Magnetic Resonance Imaging (MRI) based on Nuclear Magnetic Resonance (NMR)

Part 1

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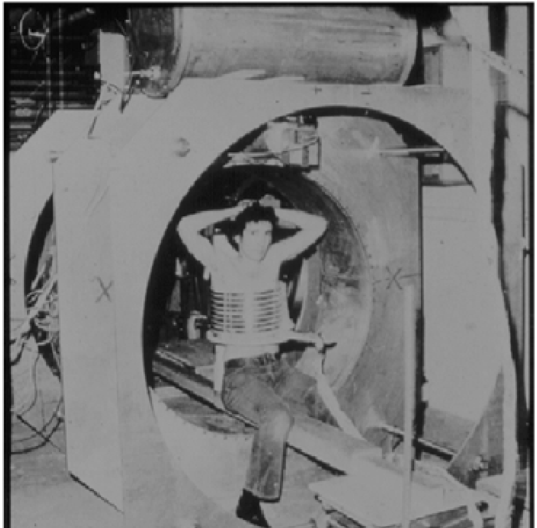
based on lectures 2008-2023 by J.Kybic, J.Hornak[1], M.Bock, J.Hozman, P.Doubek
Department of Cybernetics, FEE CTU

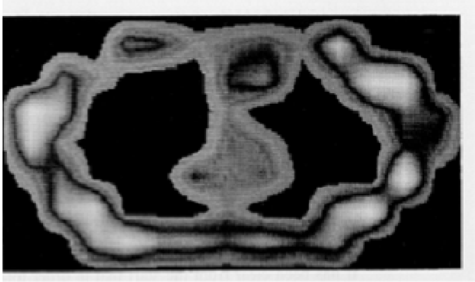
2024

[1] http://www.cis.rit.edu/htbooks/mri/

First human MRI

První obraz člověka (1977)

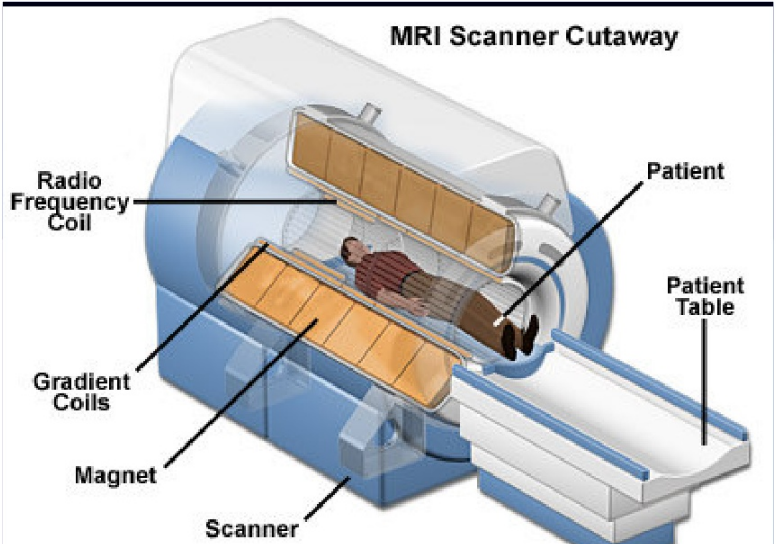




MRI scanner

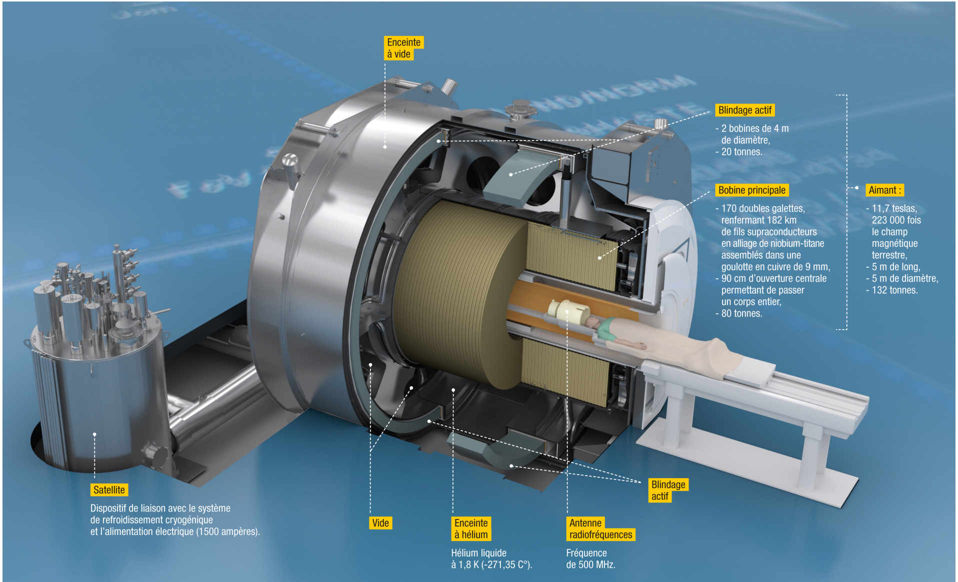
selenoid, closed-bore magnet

MRI Scanner


MRI Scanner Cutaway
Radio Frequency Coil
Patient
Patient Table
Gradient Coils
Magnet
Scanner

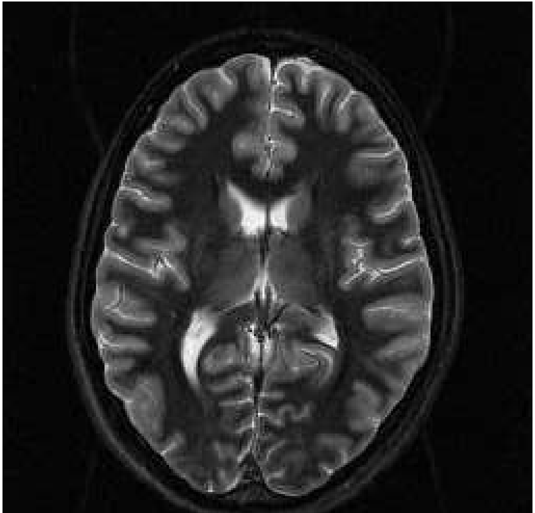
Permanentní magnety - architektura „OPEN“

MRI with 11.7T (223000 earth magnetic field)



MRI – Example

Brain slice:

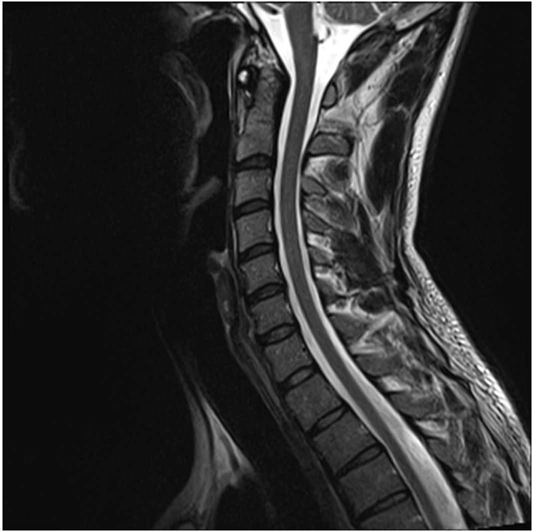


MRI – Example

Brain slice:

MRI – Example

Spine:



MRI – Example


H
MAGNETOM EXPERT
F-SP VB31B
+ : F A L
SP -102.2
SL 3.0
FoV 149*170
222 *256o
Sag>Cor 14

MRI principles

1. Insert object (subject) into a strong magnetic field.
2. (Repeatedly) send a radio-frequency impuls.
3. Spins are excited and then relax to equilibrium.
4. Receive and record emitted radio-frequency waves.
5. Reconstruct image from data.
6. Remove the object (subject) from the magnetic field.

Brief history of MRI

- 1946 – Felix Bloch, Edward Purcell, independent discovery
- 1950–1970 — NMR, spectroscopic analysis
- 1971 — Raymond Damadian, tissue relaxation times differ
- 1973 — Hounsfield, CT (showed demand for medical imaging)
- 1973 — Paul Lauterbur, tomographic MRI (backprojection)
- 1975 — Richard Ernst, Fourier MRI
- 1977 — Peter Mansfield, echo-planar imaging (EPI), later 30 ms/slice

Brief history of MRI (2)

- 1980 — Edelstein, whole-body MRI (3D), 5 min/slice
- 1986 — whole-body MRI, 5 s/slice
- 1986 — MRI microscopy, resolution 10 μm
- 1987 — beating heart imaging
- 1987 — MRA angiography without contrast agents, blood flow
- 1992 — functional MRI, brain mapping

Nobel prizes

- 1952 — Felix Bloch, Edward Purcell, physics, discovery
- 1991 — Richard Ernst, chemistry, Fourier MRI
- 2003 — Paul Lauterbur, Peter Mansfield, medicine, MRI in medicine

Numbers related to MRI

- About 40000 MRI scanners worldwide
- About 20 examination per day per scanner
- 110 scanners in Czech Republic in 2018
- One scanner costs 10 $\sim$ 100 mil. CZK (millions of EUR)
- One examination 5 $\sim$ 20 mil. CZK (hundreds of EUR)

Units review

- Time (s)
- Angle (degree) or (rad) 2π rad in 360°
- Temperature (Kelvin, K) 0 K $= -273.15$ degree Celsius
- Magnetic field strength (Tesla, T). Earth magnetic field $5 \cdot 10^{-5}$ T
- Energy (Joule, J)
- Frequency $1\,\mathrm{Hz} = 1/\mathrm{s}$
- Power (Watt, W)
- pico,p (10^{-12}), nano,n (10^{-9}) micro,μ (10^{-6}), milli,m (10^{-3}), kilo,k (10^{3}), mega,M (10^{6}), giga,G (10^{9})

Spin

- Human body: fat and water. 63 % hydrogen (10 % by mass)
- Hydrogen nucleus = proton.
- Proton has a property called a **spin** (besides a mass and charge), related to angular momentum.
- Non-zero spin particles behave like small magnets → MRI signal

Nuclear spin

- Free electrons, protons, and neutrons have a spin of $1/2$
- Spins may pair and compensate
- Nuclear spin I is a multiple of $1/2$
- $I \neq 0 \Rightarrow$ (small) magnet,

magnetic moment $\boldsymbol{\mu}$	$\|\boldsymbol{\mu}\| = \gamma\hbar\sqrt{I(I+1)}$	$\left[\frac{\text{N} \cdot \text{m}}{\text{T}}\right]$
torque	$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$	$[\text{N} \cdot \text{m}]$

γ —gyromagnetic constant $\left[\frac{\text{rad}}{\text{s}\cdot\text{T}}\right]$ or $\left[\frac{\text{MHz}}{\text{T}}\right]$
$\hbar = \frac{h}{2\pi}$ — reduced Planck constant
$h \approx 6.626 \cdot 10^{-34}\ \text{J} \cdot \text{s}$

Isotopes useful for MRI

- Only unpaired spins ($I \neq 0$) are useful for MRI
- Total nuclear spin — no easy rule
- Even atomic number Z (number of protons) and even mass number A (total number of protons and neutrons) $\Rightarrow \quad I = 0$ (^{12}C, ^{16}O)
- Most abundant isotopes for even Z have $I = 0$
- Isotopes with $I \neq 0$ are often
  - rare isotopes (1.11% for ^{13}C)
  - biologically rare elements
  - give small signal

Biological abundance of elements

(by count)

Element	Abundance [%]	
H	63	
O	26	main isotope ^{16}O with zero spin
C	9.4	main isotope ^{12}C with zero spin
N	1.5	
P	0.24	
Ca	0.22	
Na	0.041	

Abundance of MRI active isotopes

by count

Isotope	Abundance [%]
^{1}H	99.985
^{2}H	0.015
^{13}C	1.11
^{14}N	99.63
^{15}N	0.37
^{23}Na	100
^{31}P	100
^{39}K	93.1
^{43}Ca	0.145

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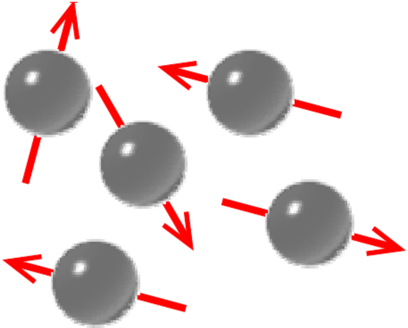
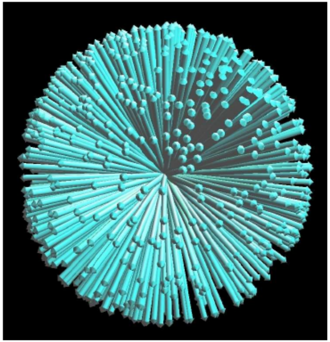
Practical MRI exists for

- ^{1}H — most often used, strongest signal, best quality
- ^{19}F, ^{23}Na, ^{31}P... — mostly research

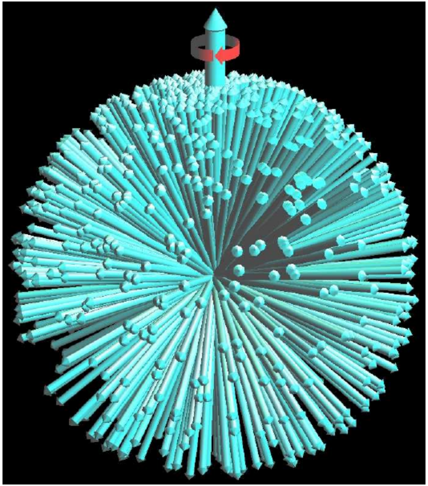
Spins in magnetic field





magnetic induction $B_0 = 0$, random orientation

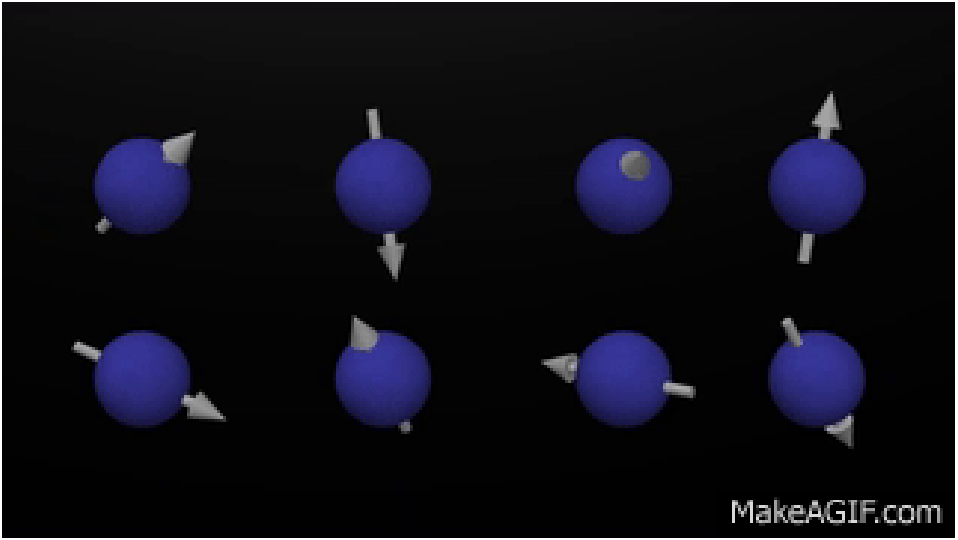
Spins in magnetic field



$B_0 \neq 0$ (around $0.1 \sim 10\,\mathrm{T}$ needed)

