-wise procedure (for 1 or more dimensions): *<u>phase encoding</u>*
  - Very common, simultaneous with excitation: *<u>slice-selection</u>*



- Gradients in x, y, and z-direction (dB_z/dx, dB_z/dy, dB_z/dz)

- Complex pulse sequences are programmed to obtain all necessary data for a complete reconstruction of the subject. Often: loop-structure.

- General goal: fill the "*k*-space" most quickly.
  (<u>image space ←FFT→ *k*-space</u> = FT-coefficients = spatial frequencies).

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Basic Safety Issues – The Main Field

- Permanently cooled-down (liquid Helium, ~ 4K) superconductor produces the high, static magnetic field B_0 ~ 0.1 – 3 Tesla (1T = 10000 Gauss).
- Compare: the Earth's magnetic field on its surface ~ 0.5 Gauss.

➔ Huge force on ferromagnetic material growing rapidly when approaching the magnet.

➔ Objects like a normal fire extinguisher, surgical instruments, tools, keys etc. can cause immense (live-threatening) damage.

➔ Credit cards, cell phones, pacemakers will not work anymore.

Basic Safety Issues – RF fields

- High frequency em-waves are emitted to the patient in the order of 100 MHz.

➔ This can lead to hot spots at metallic edges, e.g. cables in contact with the skin or MR-unsafe implants.

➔ Make-up containing metallic particles can heat (also tattoos!)

- For higher frequencies the wavelength of the radio-waves inside tissue approaches the extent of, e.g., the head.

➔ High amplitudes due to standing-wave effects.

➔ Amplitude and duration of RF must be controlled due to SAR (Specific Absorption Rate) constraints. SAR is an important issue, particularly at high field strengths because of the reduced wave length.

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Thank you for your attention

Introduction to MRI