BPS 4103 Medical Imaging

Tuesday January 10, 2012

An Extension on NMR Spectroscopy to MRI

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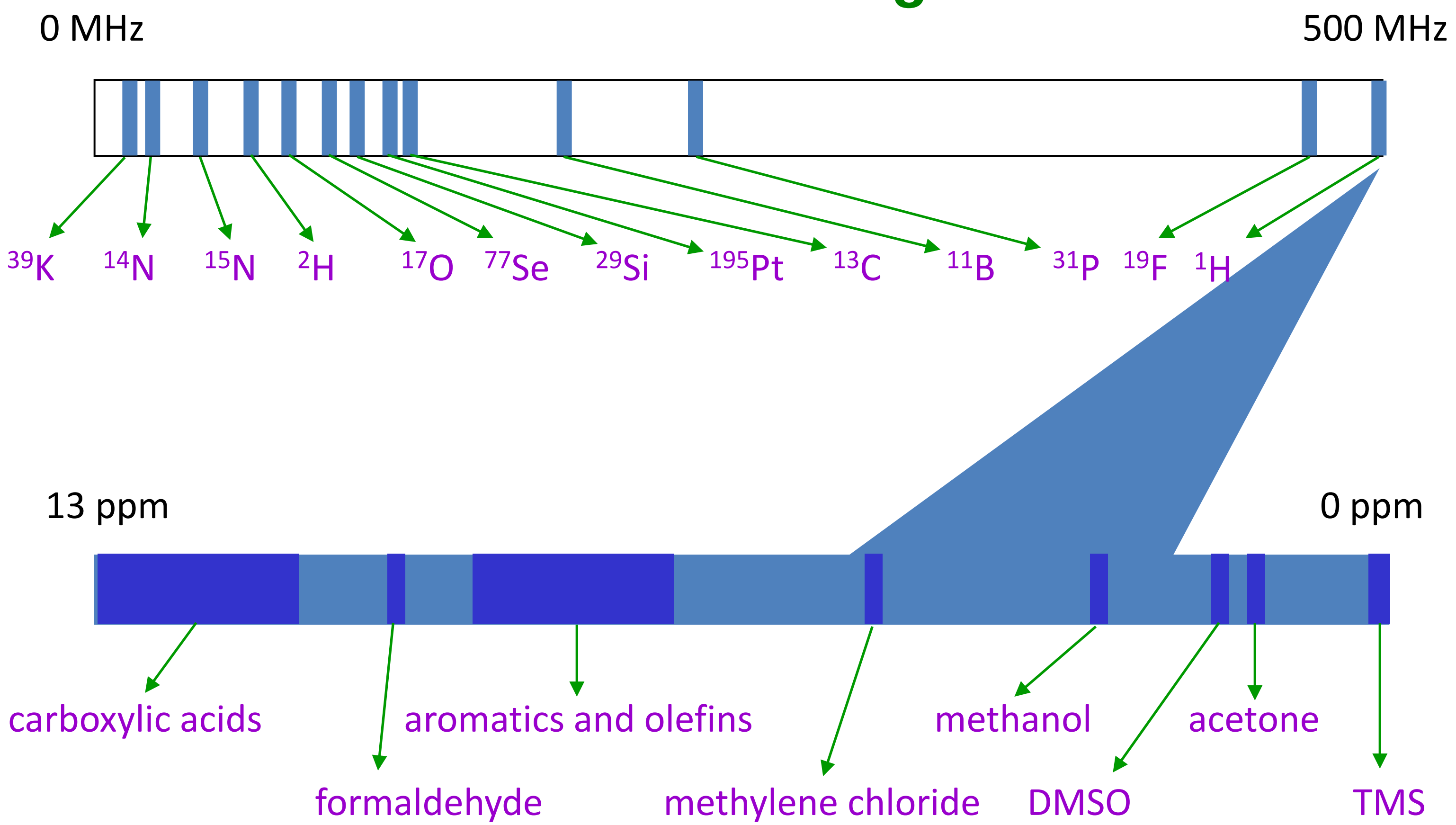
Resonance Frequencies of Various nuclei in an 11.7 Tesla Magnet

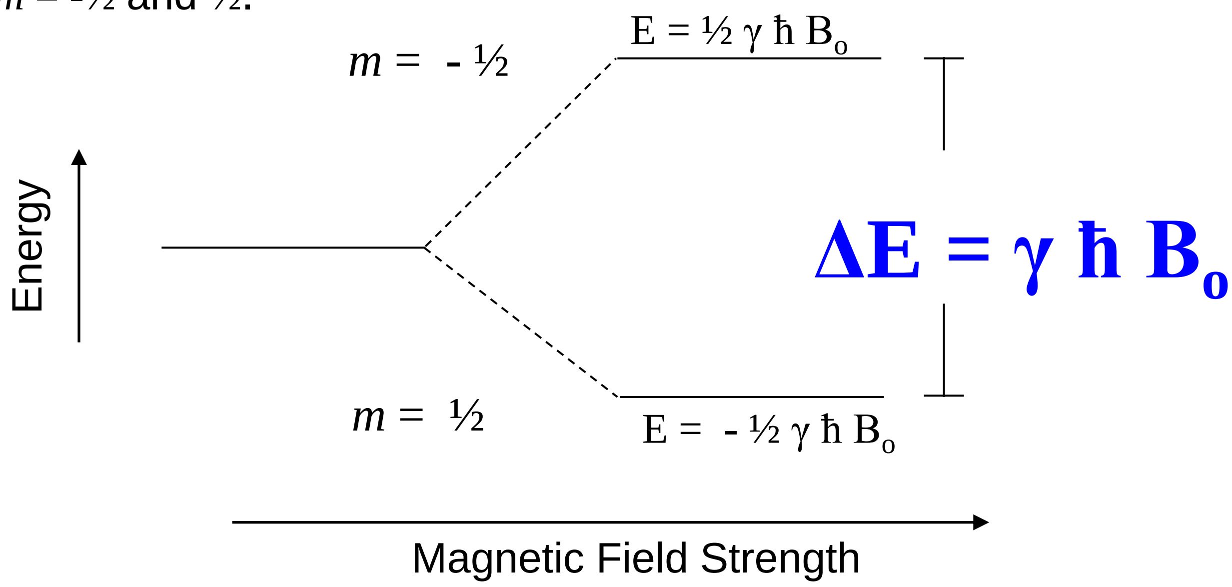


Nuclei with spin quantum number $I = ½$ can be thought of as small bar magnets. If an external magnetic field, B_o, is applied, the Energy, E, of the nucleus is given by:

$$E = -\gamma \hbar m B_o$$

where γ is a constant for the nucleus called the gyromagnetic ratio and m is a quantum number which takes on values of ½ and – ½ for a spin $I = ½$ nucleus.

For $I = ½$, $m = -½$ and ½.



There is no net magnetization in the absence of a magnetic field. The net bulk magnetization builds up when the sample is placed in the magnet.