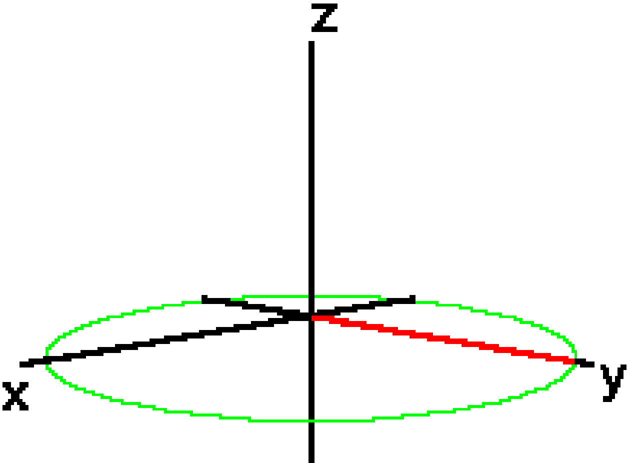
- Spin packet

Spin Precession



Precession

- For B_0 along z axis
- $\mathbf{M}$ rotates around z axis
- $\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$



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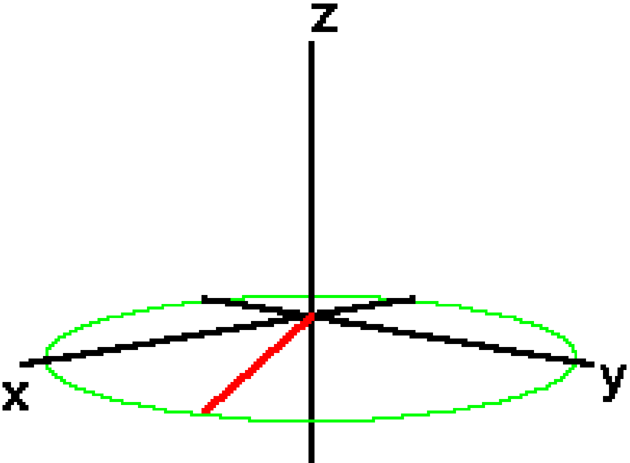

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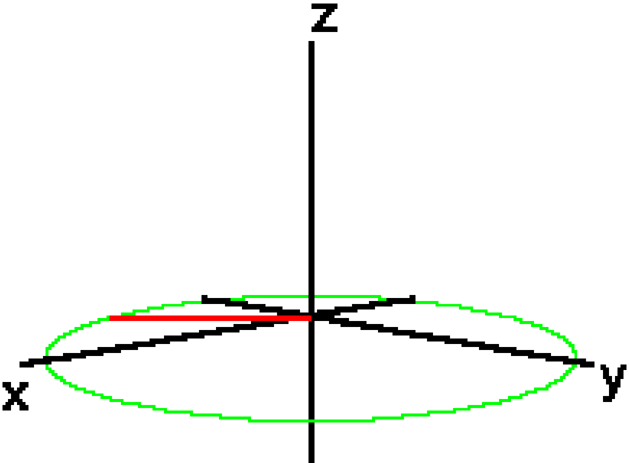

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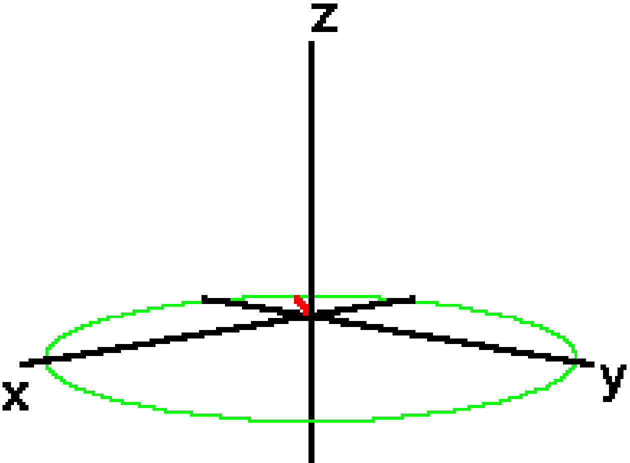

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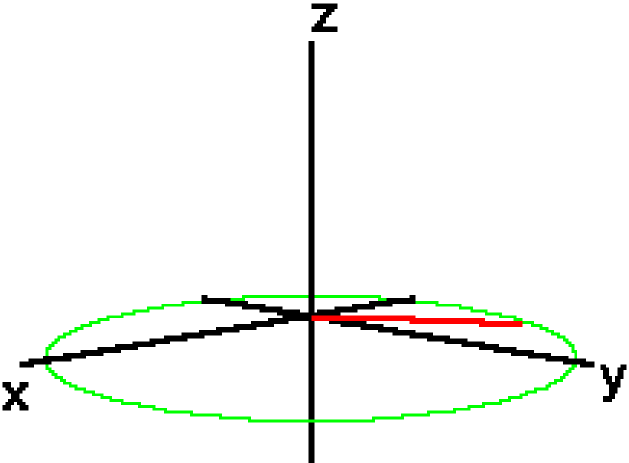

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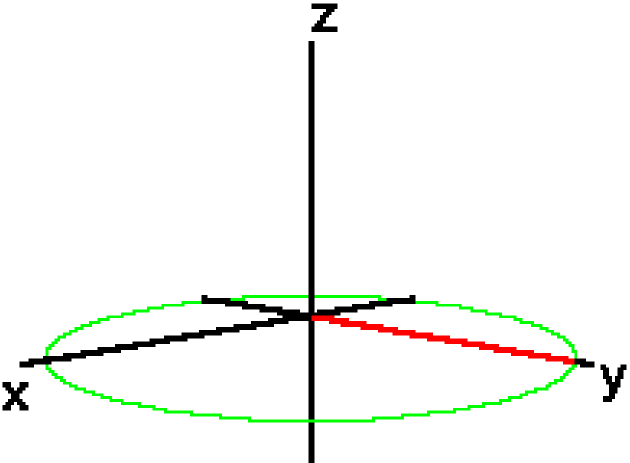

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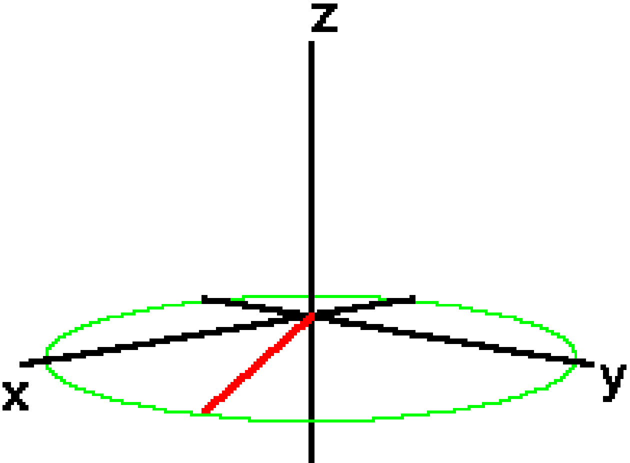

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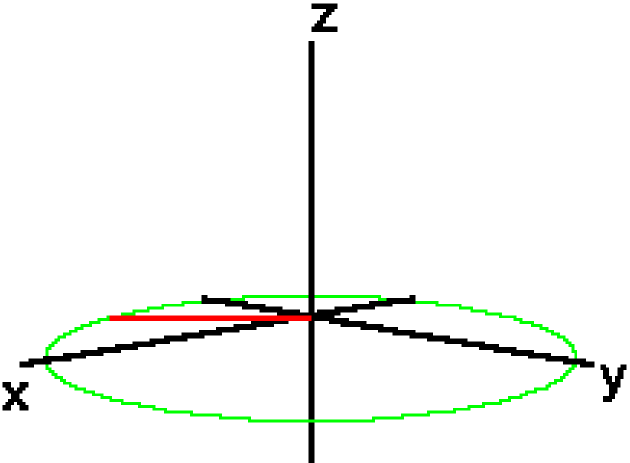

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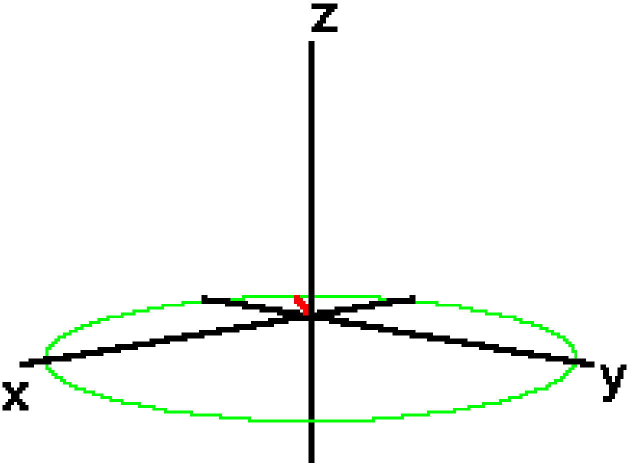

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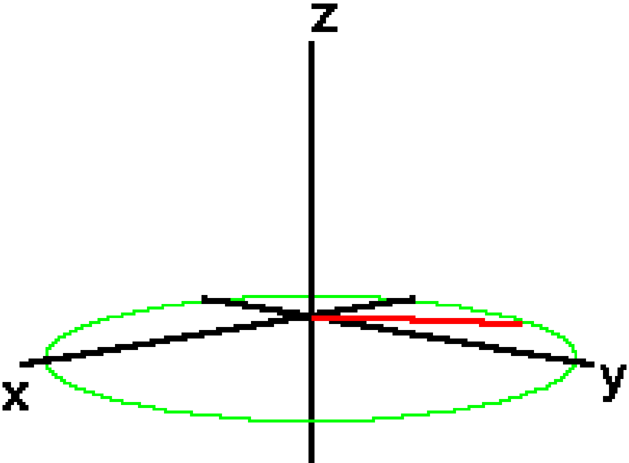
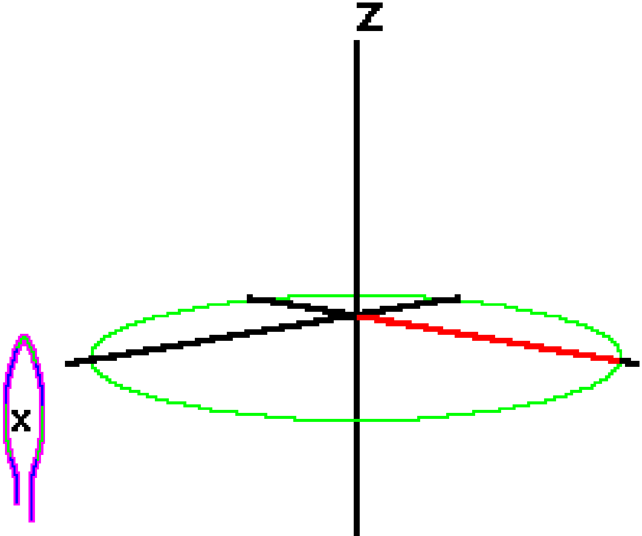


RF signal

Precession in the *xy* plane gives measurable RF signal.



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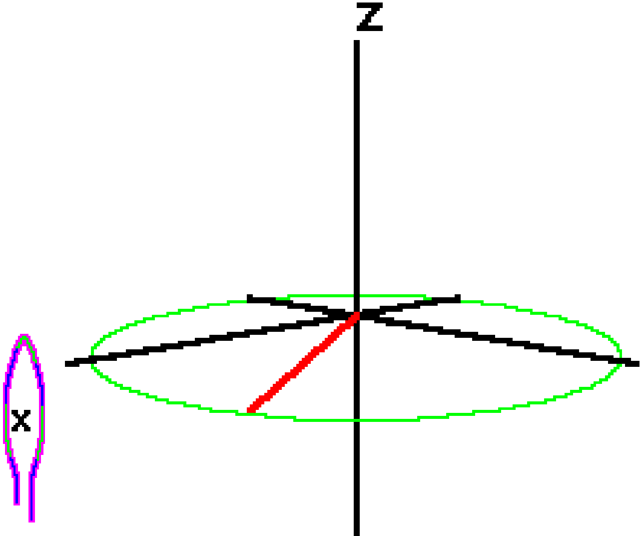

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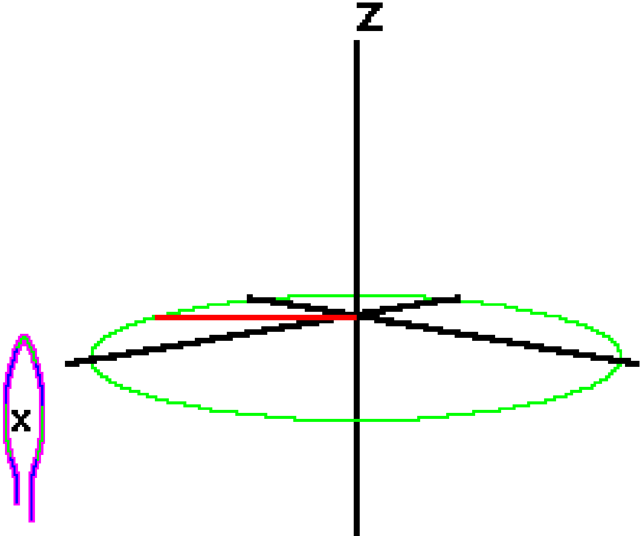

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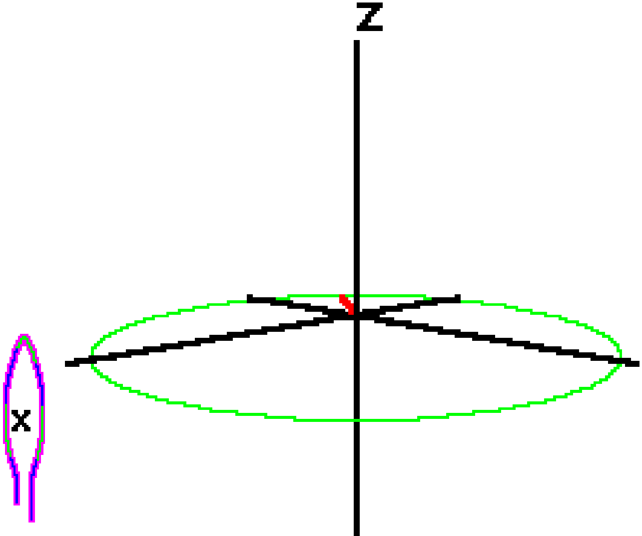

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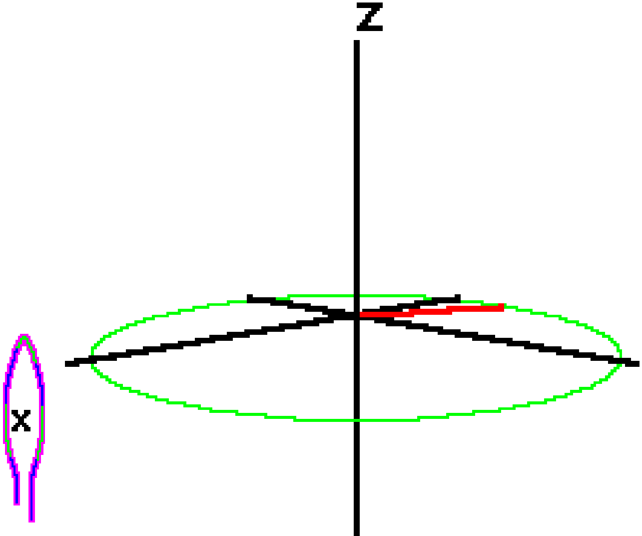

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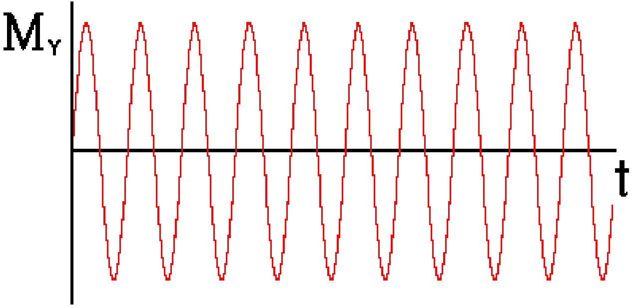
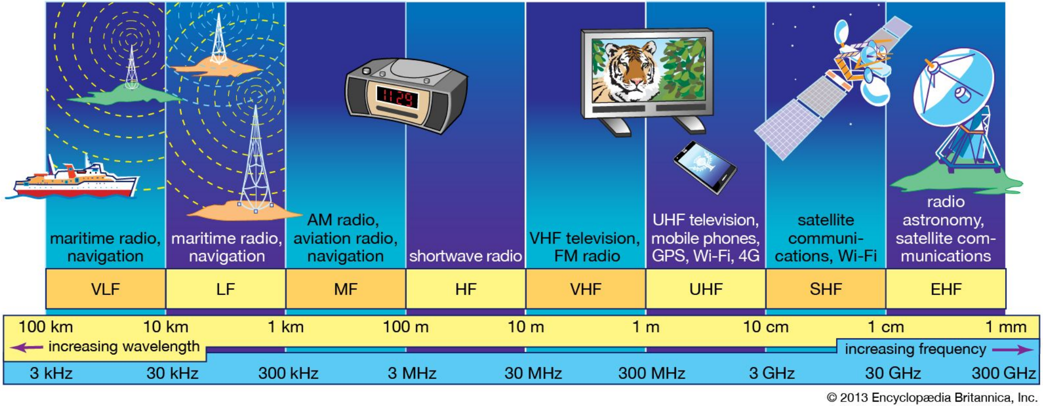


Radio Frequency

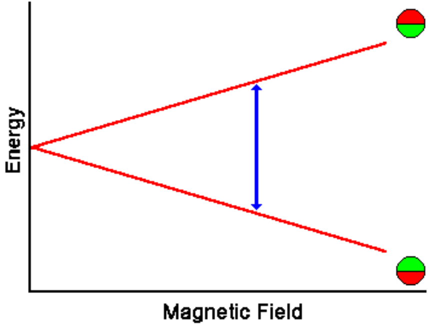


Larmor frequency

$$f = \gamma B$$

- B [Tesla] magnetic field intensity
- γ gyromagnetic constant
- For hydrogen ^{1}H, $\gamma = 42.58\,\text{MHz/T}$
- f is a frequency of:
    - the precession
    - the received signal
    - the excitation signal

Energy diagram



$$f = \gamma B, \qquad E_p = hf, \quad \Delta E \propto \gamma B$$

- low (parallel) and high (antiparallel) orientations
- For H, typically $f = 15 \sim 80\,\text{MHz}$.
- Energy difference $\sim$ signal amplitude

Boltzmann statistics

For a closed (non-quantum) system in thermal equilibrium:

- Number of low-energy spins N^-
- Number of high-energy spins N^+

$$\frac{N^+}{N^-} = \mathrm{e}^{-\frac{\Delta E}{kT}}$$

Boltzmann constant $k = 1.3805 \cdot 10^{-23}$
Temperature T [K]

Boltzmann statistics

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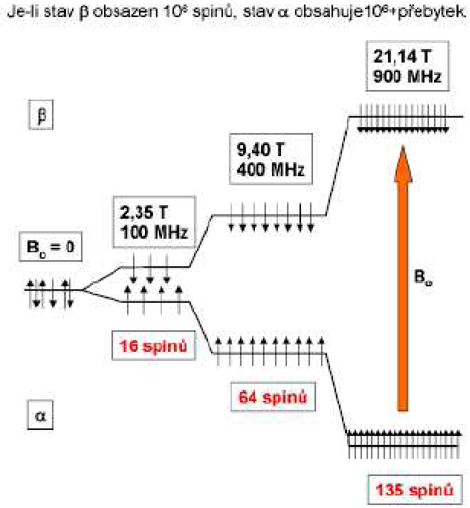
Boltzmann constant $k = 1.3805 \cdot 10^{-23}$
Temperature T [K]

- MRI signal $\propto \|\mathbf{M}\| \propto N^- - N^+$
- low T, high B $\rightarrow$ high signal
- high T, low B $\rightarrow$ low signal

Boltzmann statistics example



Example ^{1}H:

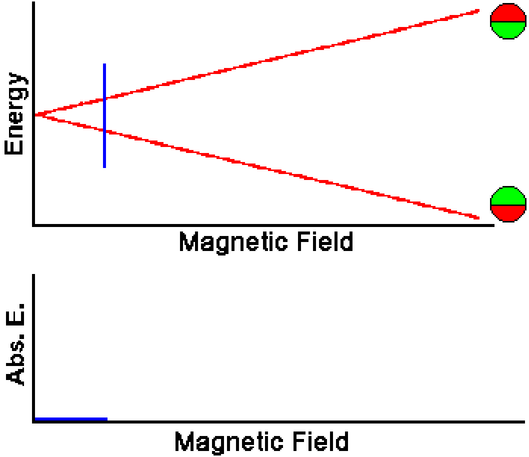
$$f = 400\,\text{MHz}$$
$$B = 9.5\,\text{T}$$
$$\Delta E = 3.8 \cdot 10^{-5}\,\frac{\text{Kcal}}{\text{mol}}$$

$$\frac{N^-}{N^+} = 1.000064 \sim 64\,\text{ppm}$$

→ very low SNR in MRI.

Continous wave NMR (1)

- Constant frequency
- Variable magnetic field
- Measuring absorbed energy



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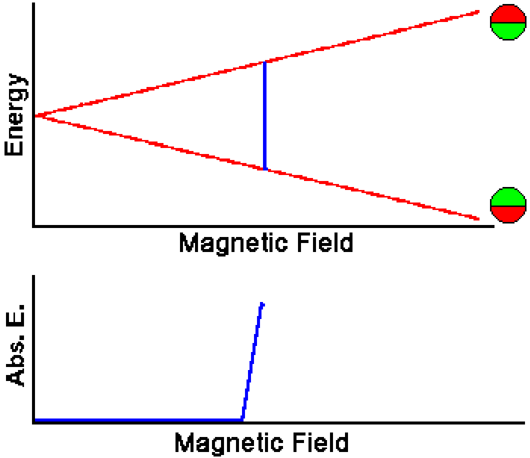

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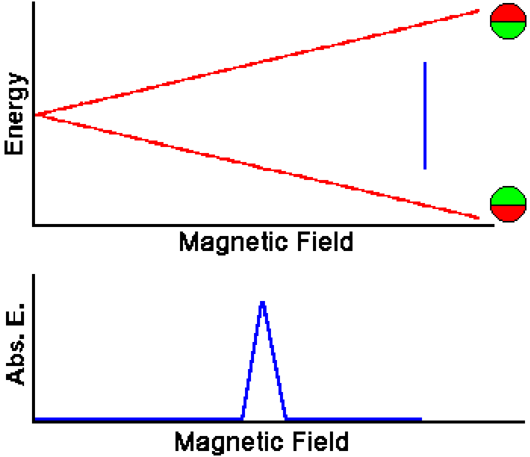
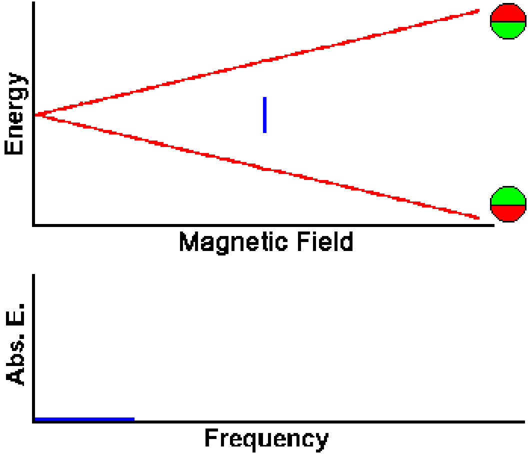


Continous wave NMR (2)

- Constant magnetic field
- Variable frequency
- Measuring absorbed energy



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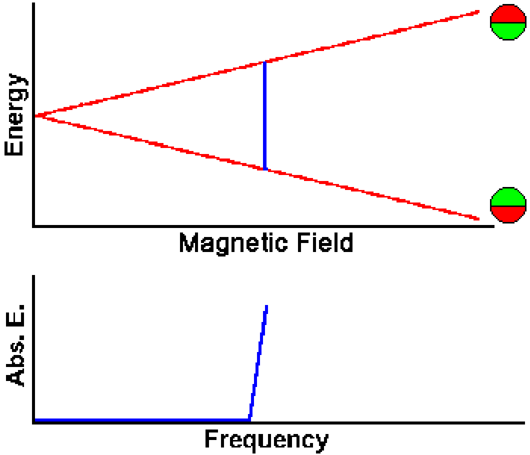

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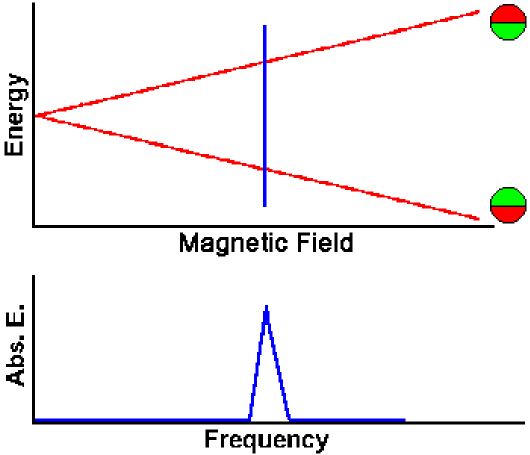
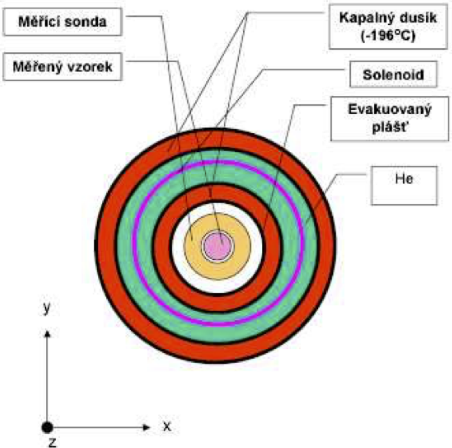
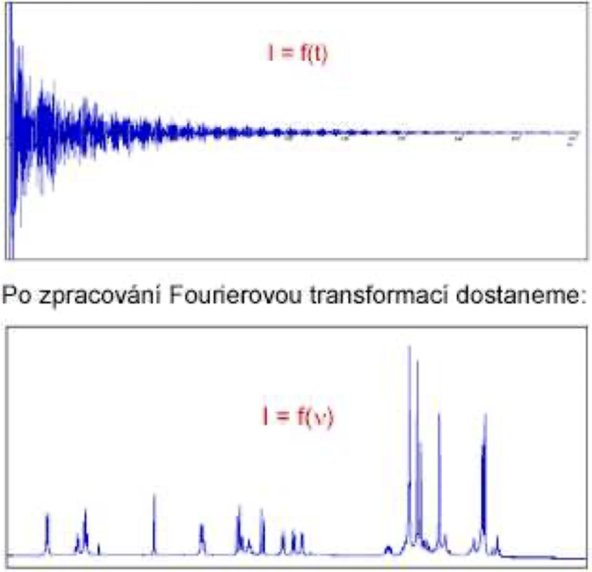


NMR spectroscopy



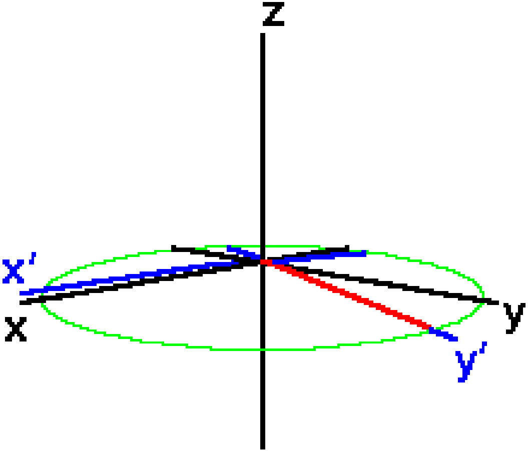
Free Induction Decay (FID)

- In a real sample there are many spin systems whose frequencies are different from the carrier frequency B
- Since we have effectively excited all these spins, we get a combination of signals and different frequencies



Rotating frame of reference

...rotates around z with Larmor frequency f



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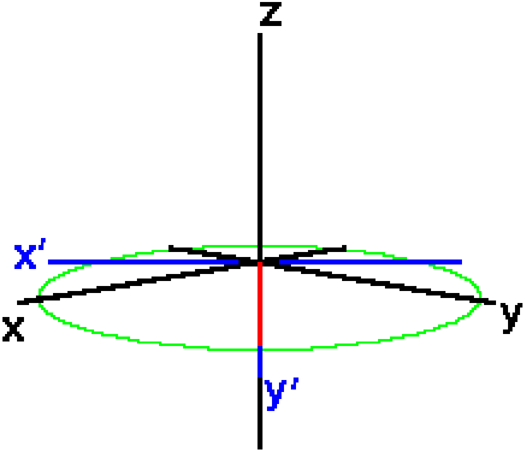