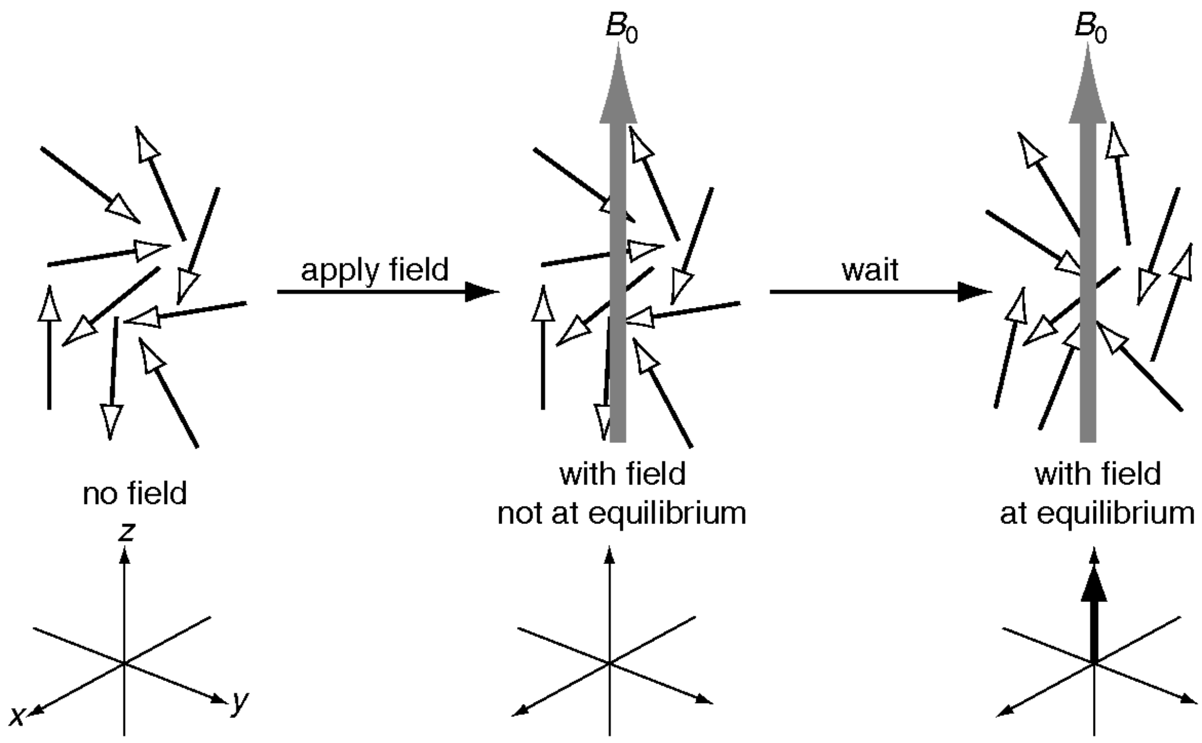


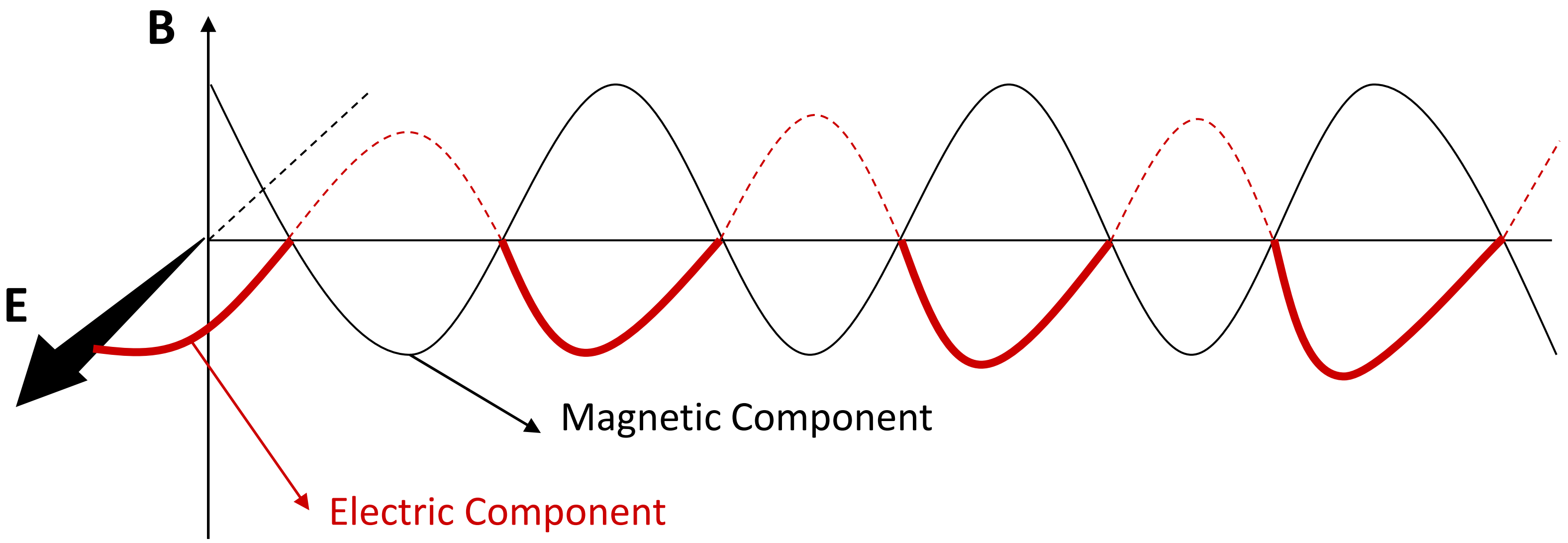
Figure taken from James Keeler, *Understanding NMR Spectroscopy,* Wiley (2005).

Since Energy and frequency are related by $\Delta E = h\,\upsilon$, we can express the energy as a frequency as follows:

$$\upsilon = (\gamma/2\pi)\, B_o$$ **Larmor Equation**

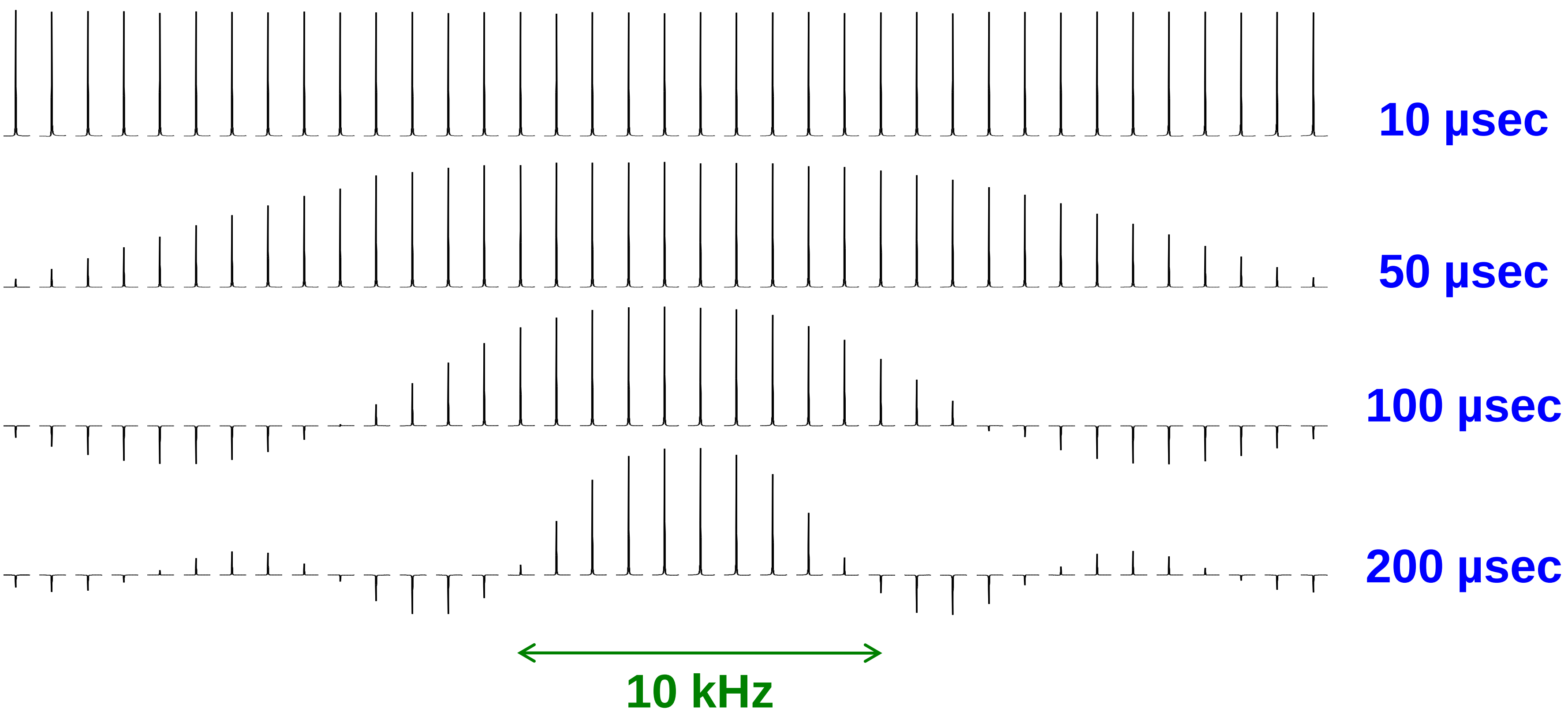
For readily available magnets, υ is in the radio frequency region of the electromagnetic spectrum. The Larmor frequency of a nucleus depends not only on the gyromagnetic ratio, γ, but also on the strength of the external applied magnetic field, B_o.

In order to go from one energy state to another, electromagnetic radiation must be applied with an energy equal to the energy difference between the states. This is typically radio energy. Expressed differently, the frequency of the oscillating magnetic component of the electromagnetic wave must be equal to the Larmor frequency of the nucleus.

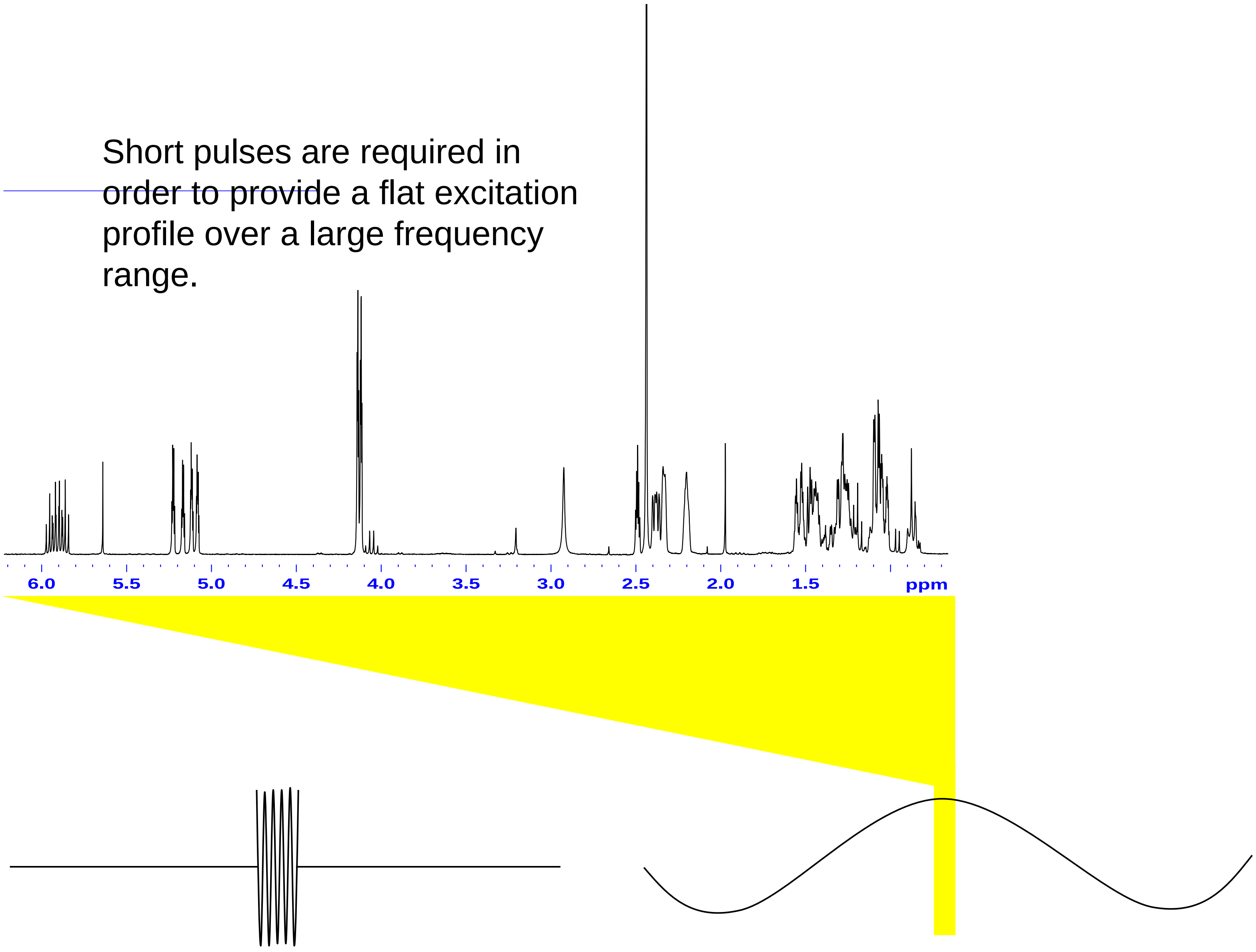


Pulse Widths and Excitation Profiles

In Fourier transform (FT) NMR spectrometers, a short (i.e 1 – 100 μsec) pulse of radio frequency (rf) at the Larmor frequency, υ_o, is applied to the sample. The excitation profile of the pulse is determined by Fourier analysis. Very long pulses (i.e. msec – sec) excite very narrow frequency ranges while very short pulses (μsec) excite very wide frequency ranges.