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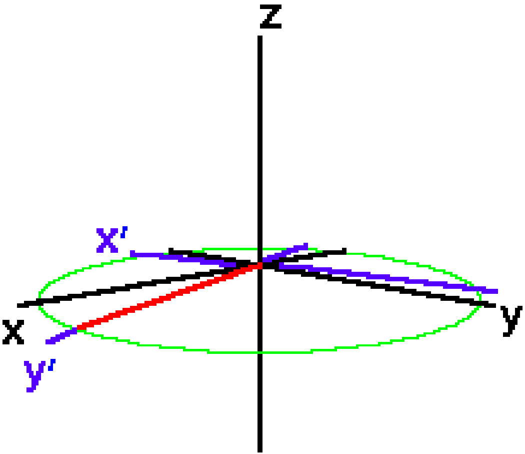

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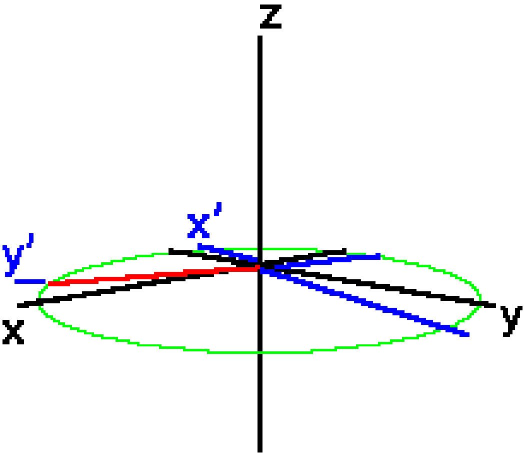
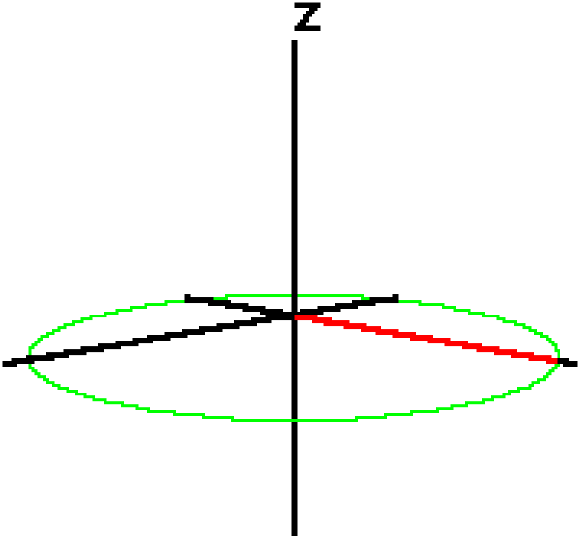


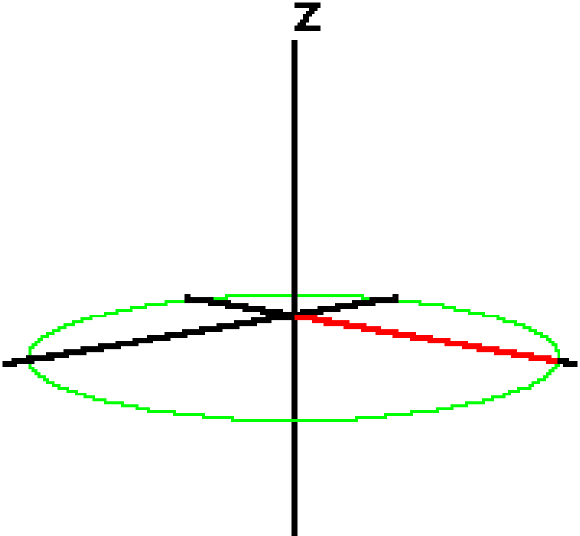
Rotating frame of reference (2)

$\boldsymbol{\mu}$ rotating with frequency f appears stationary



Rotating frame of reference (3)

$\boldsymbol{\mu}$ rotating faster than f appears rotating in the same direction



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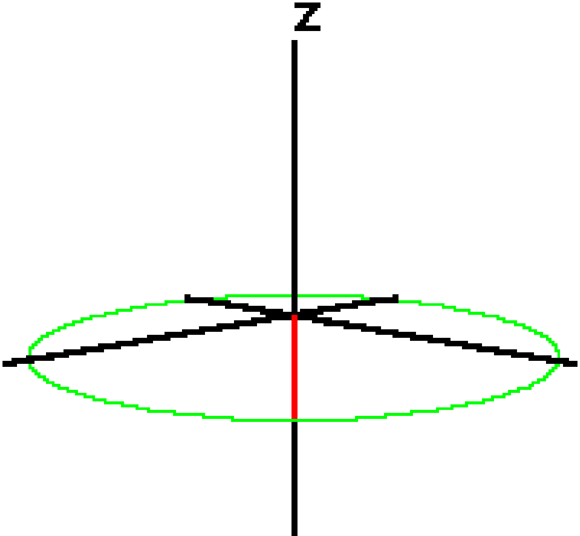

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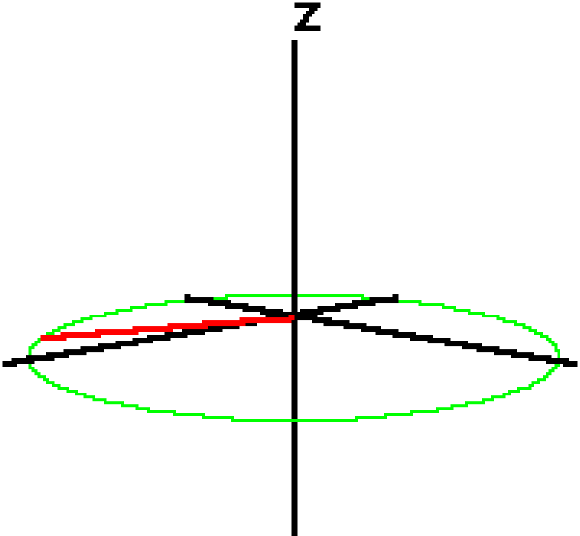

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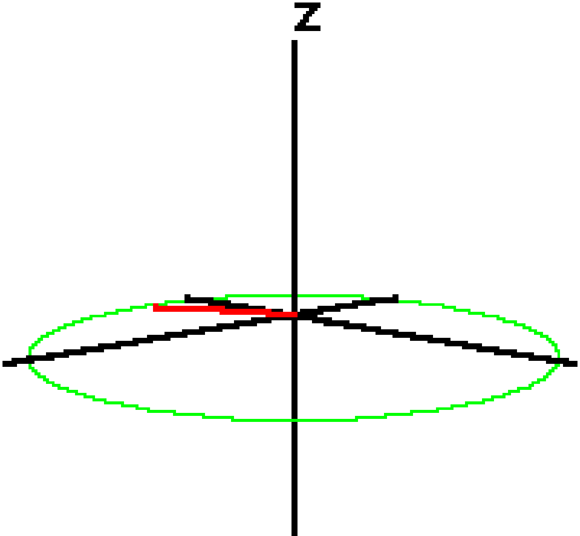
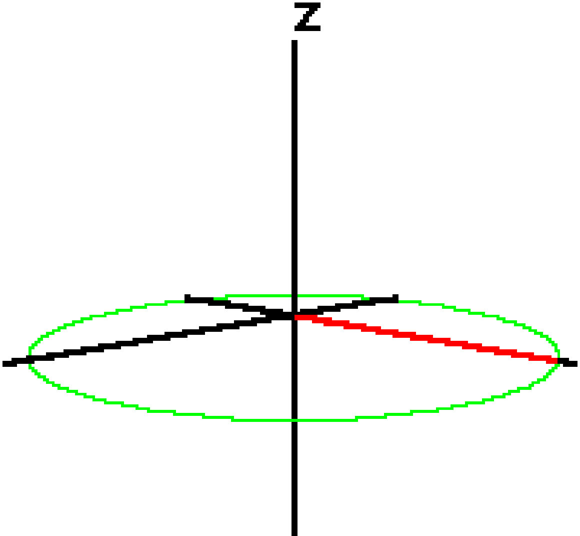


Rotating frame of reference (4)

$\boldsymbol{\mu}$ rotating slower than f appears rotating in the opposite direction



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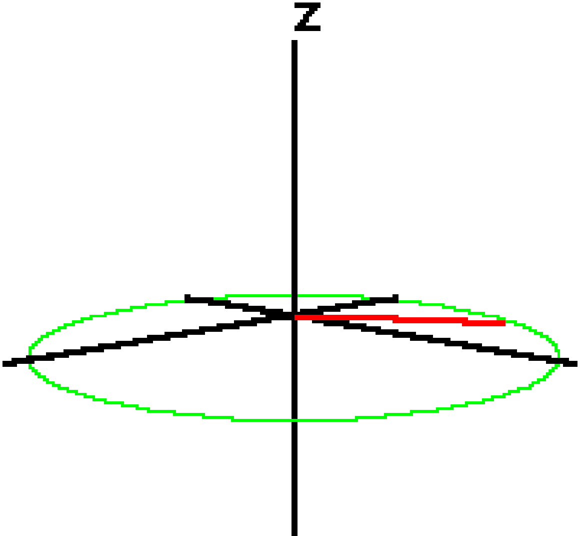

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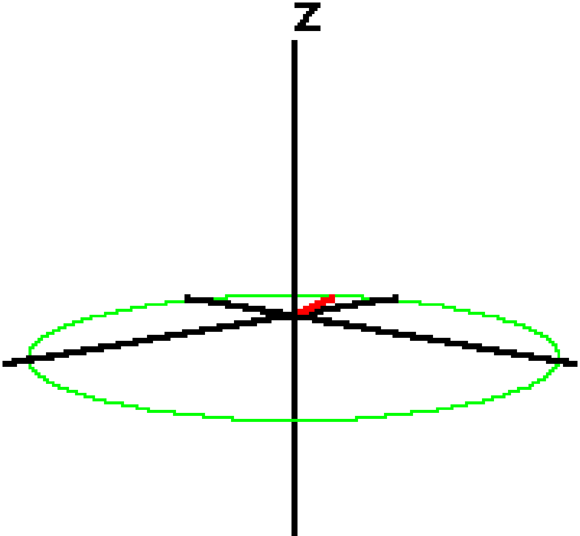

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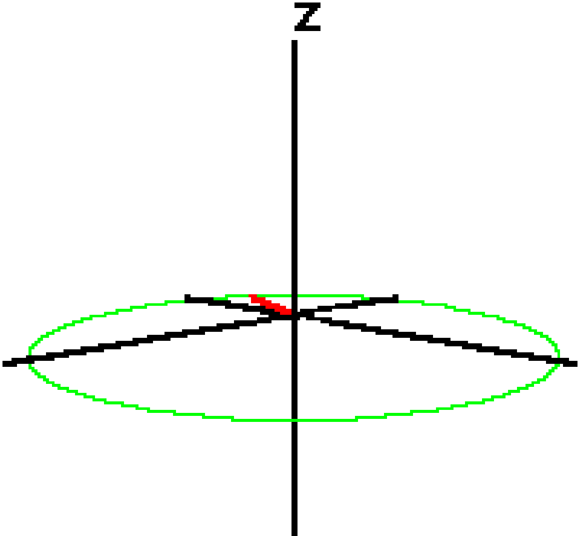
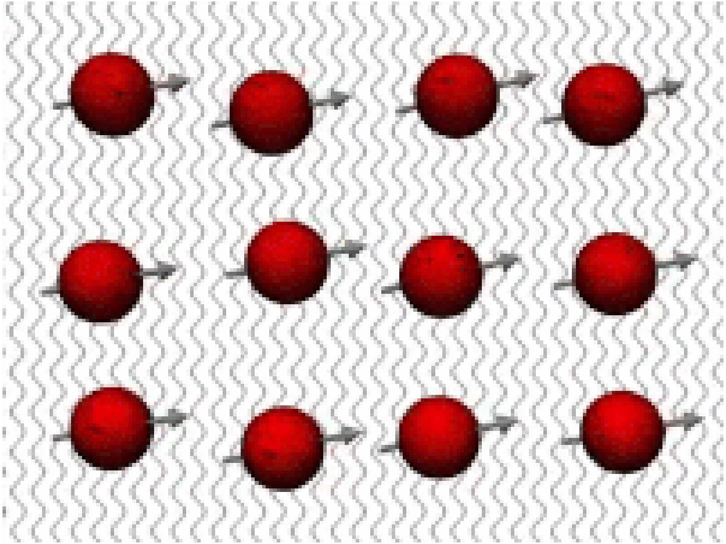
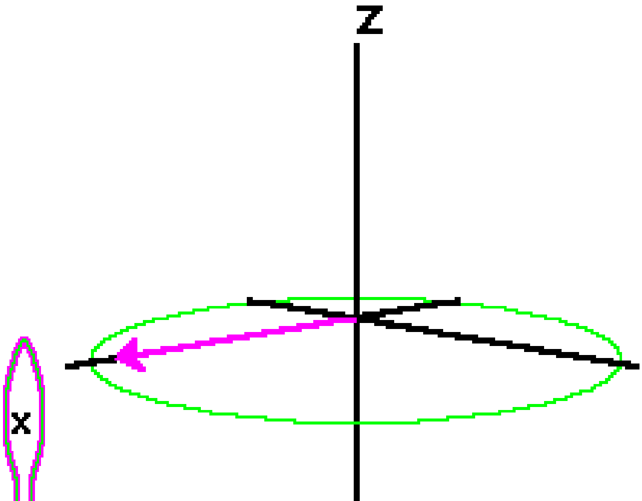


Spin Precession in Radio Frequency (RF) Field



Electromagnetic excitation

- Coil around x axis creates magnetic field along x



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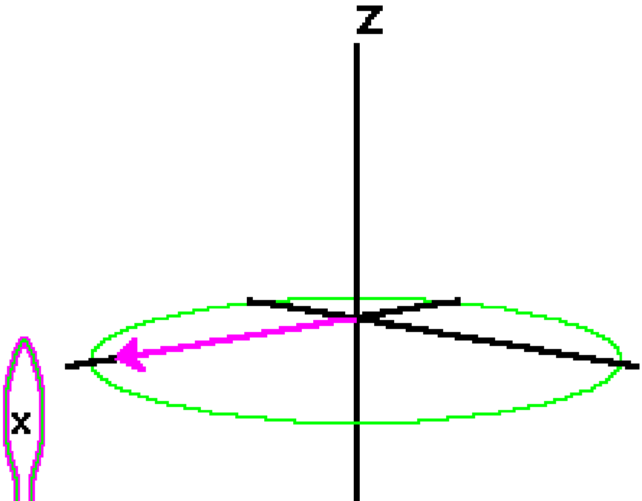

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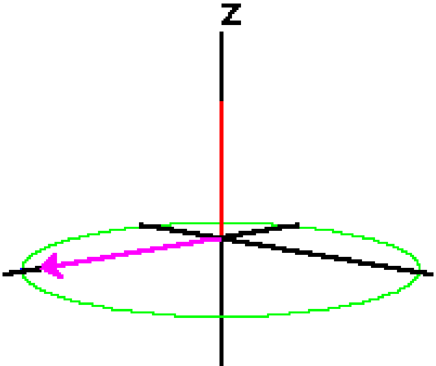
- $\rightarrow$ alternating field $\mathbf{B}_1$ will appear stationary along x' in the rotating frame of reference.