Short pulses are required in order to provide a flat excitation profile over a large frequency range.

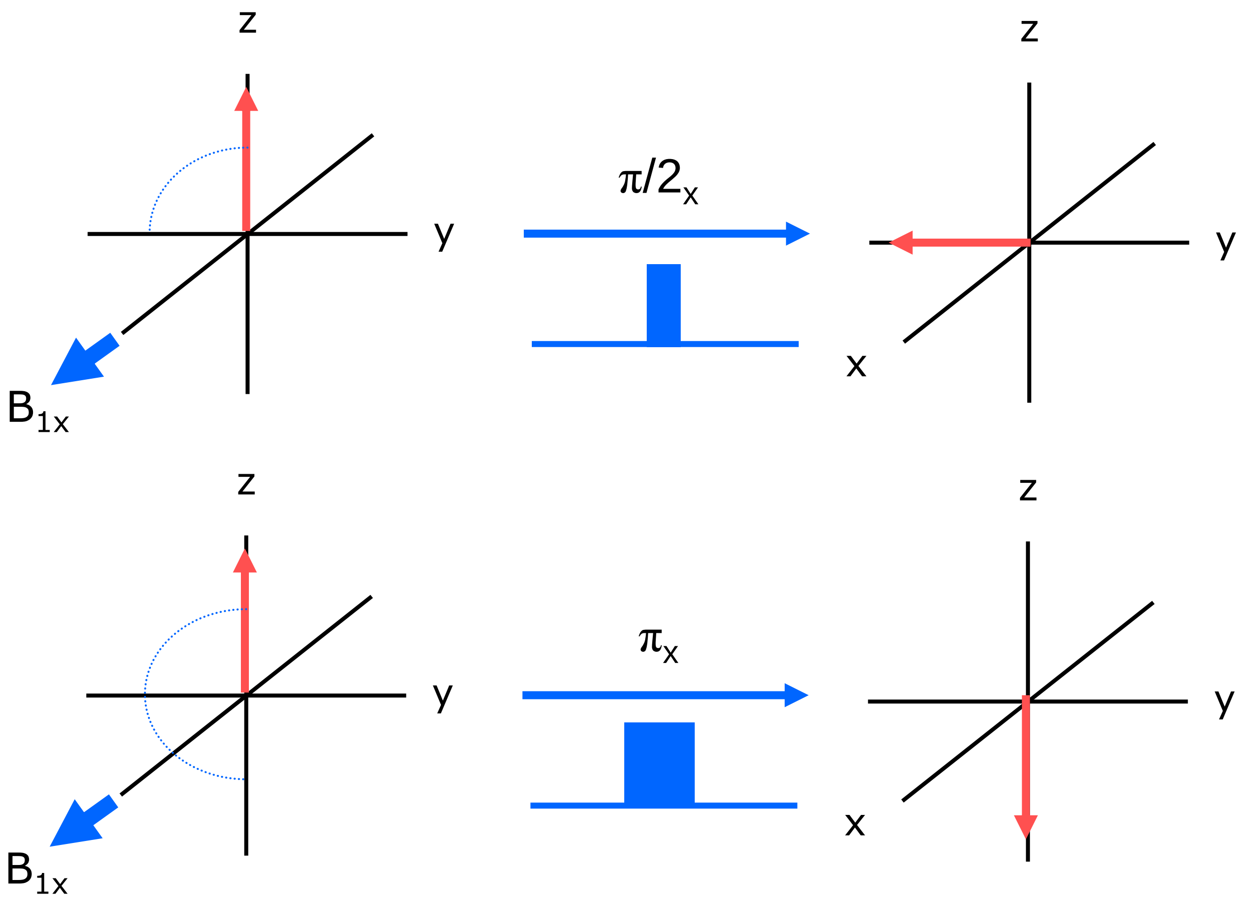


Effect of Radio Frequency Pulses

Pulses of radio waves at the Larmor frequency can be applied at any desired phase. During the pulse, the net magnetization vector rotates about the axis of the pulse phase. The rotation angle, α, is given by,

$$\boldsymbol{\alpha = \gamma B_1 t_p}$$

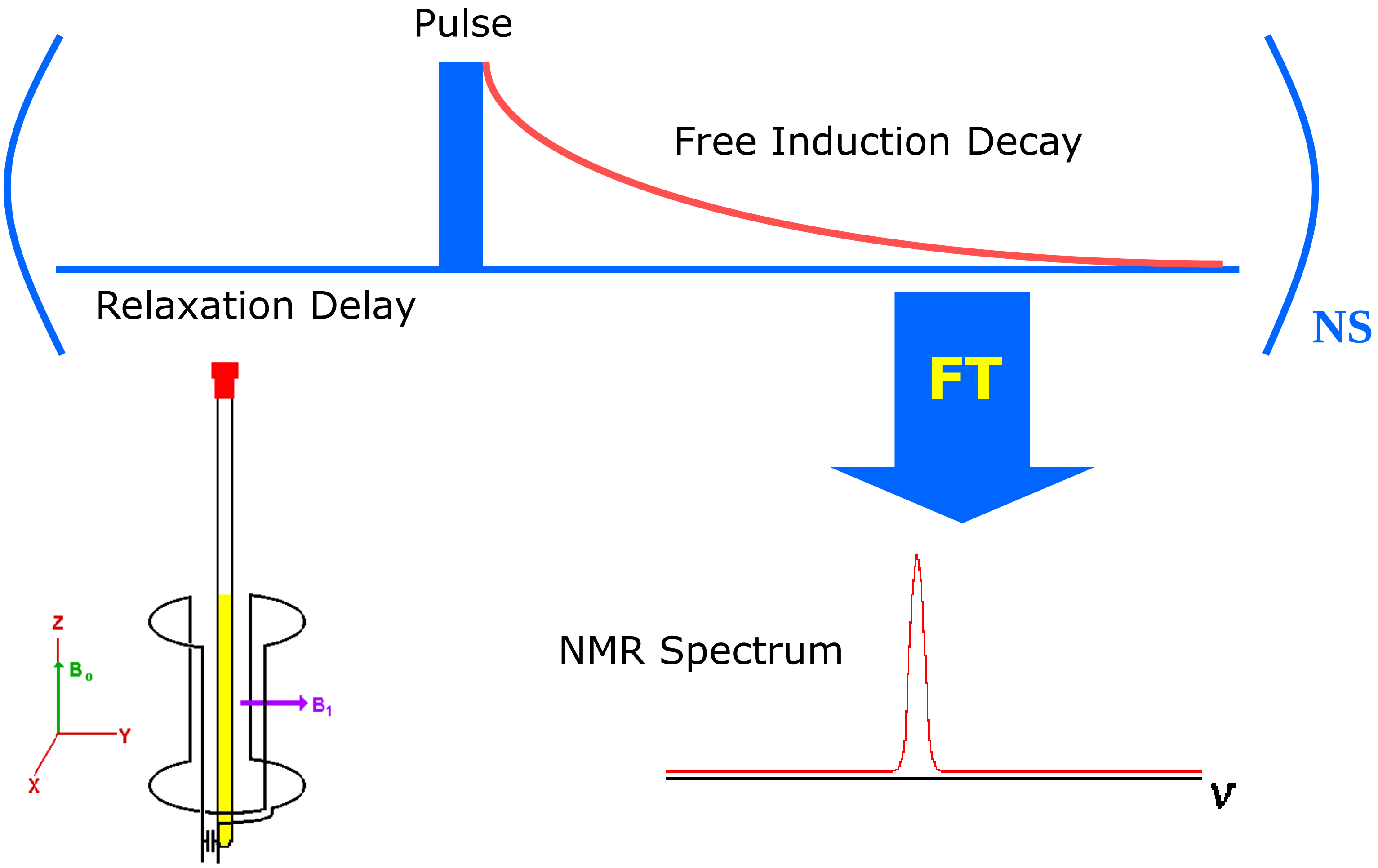
Where γ is the gyromagnetic ratio for the nucleus, B_1 is the amplitude of the pulse and t_p is the duration of the pulse.