Magnetization vector flip (rotation)

- RF impuls at Larmor frequency f (*resonance*), with amplitude B_1 and duration τ
- $\rightarrow$ magnetization **M** will turn around B_1 $(= x')$ by angle

$$\alpha = 2\pi\gamma\tau B_1 \qquad \text{flip angle}$$



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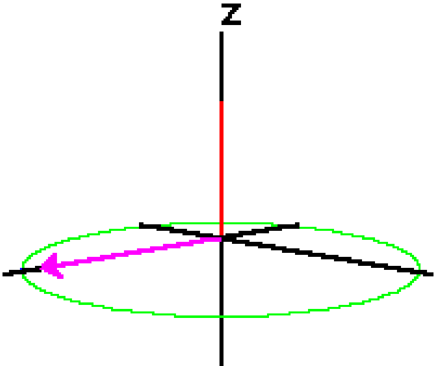

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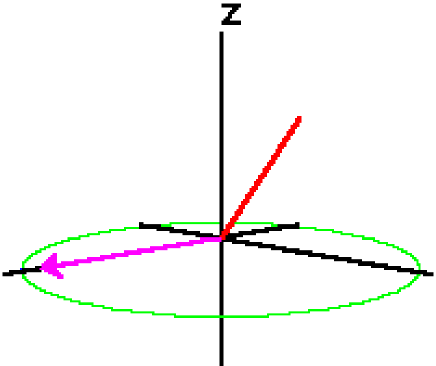

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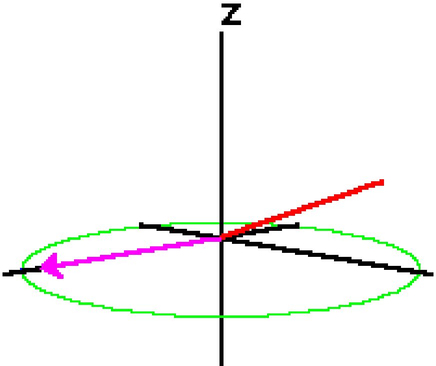

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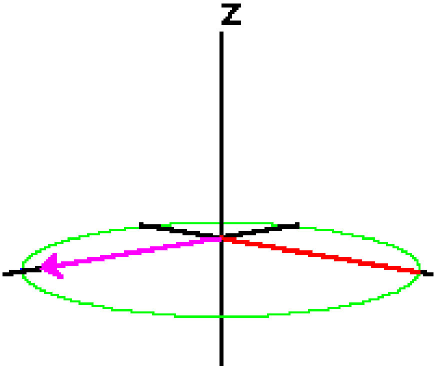

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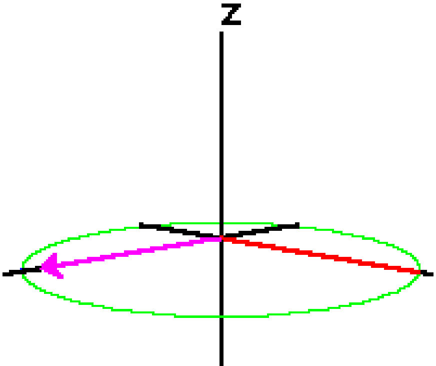

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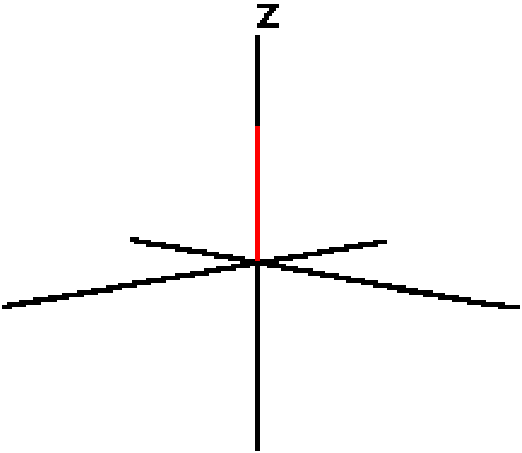

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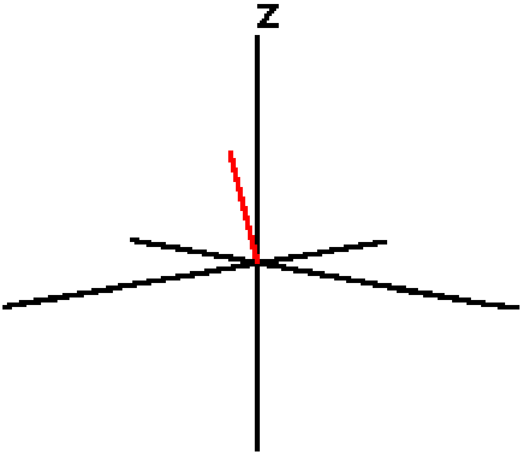

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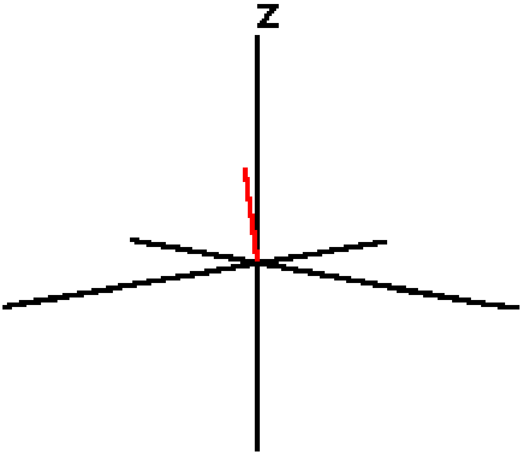

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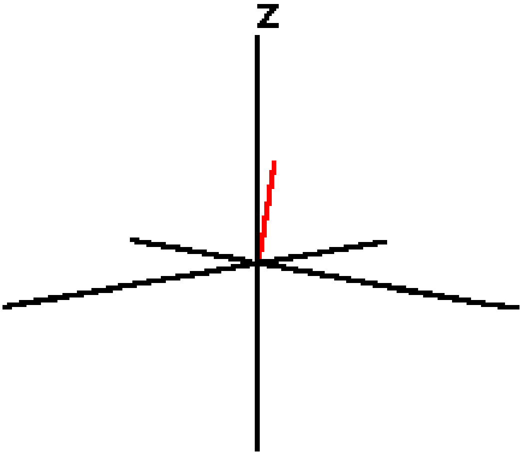

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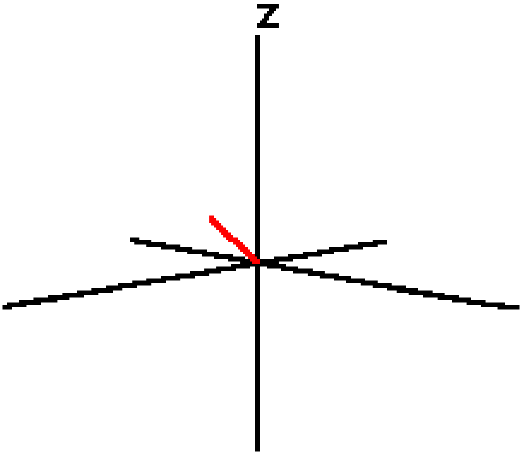

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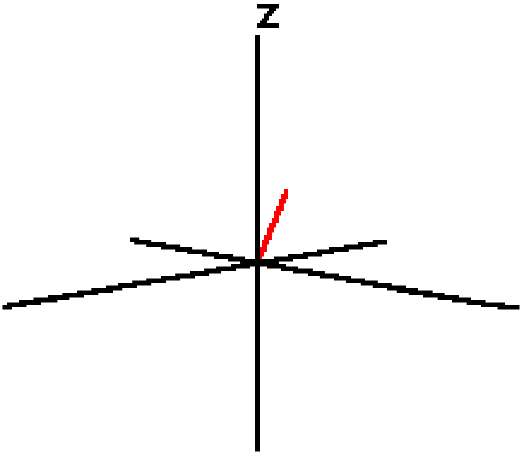

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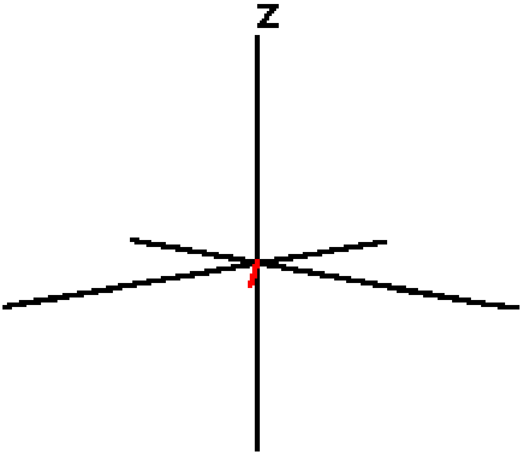

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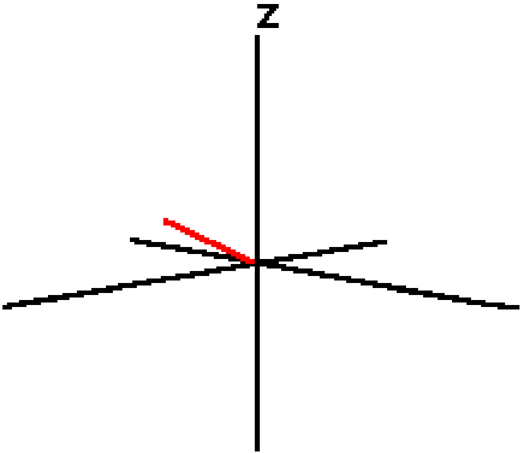

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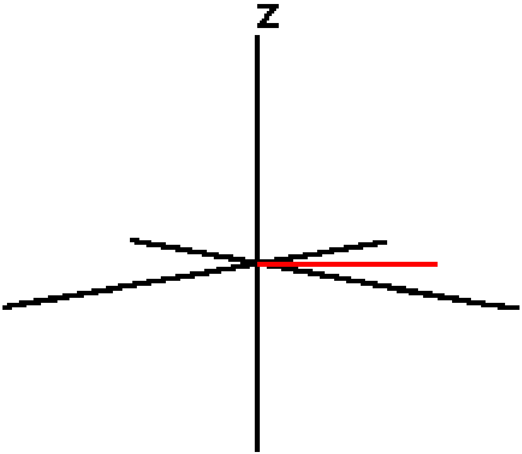

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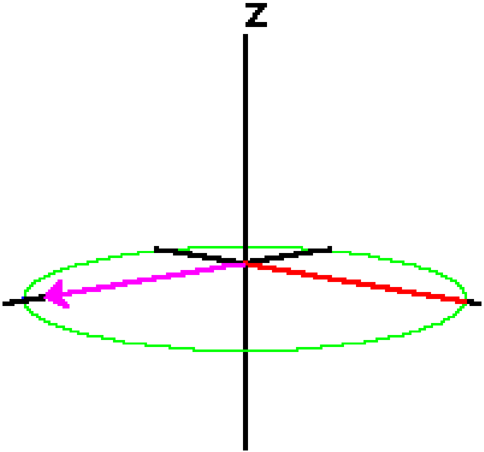

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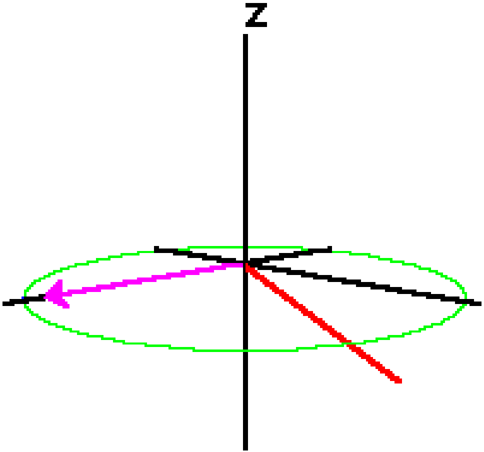

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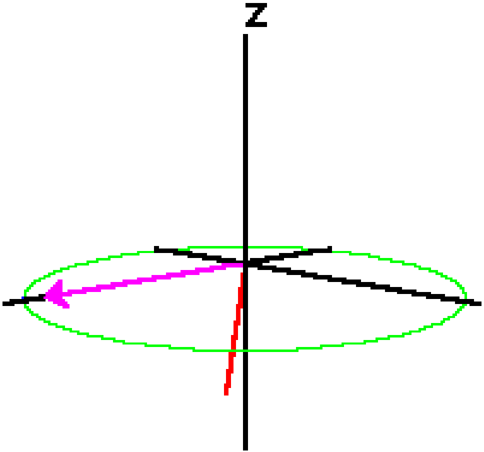

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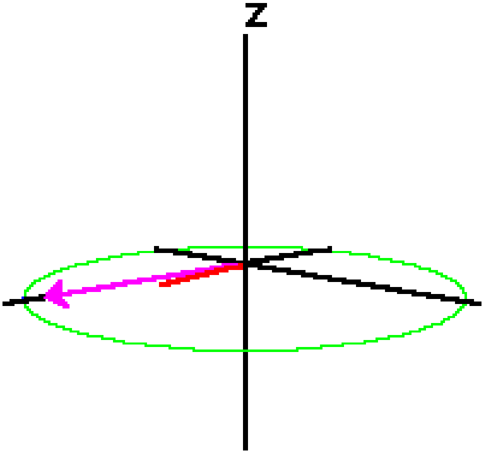
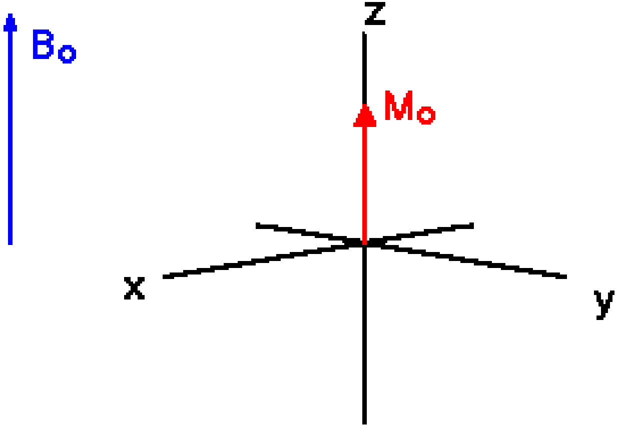


T_1 relaxation

- In equilibrium, $\mathbf{M} = M_0 \mathbf{e}_z$, $M_z = M_0$



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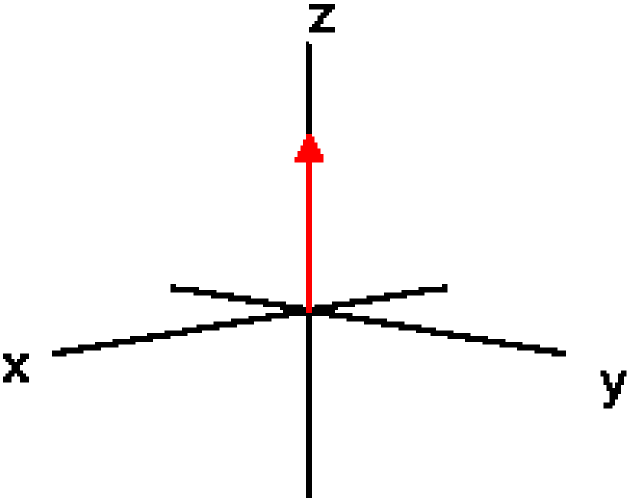