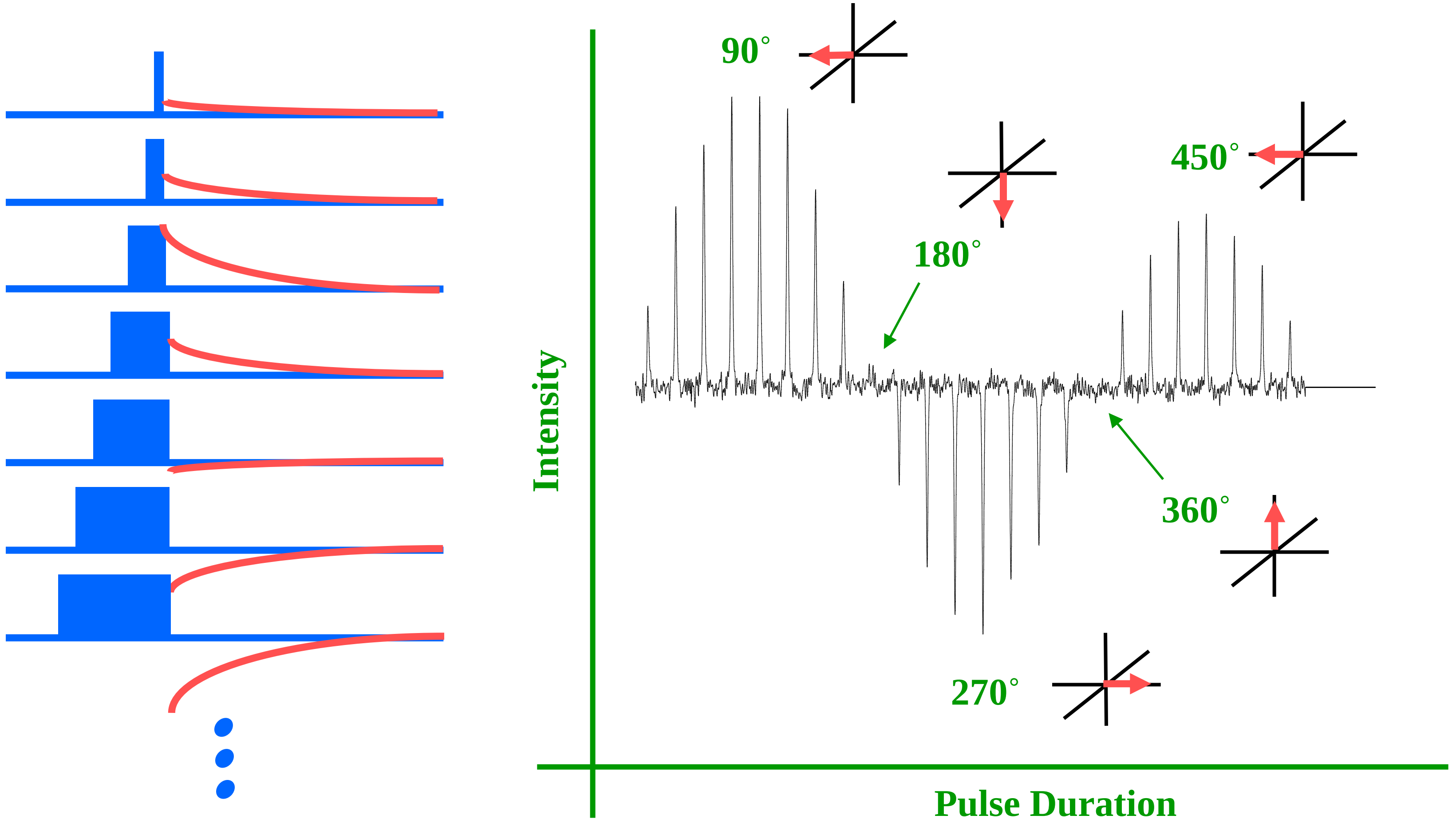
The NMR spectrometer measures magnetization only in the xy plane.

Delivery of Pulses and Detection of The NMR Signal

The change in magnetization in the xy plane after the pulse induces a time dependant voltage in a coil around the sample. This signal is called the Free Induction Decay (FID). The Fourier transform of this signal is the NMR spectrum.

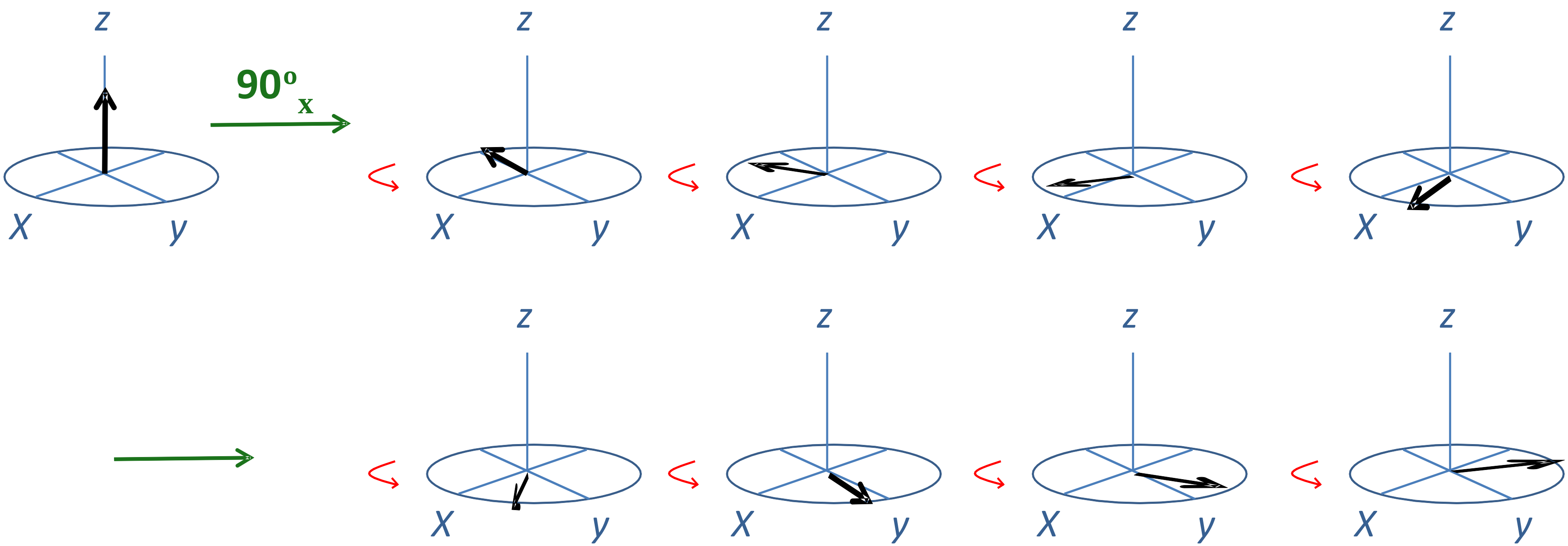


Pulse Calibration

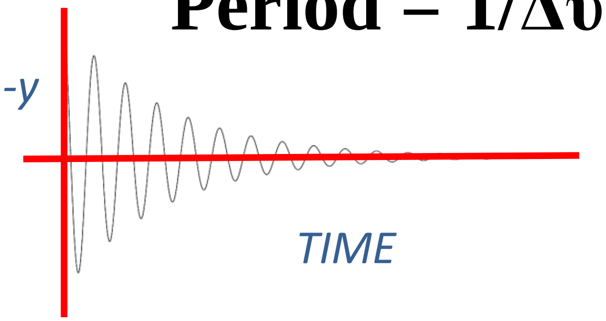


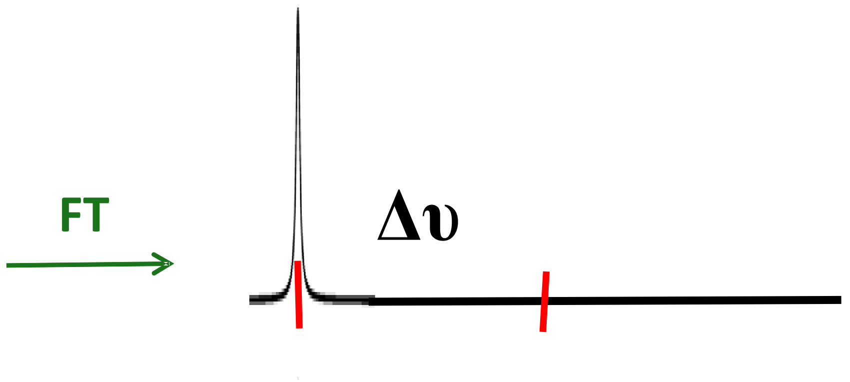
For NMR pulse sequences, it is very important to know what the 90 degree pulse duration must be set to at a particular power level.