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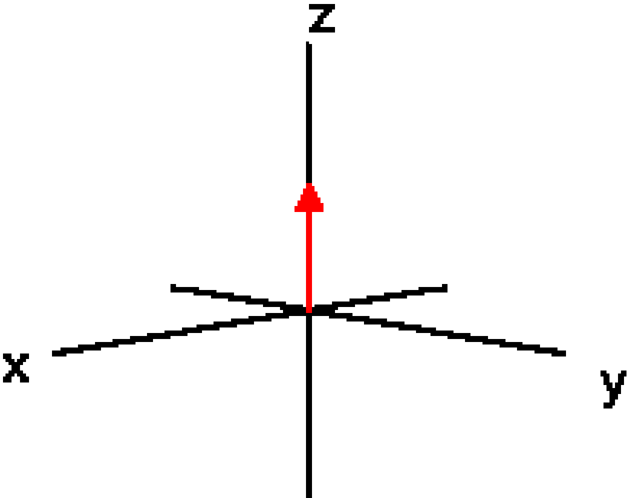

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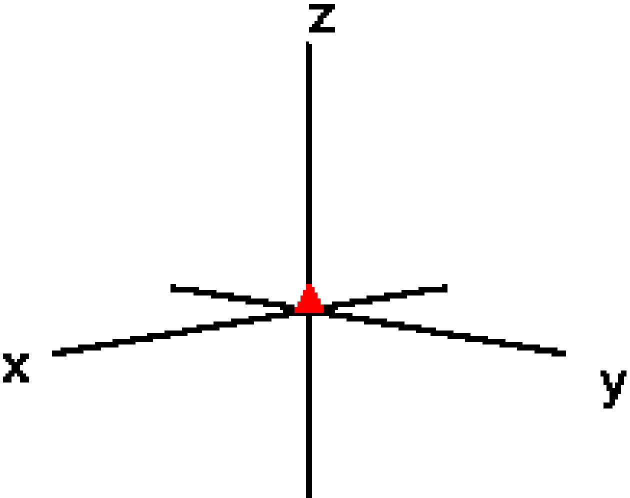

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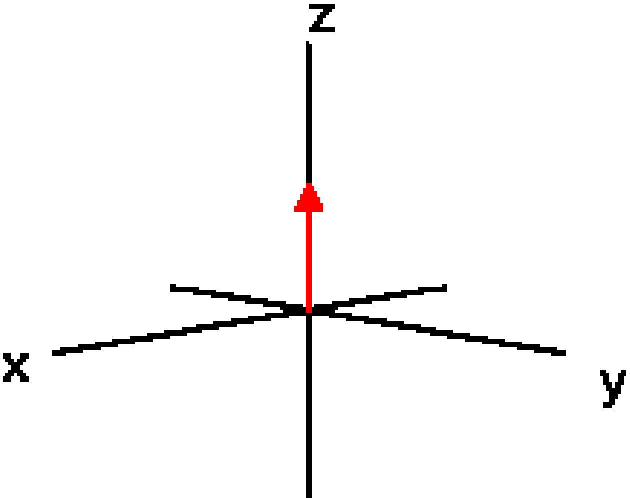

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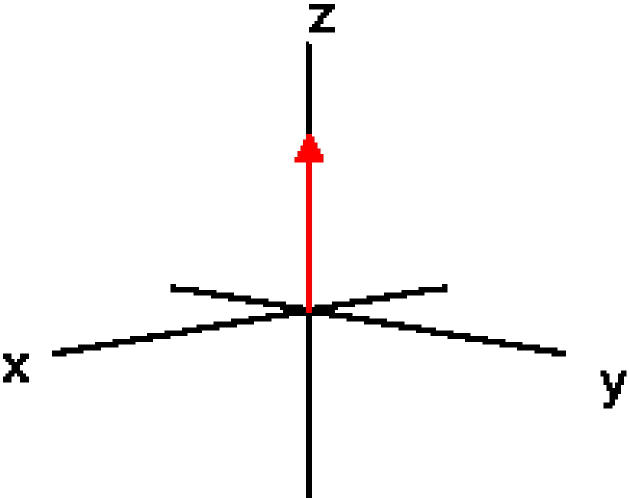
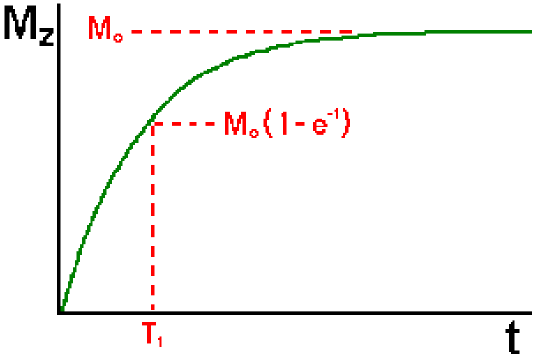


T_1 relaxation (2)

After the pulse M_z returns to equilibrium.

$$M_z = M_0 \left(1 - \mathrm{e}^{-\frac{t}{T_1}}\right)$$



T_1 — spin-lattice relaxation time
the energy is dissipated into the lattice as heat

T_1 relaxation (3)

A stronger/longer pulse may cause e.g. $M_z = -M_0$.

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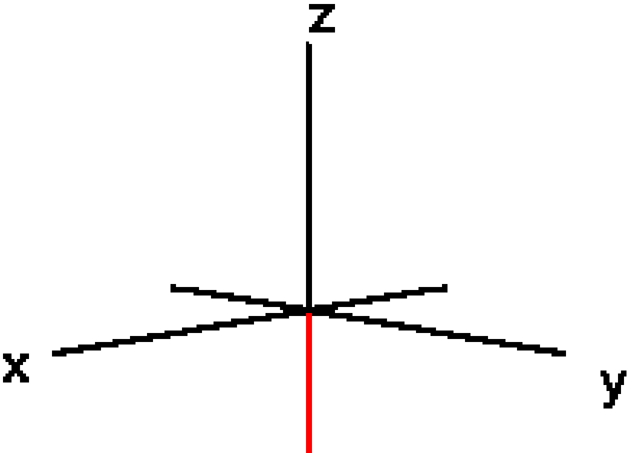

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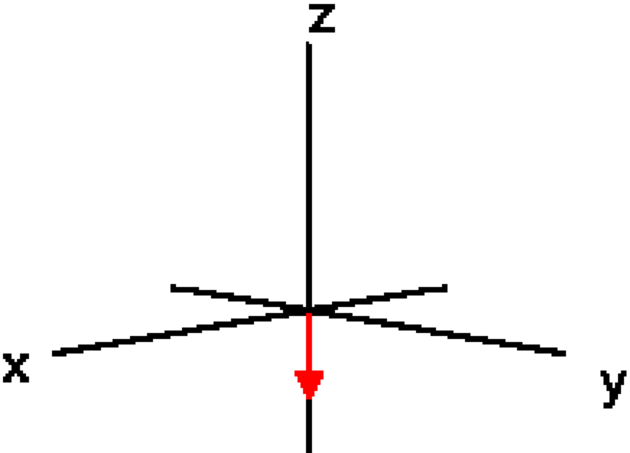

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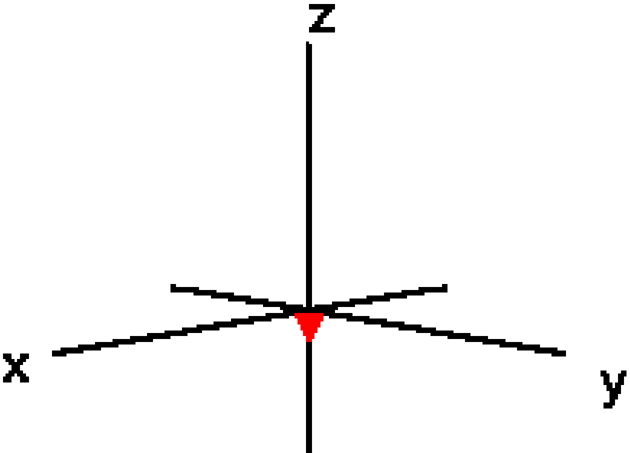

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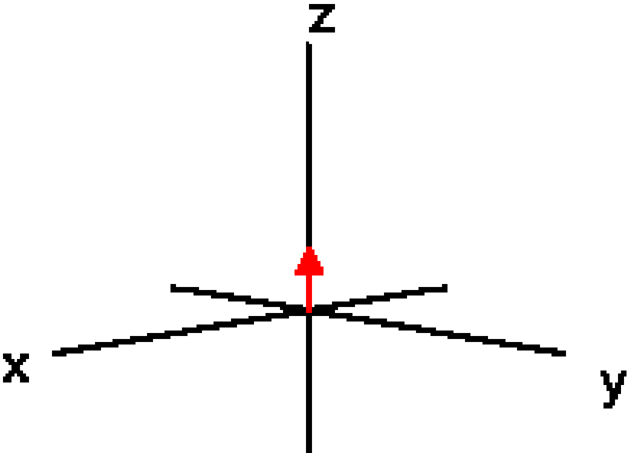

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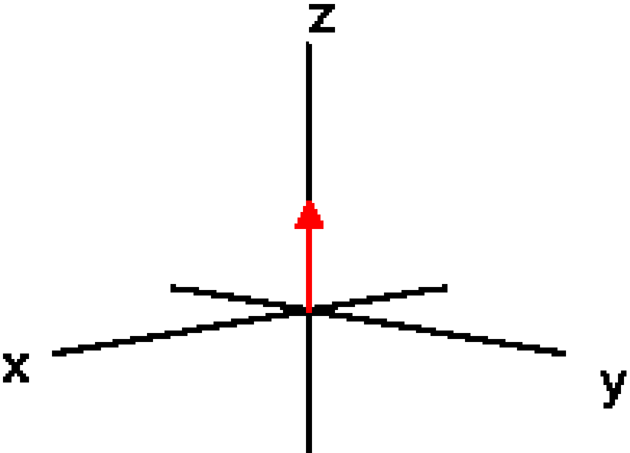

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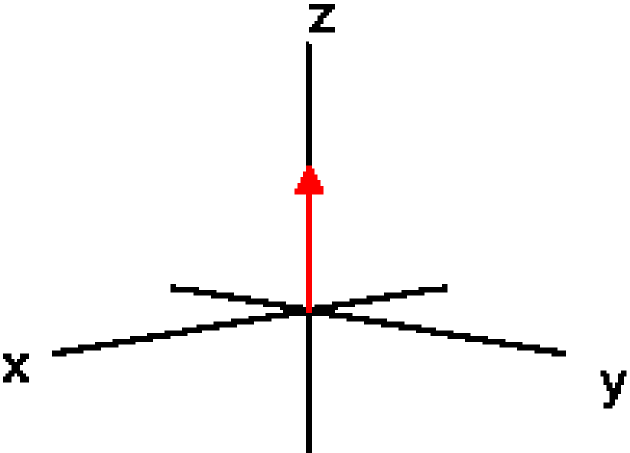

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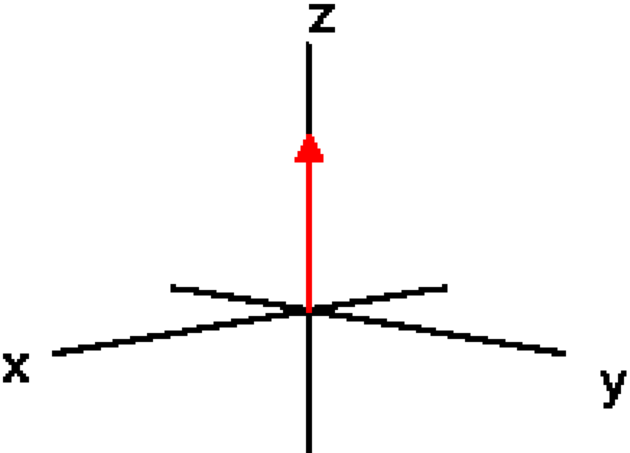

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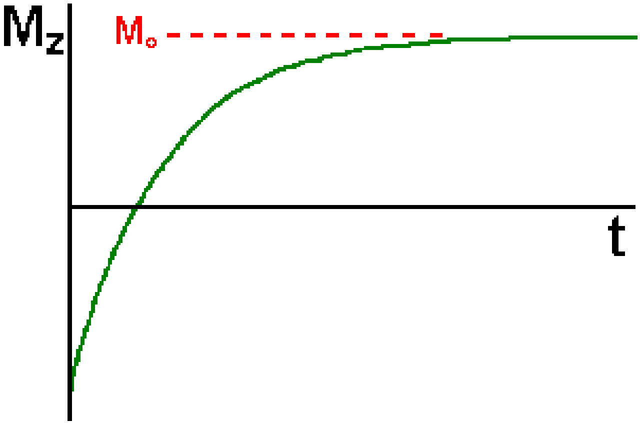

Precession (2)

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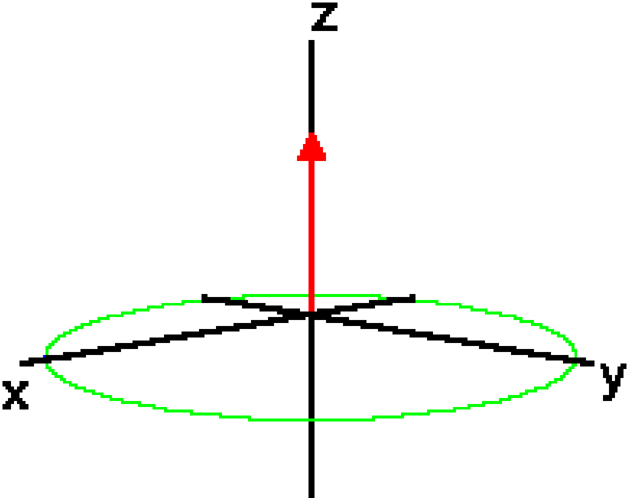

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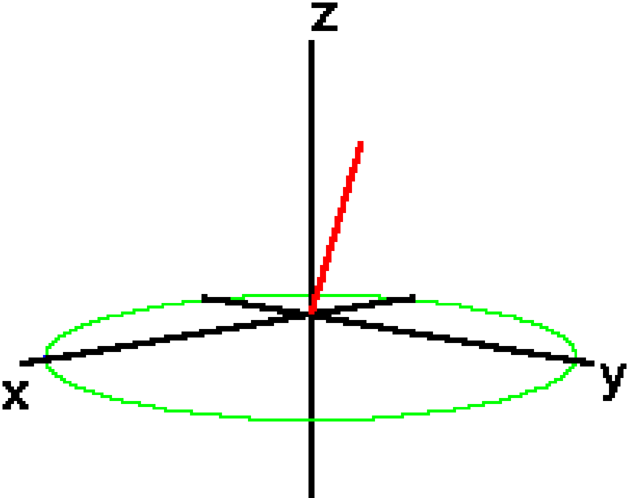

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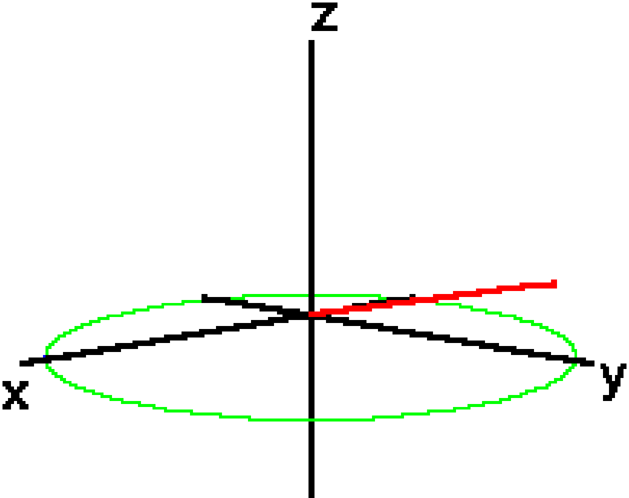

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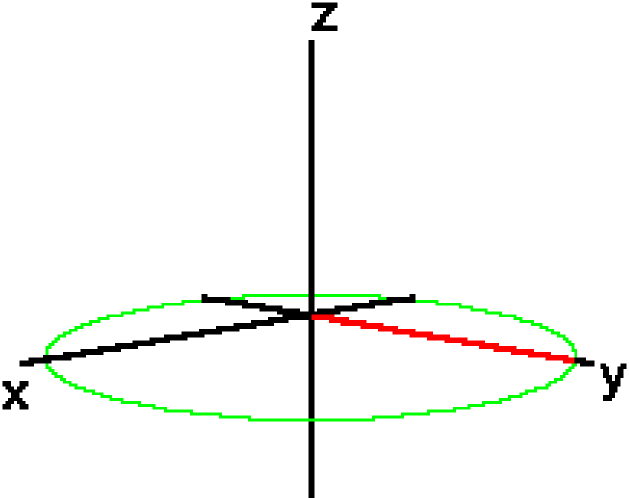

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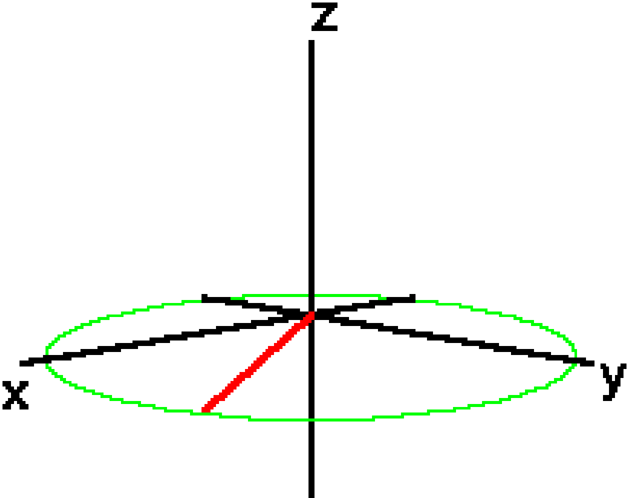

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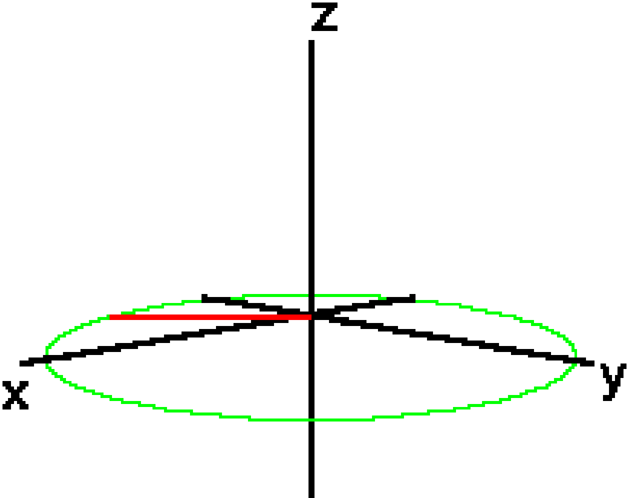

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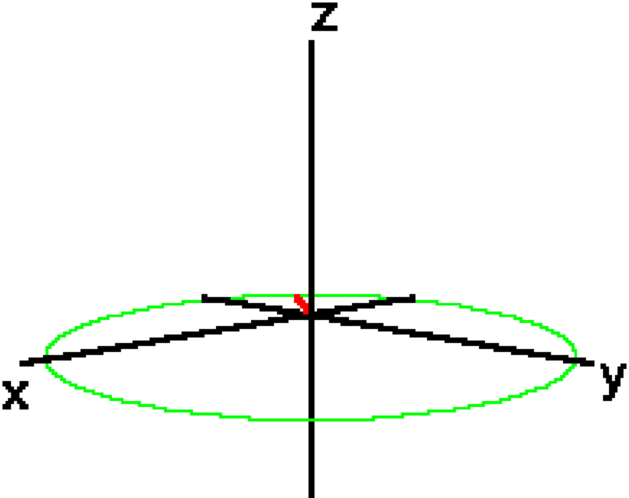

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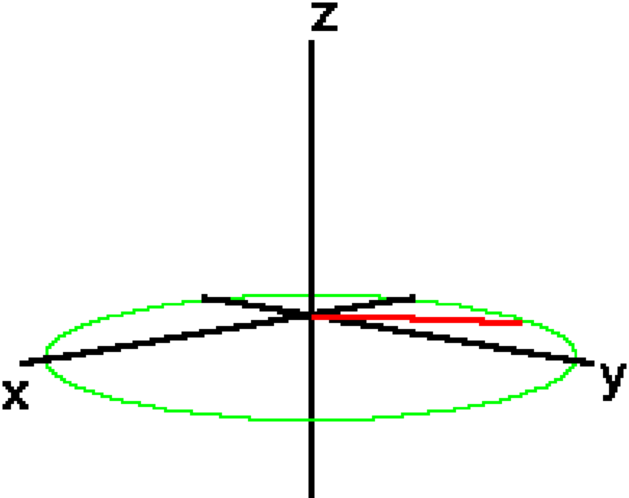

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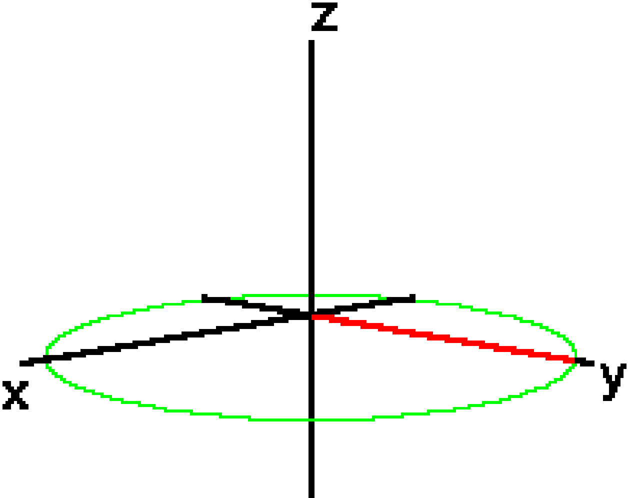

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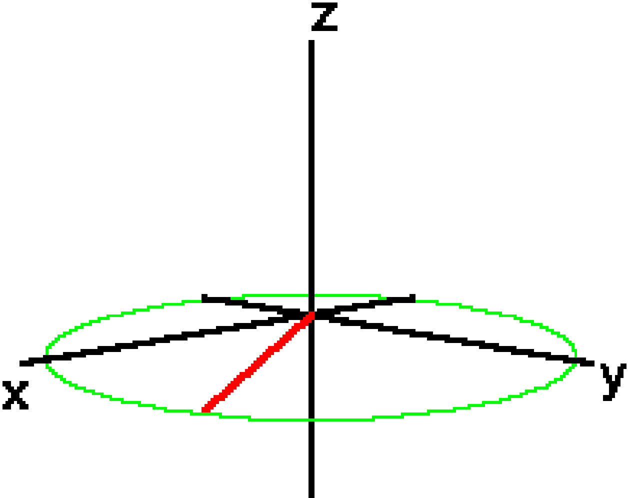

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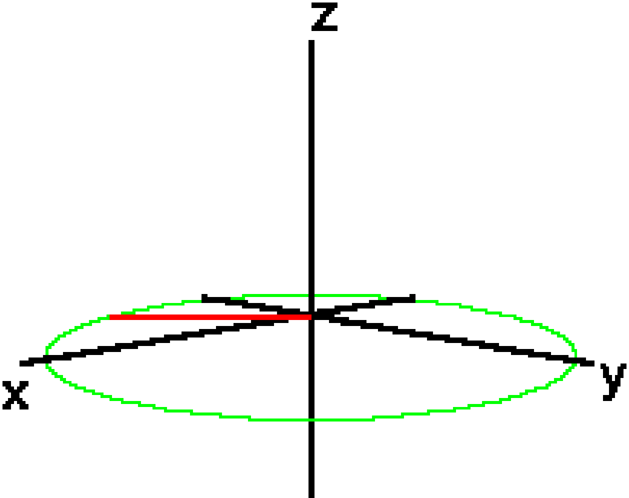

Precession (2)

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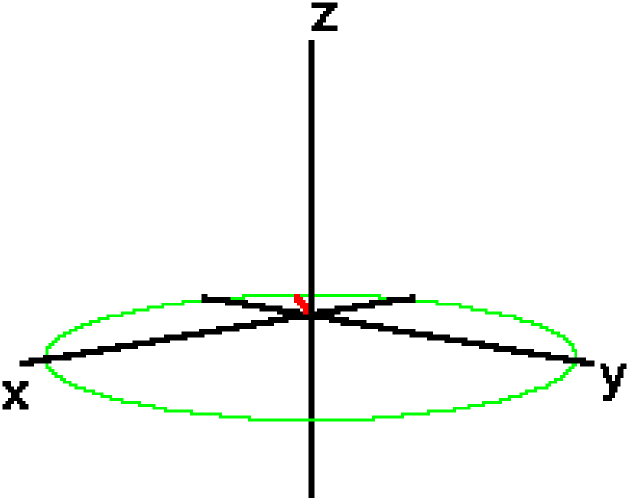

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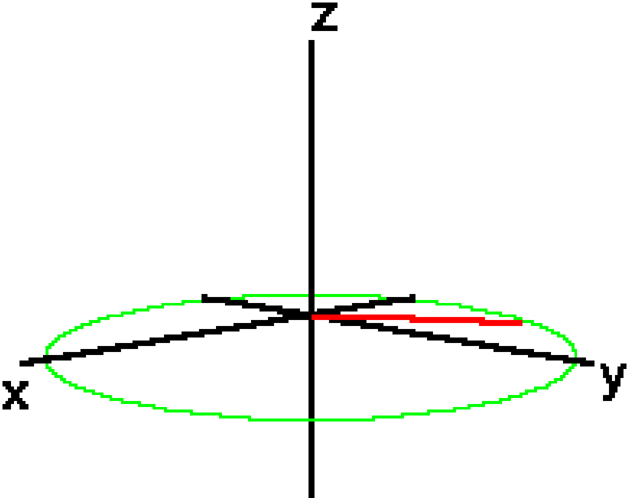
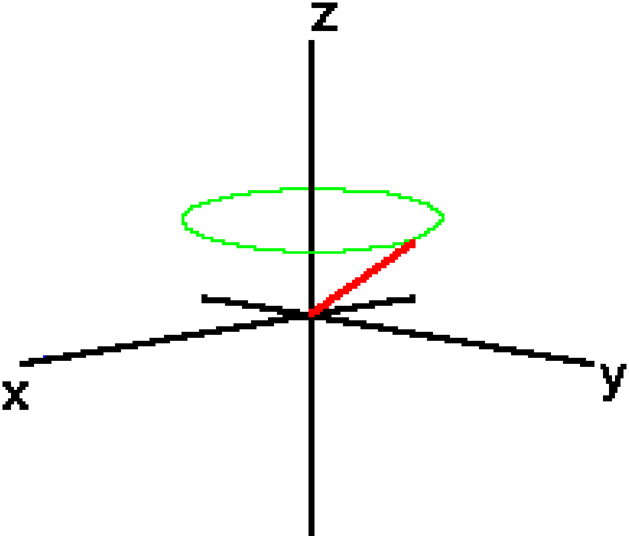


Precession (3)

M does not have to be completely in the *xy* plane



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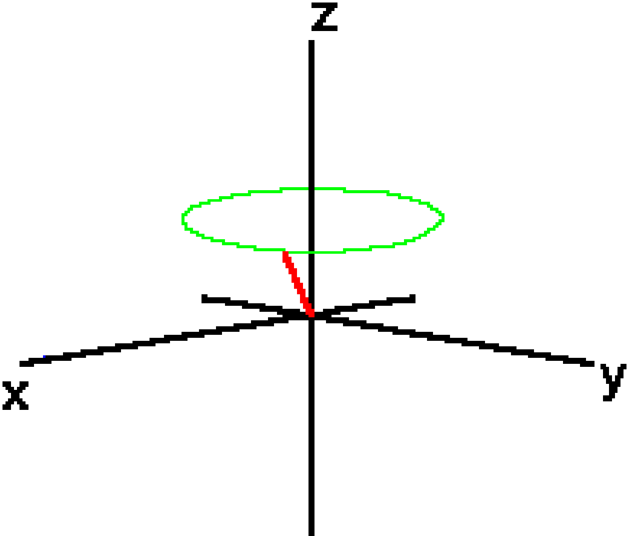

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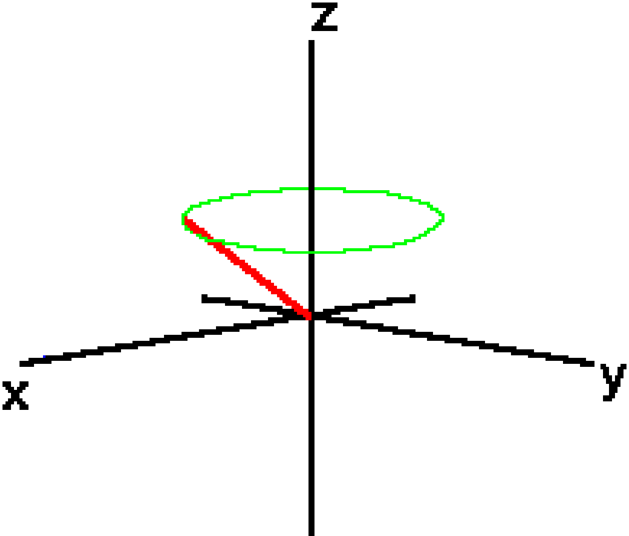