The Frequency of an NMR Signal

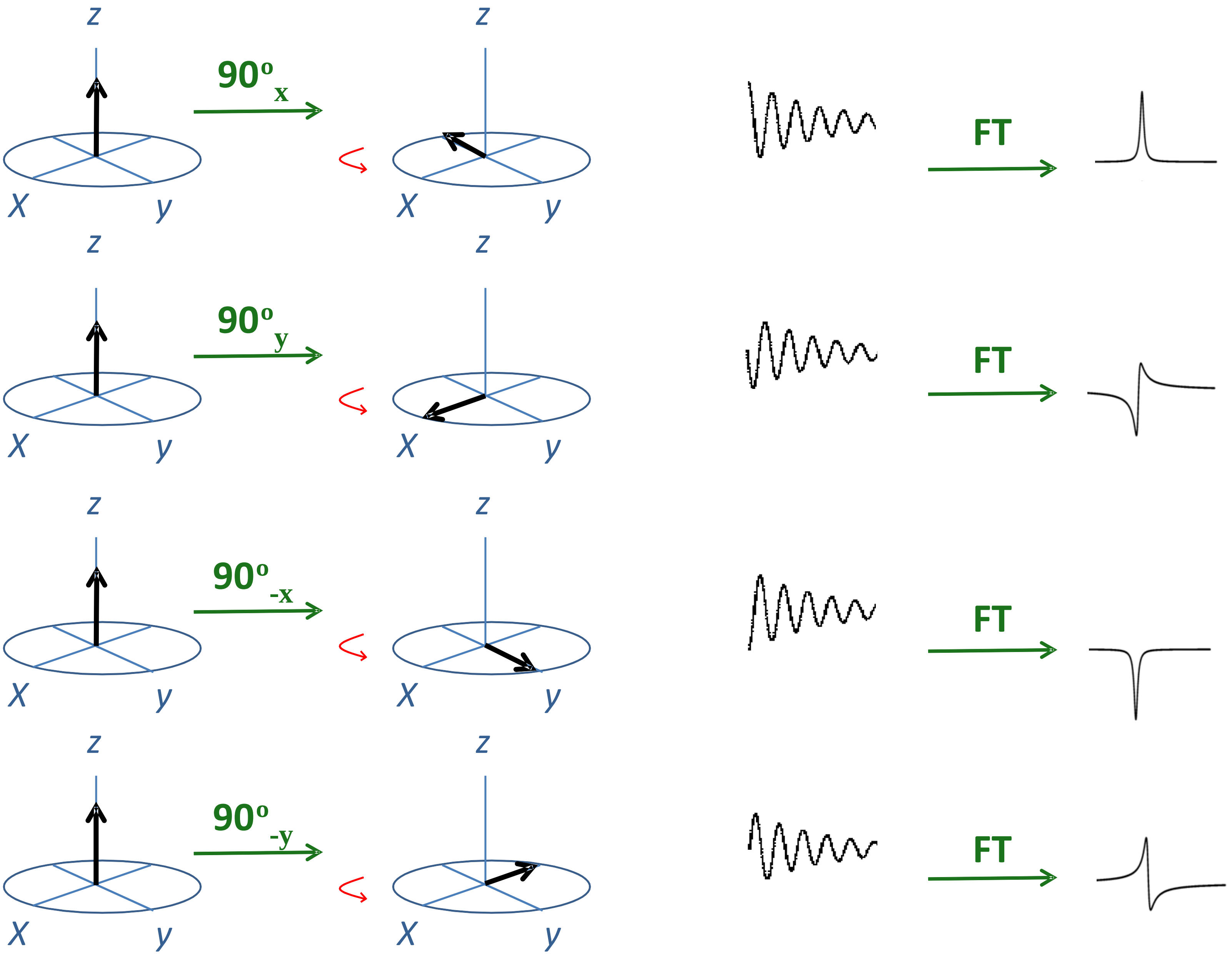


Period = 1/Δυ





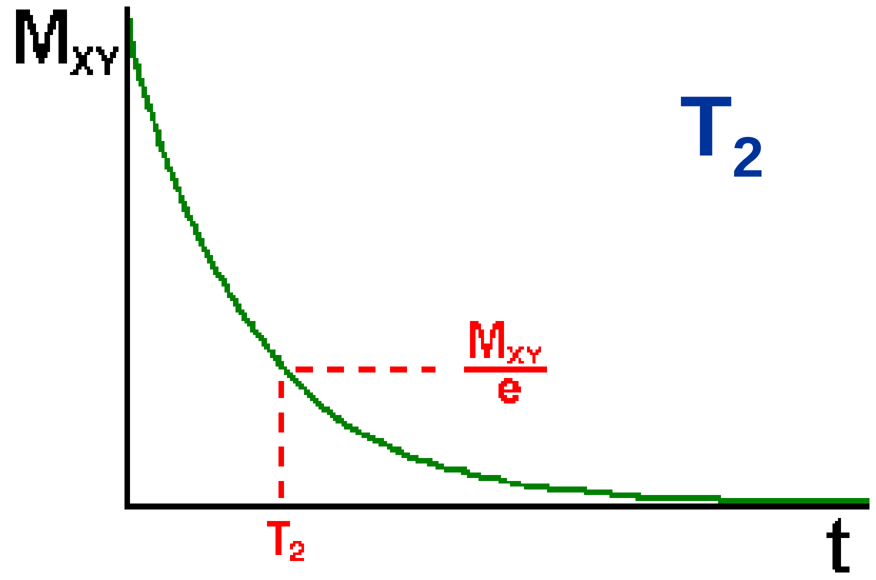
The Phase of an NMR Signal



Relaxation

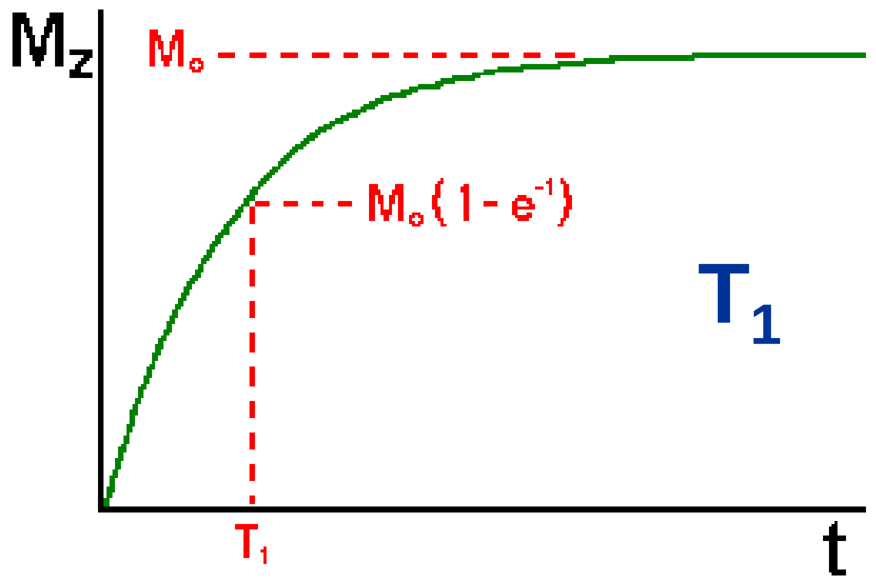
T_2 relaxation is the decay of transverse magnetization