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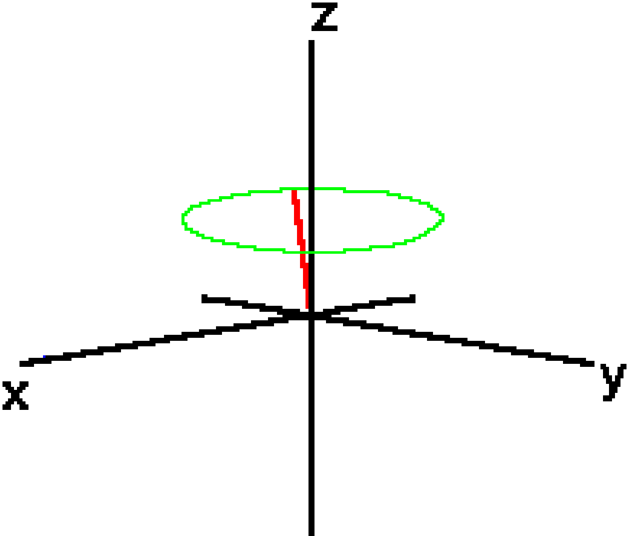

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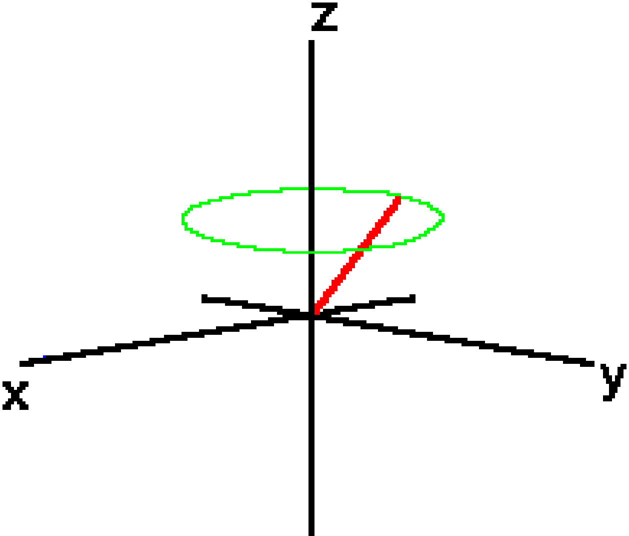
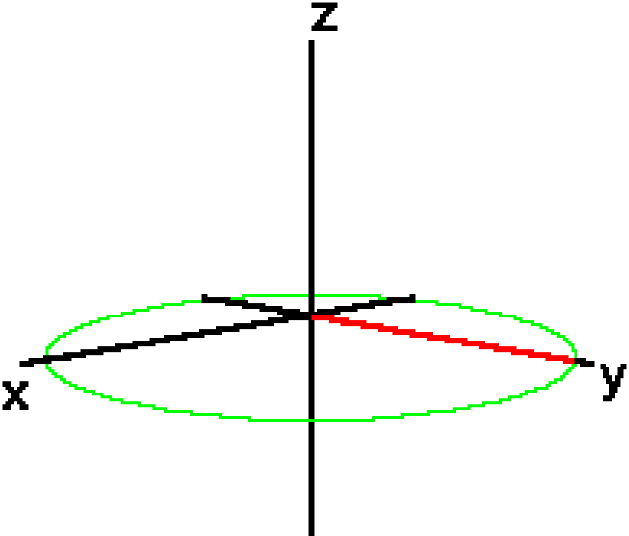


T_2 relaxation

Every spin has a slightly different f $\rightarrow$ desynchronization



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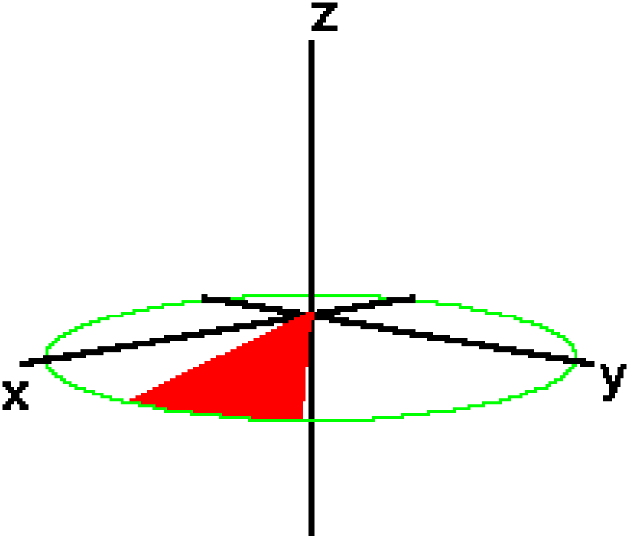

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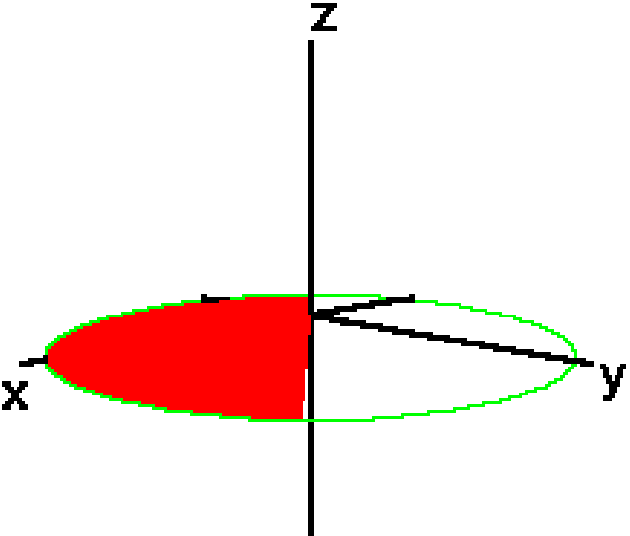

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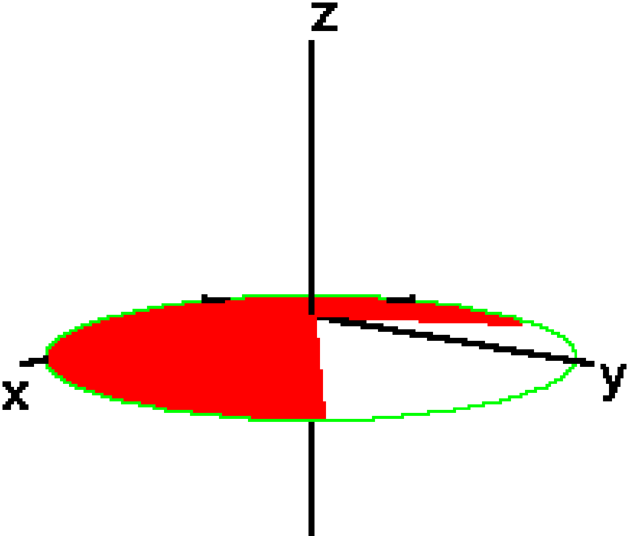

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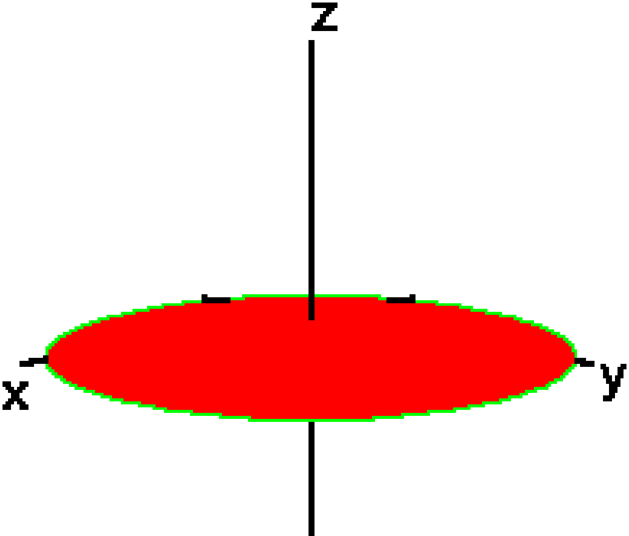
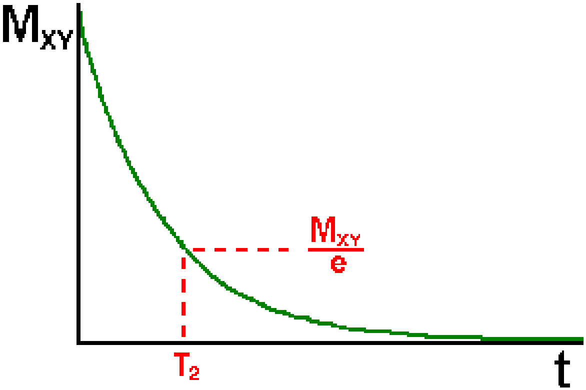


T_2 relaxation (2)

Transversal magnetization M_{xy} decreases

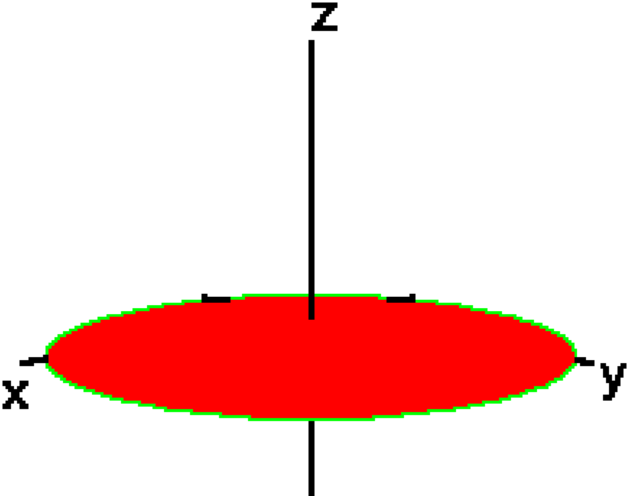
$$M_{xy} = M_{xy0}\mathrm{e}^{-\frac{t}{T_2}}$$



T_2 — spin-spin relaxation time, $T_2 < T_1$

T_1 and T_2 relaxations

- Transversal magnetization M_{xy} decreases
- At the same time (but more slowly) M_z returns to M_0.



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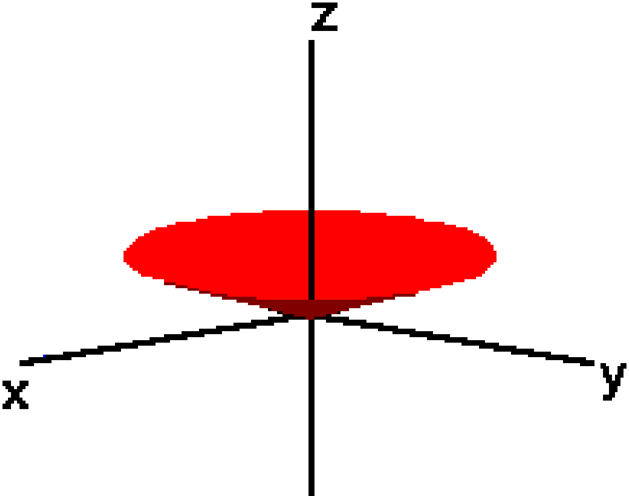

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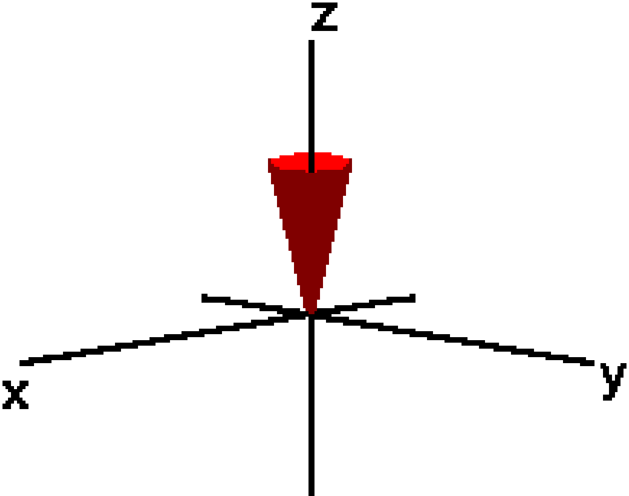

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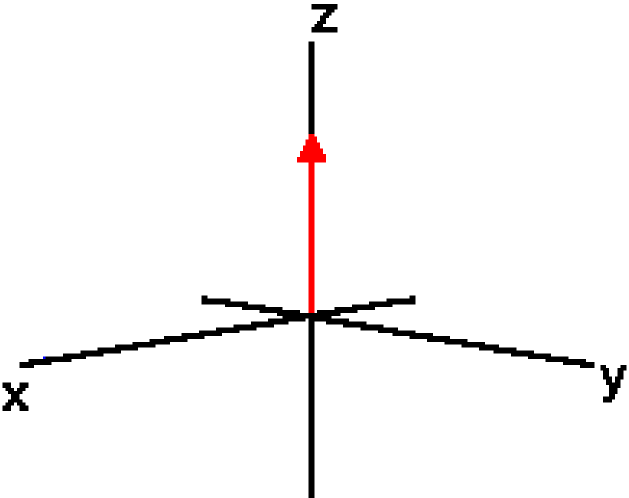

Reasons for the T_2 relaxation

- Molecular interation (T_2)
- Inhomogeneity of the magnetic field (T_2^{inhom})

Combined time constant T_2^*:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^{\text{inhom}}}$$

Other factors influencing relaxation

- Molecular movement (because of the magnetic field inhomogeneity)
- Temperature
- Viscosity

Typical relaxation times

	1.5 T		3 T	
tissue	T_1 [ms]	T_2 [ms]	T_1 [ms]	T_2 [ms]
fat	260	80	420	100
muscle	870	45	1300	40
brain (gray matter)	900	100	1600	100
brain (white matter)	780	90	900	70
liver	500	40	800	34
cerebrospinal fluid	2400	160	4100	500

Reported values differ significantly.

Bloch equation

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = \gamma \mathbf{M} \times \mathbf{B}$$

where **B** is the total magnetic field $(\mathbf{B}_0 + \mathbf{B}_1)$.

Bloch equation (2)

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = \gamma \mathbf{M} \times \mathbf{B}$$

substituting for **B**, add losses and use the rotating frame of reference

$$\frac{\mathrm{d}M_{x'}}{\mathrm{d}t} = (\omega_0 - \omega)M_{y'} - \frac{M_{x'}}{T_2}$$
$$\frac{\mathrm{d}M_{y'}}{\mathrm{d}t} = -(\omega_0 - \omega)M_{x'} + 2\pi\gamma B_1 M_z - \frac{M_{y'}}{T_2}$$
$$\frac{\mathrm{d}M_z}{\mathrm{d}t} = -2\pi\gamma B_1 M_{y'} - \frac{M_z - M_{z0}}{T_1}$$

where $\omega_0 = 2\pi f_0 = 2\pi\gamma B_0$, ω is the spin rotation frequency.

Bloch equation diagram