Line Width

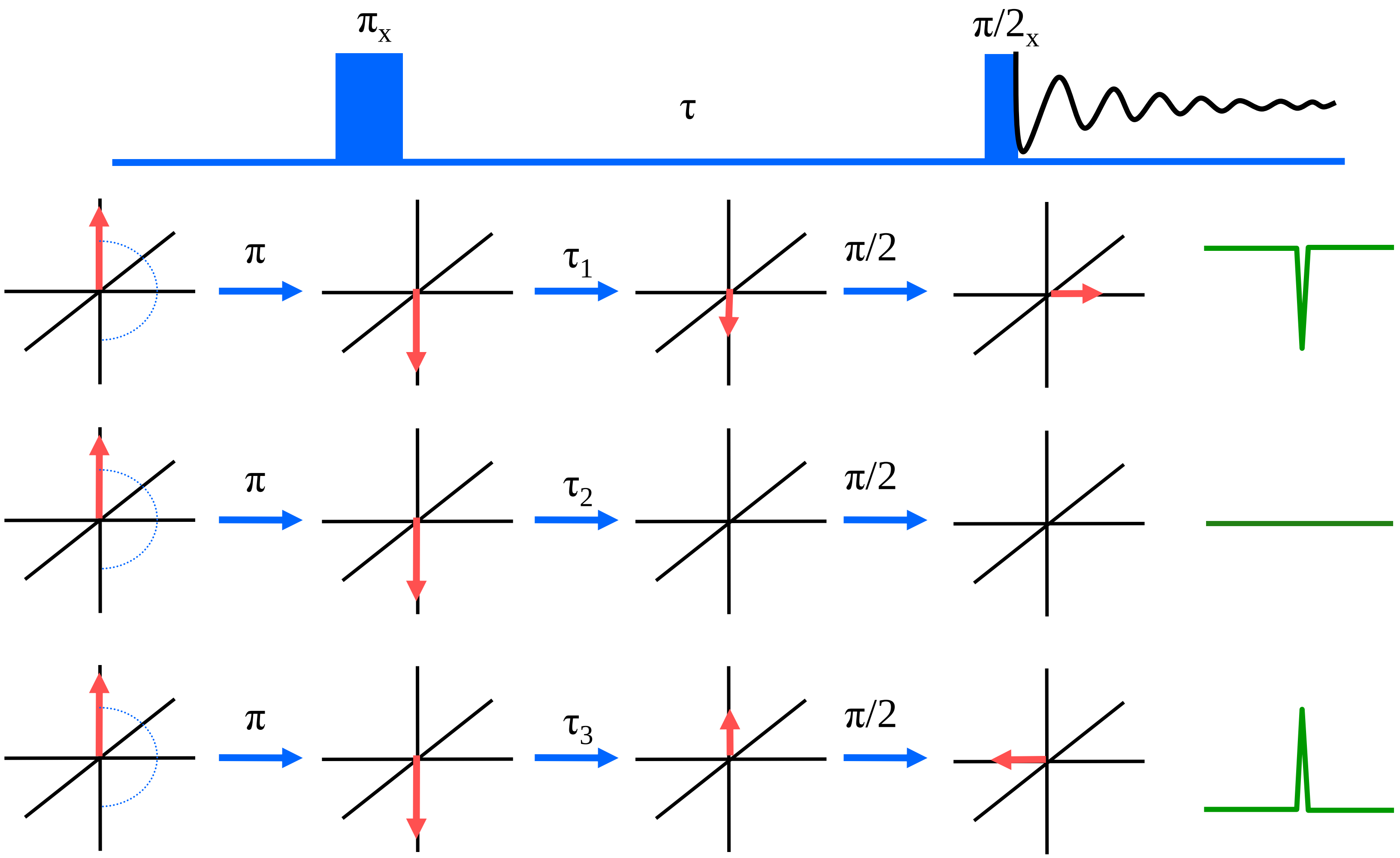


T_1 relaxation is the growth of magnetization along the z axis

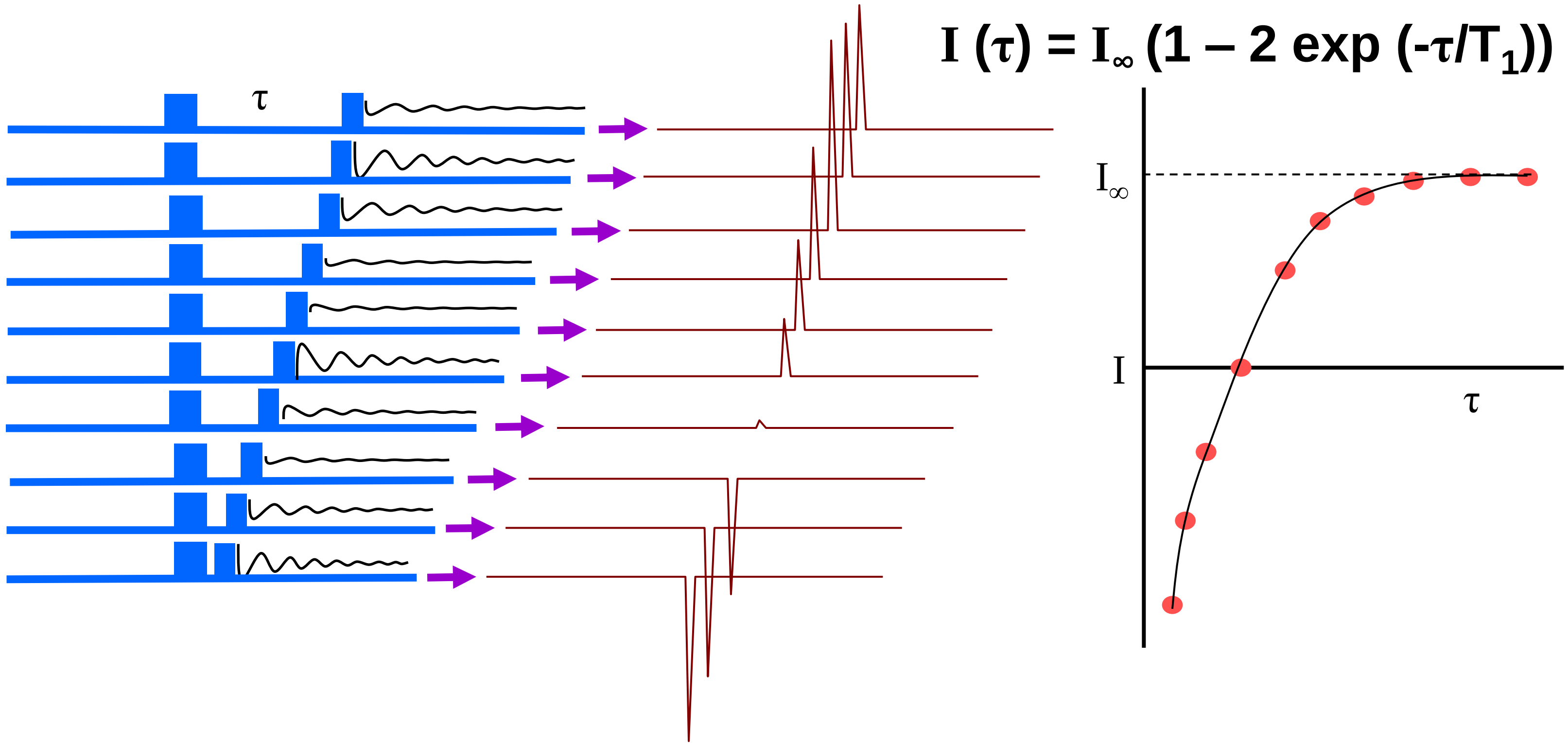
Repetition Time



T_1 Relaxation Time Measurement



T_1 Relaxation Time Measurement

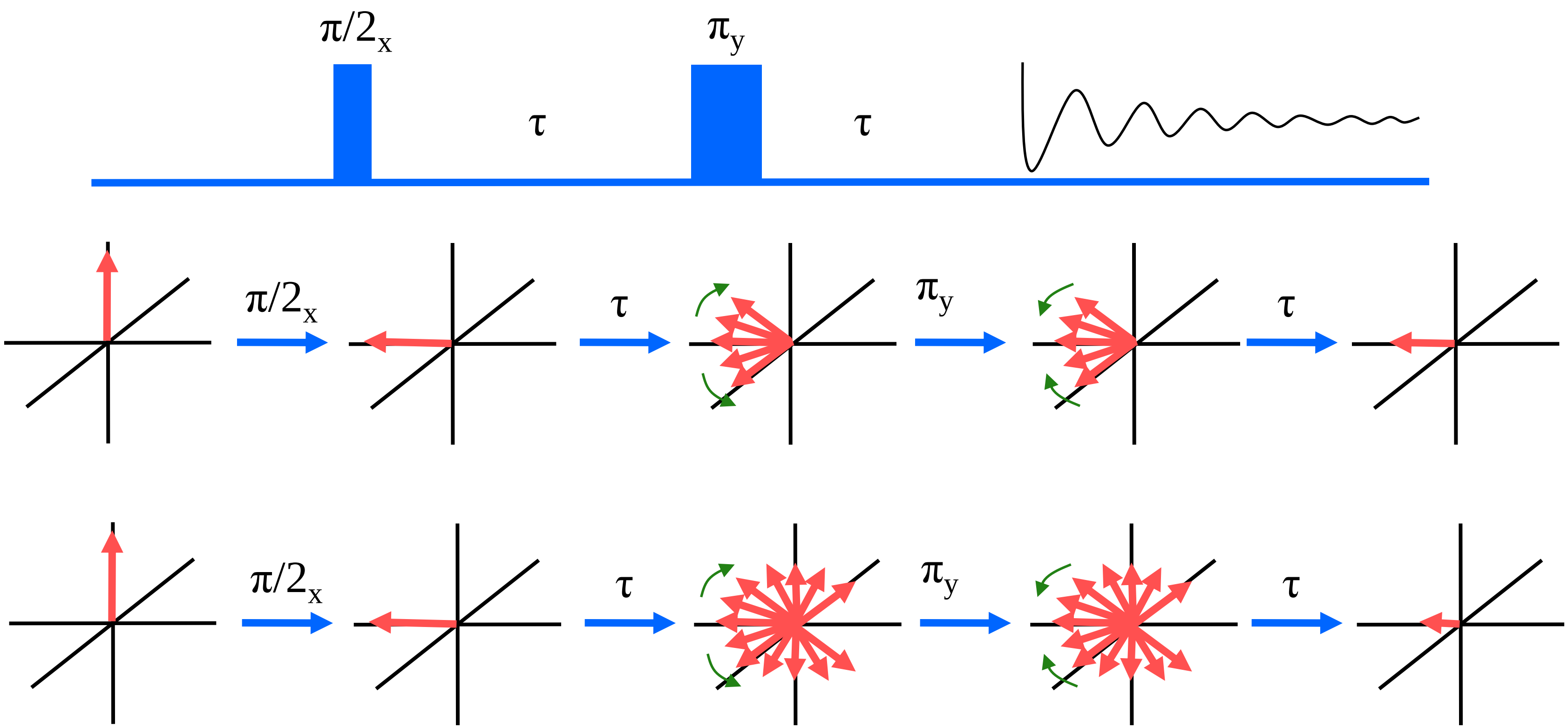


T_2 Relaxation Time Measurement

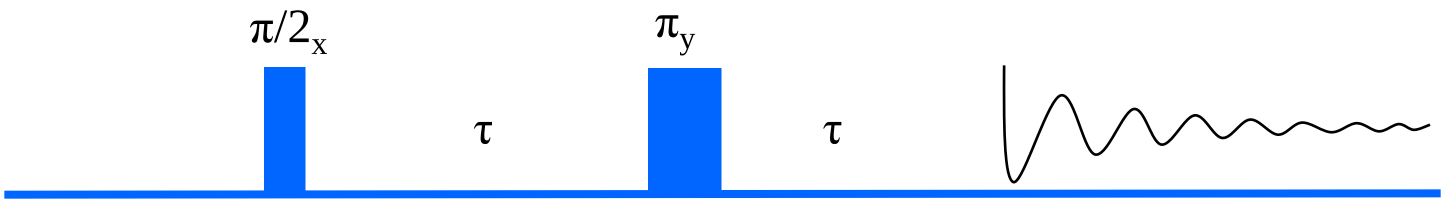
In principle, T_2 can be measured directly from the decay of the FID however, in practice, the FID will decay faster than expected due to magnetic field inhomogeneity.

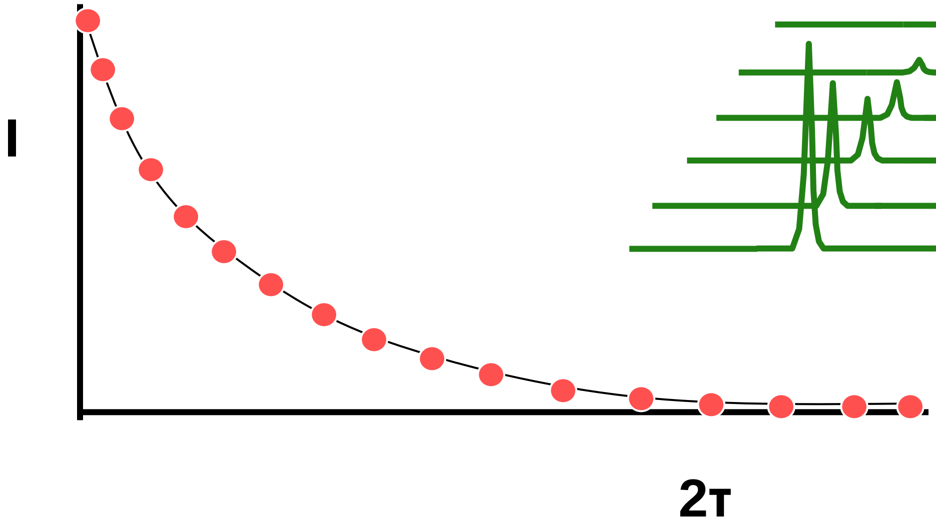
$$(1/T_2^*) = (1/T_2) + (1/T_2^{ih})$$

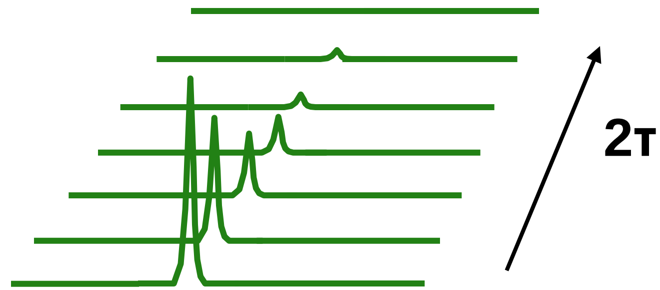
where $(1/T_2^*)$ is the observed decay rate of the FID and $(1/T_2^{ih})$ is the decay rate due exclusively to magnetic field inhomogeneity. To measure T_2, one must use a technique independent of magnetic field inhonogeneity.



T_2 Relaxation Time Measurement

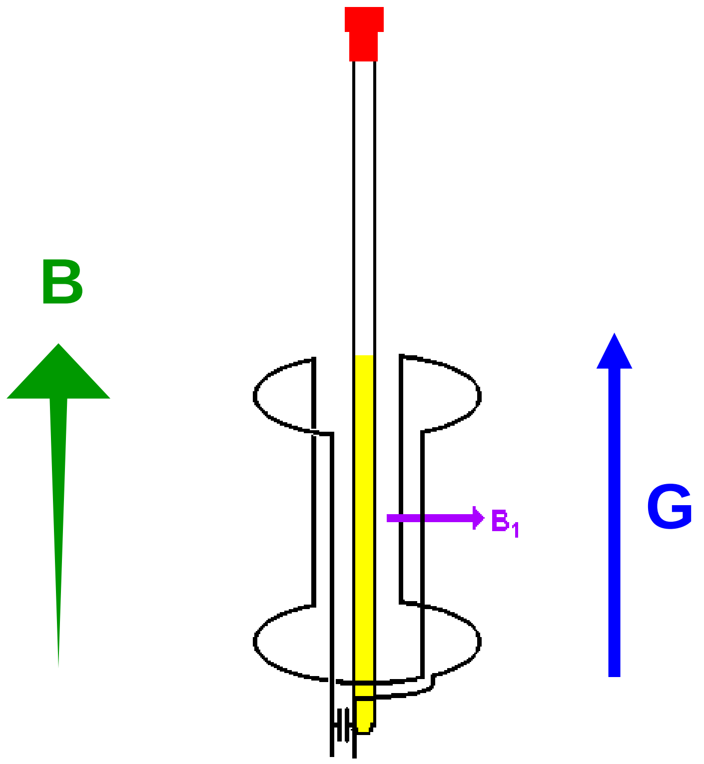






$$I\,(2\tau) = I_o\ \exp\,(-2\tau/T_2)$$

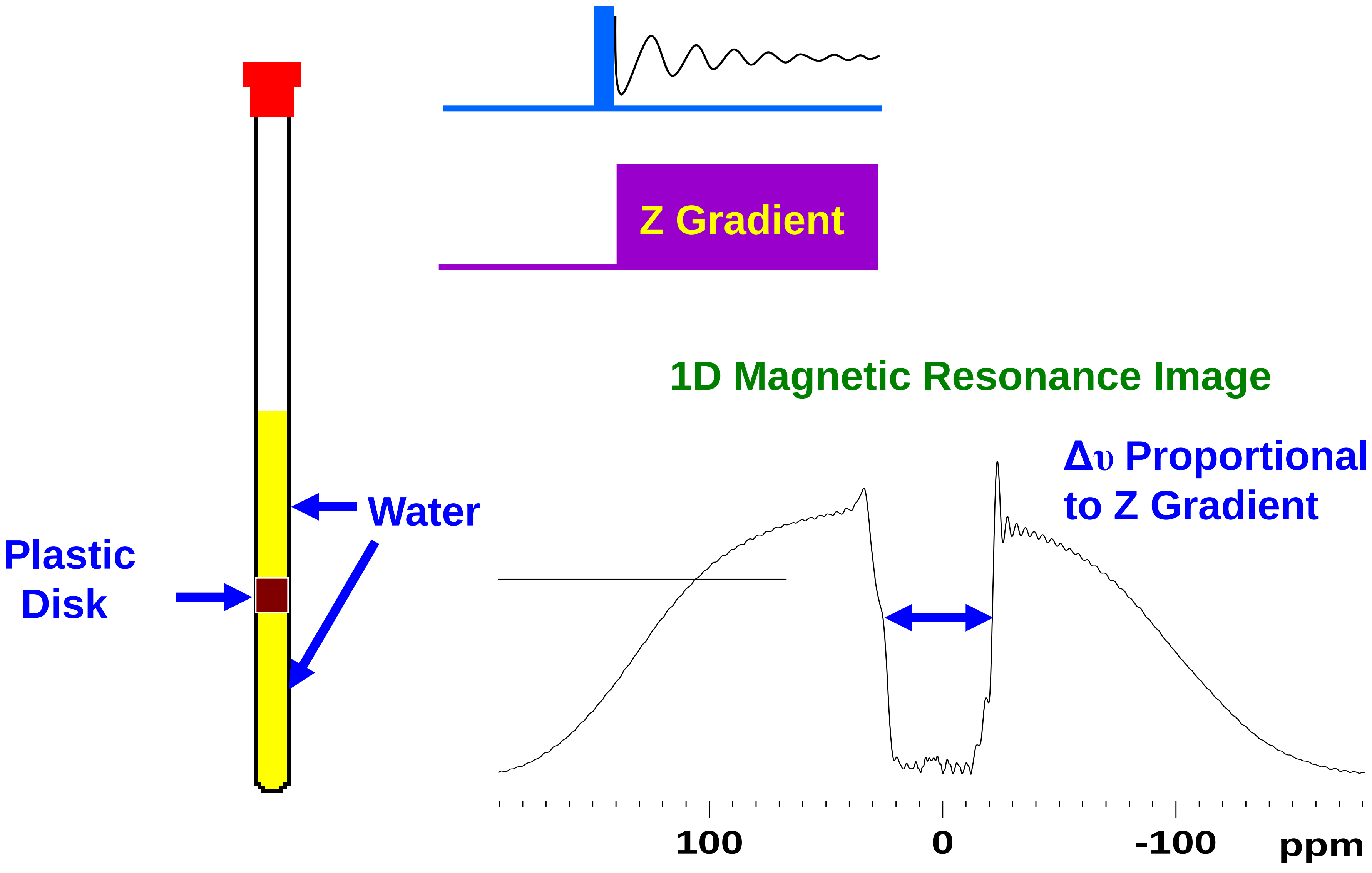
Pulsed Field Gradients



Uses for Pulsed Field Gradients

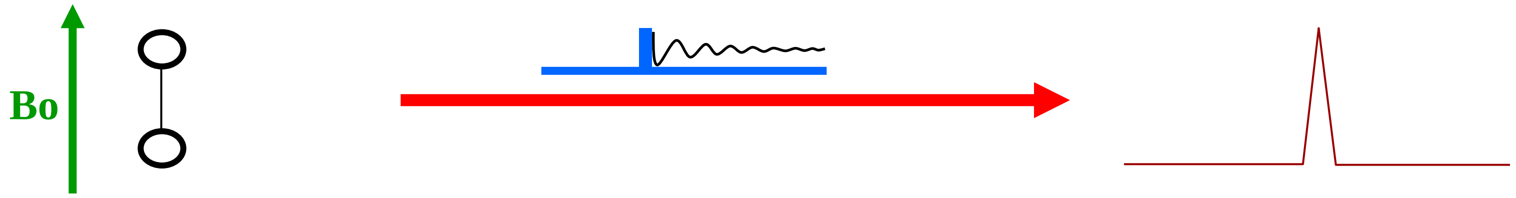
- Remove unwanted signals by destroying magnetic field homogeneity
- Eliminate or minimize the need to phase cycle pulses (gradient accelerated spectroscopy)
- Measure molecular diffusion
- Obtain magnetic resonance images

Frequency Encoding - 1D MRI

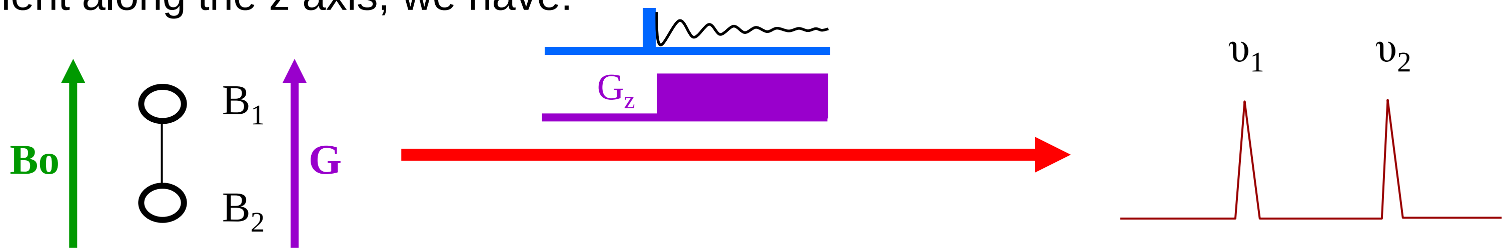


Magnetic Resonance Imaging (MRI)

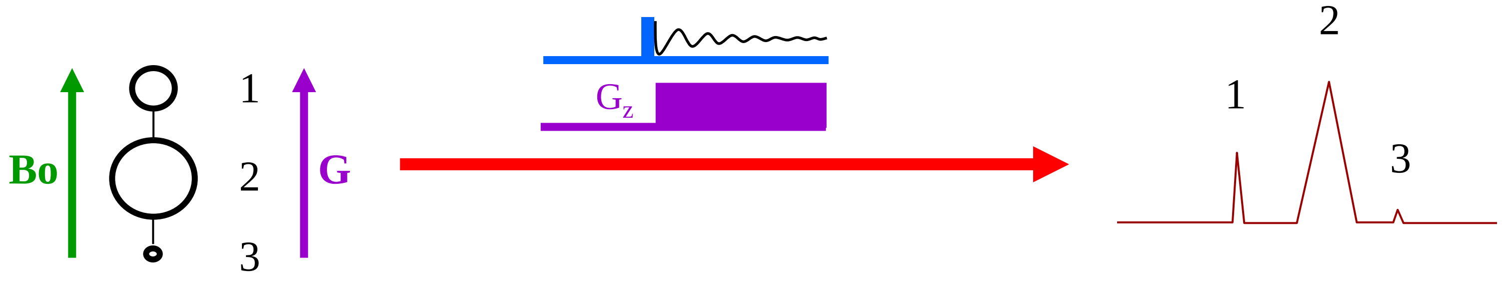
NMR imaging is usually called magnetic resonance imaging (MRI). It uses NMR spectroscopy in a magnetic field with controlled inhomogeneity to give spatial information. If B_o varies linearly with distance then the frequency of an NMR line will have the same dependence. Imagine a sample shaped like a dumbbell (two spherical vessels containing water) placed in a constant magnetic field.



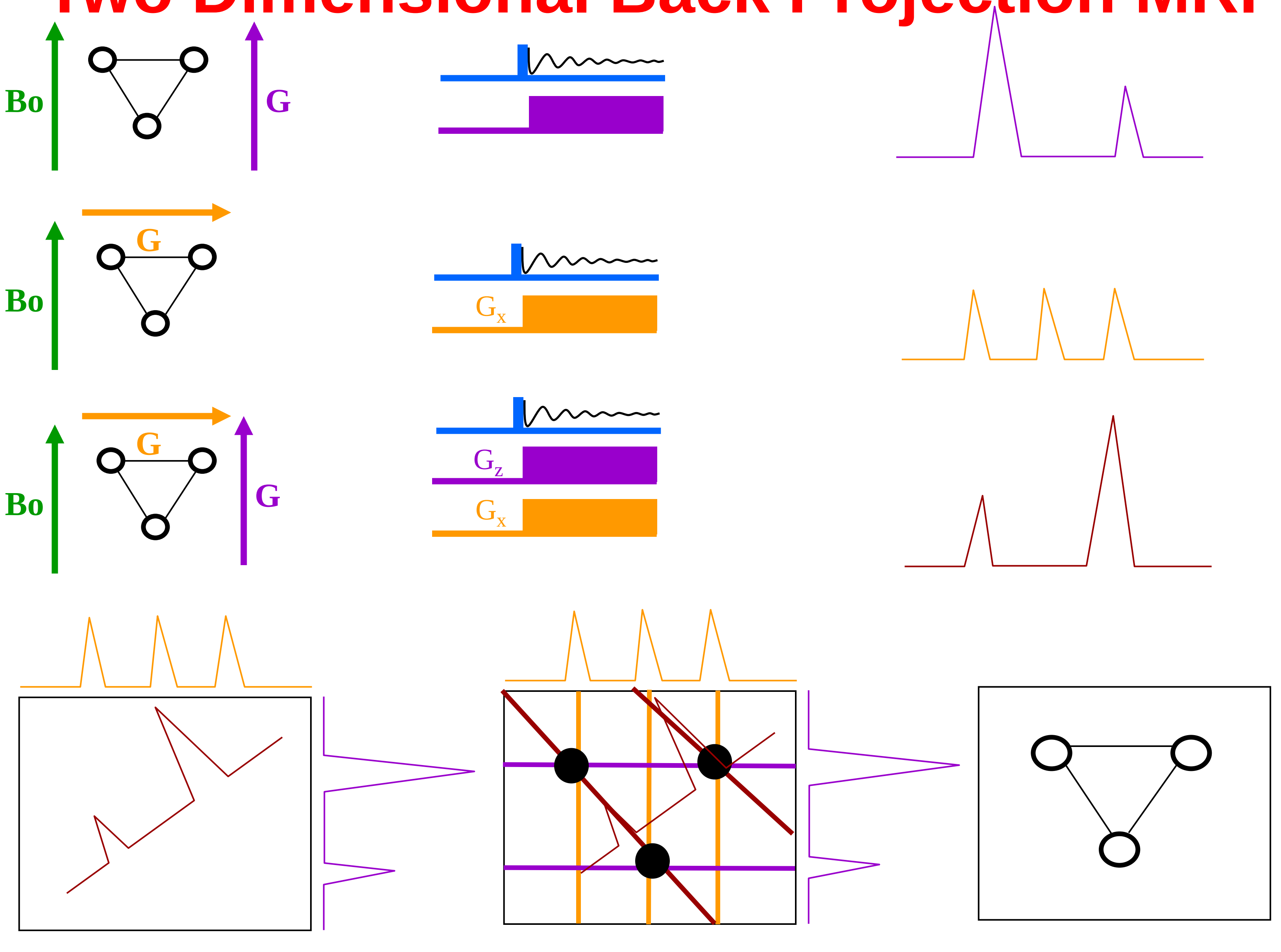
When the same sample is placed in a magnetic field with a linear magnetic field gradient along the z axis, we have:



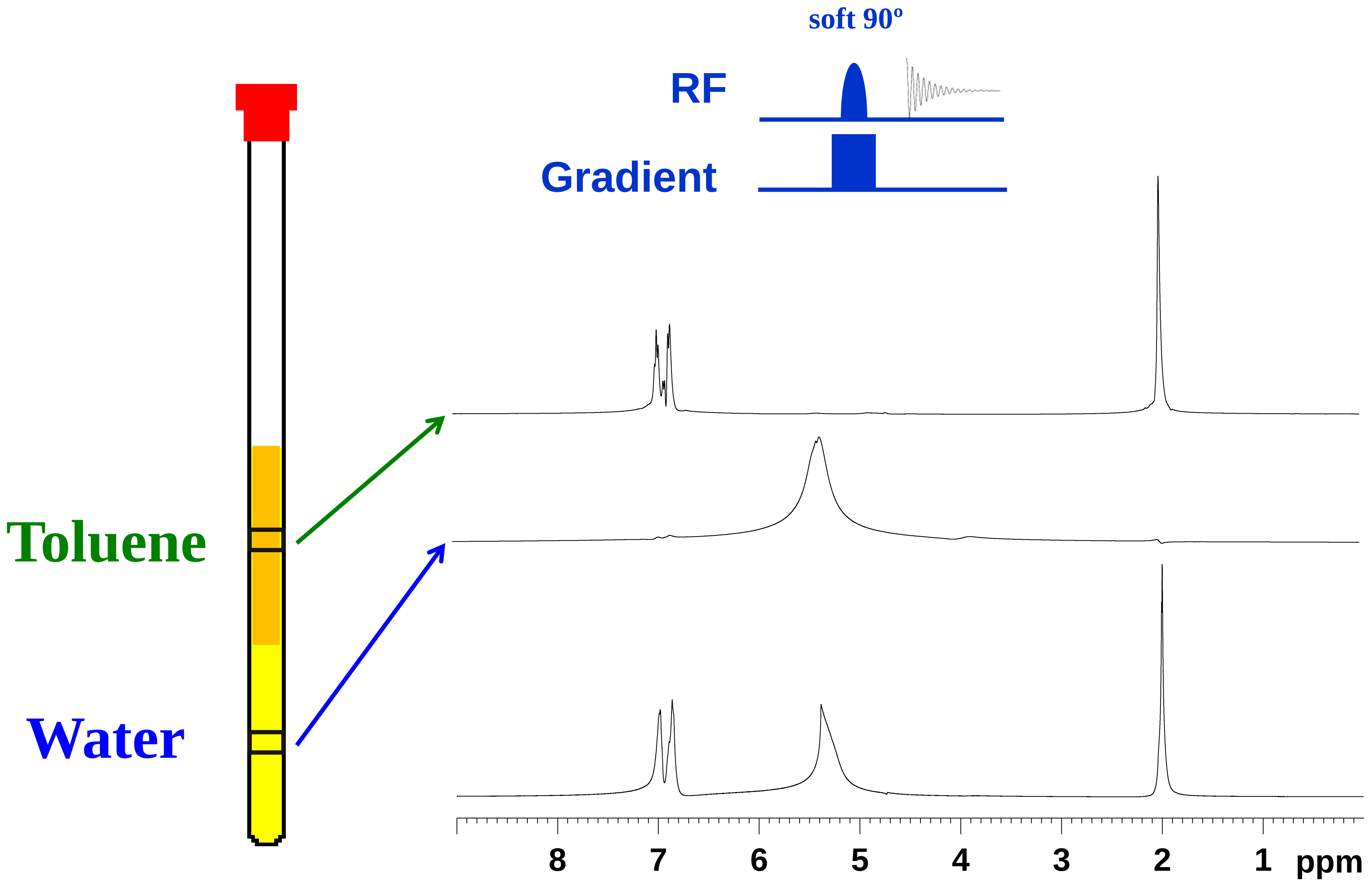
The spectrum is a one dimensional image of the sample where the frequency difference between the peaks is proportional to the distance between the water drops in the sample. Imagine a more complex sample:



Two Dimensional Back Projection MRI



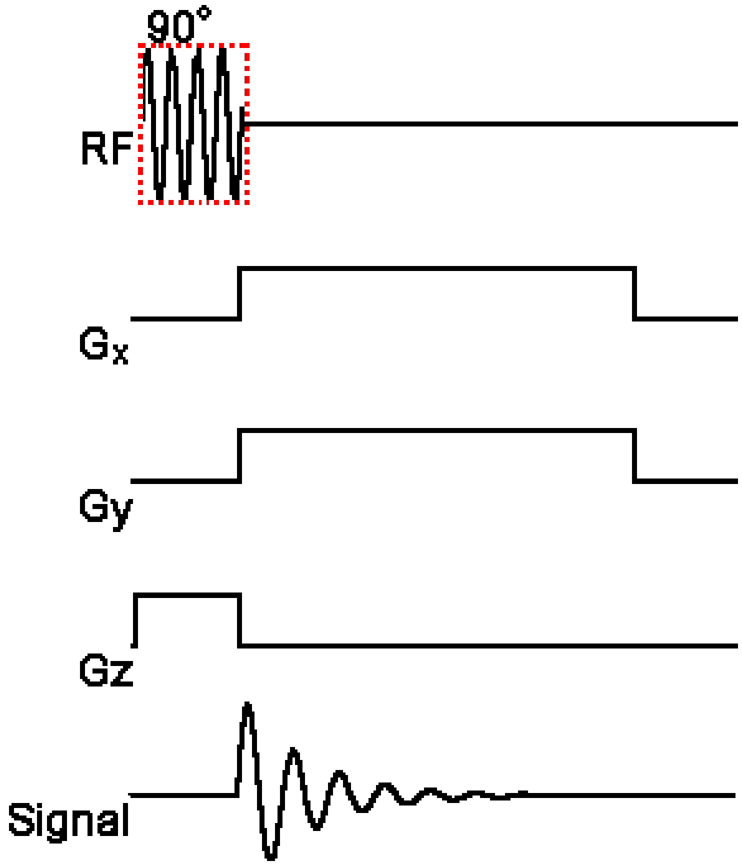
Slice Selection in NMR Spectroscopy



Slice Selection in MRI

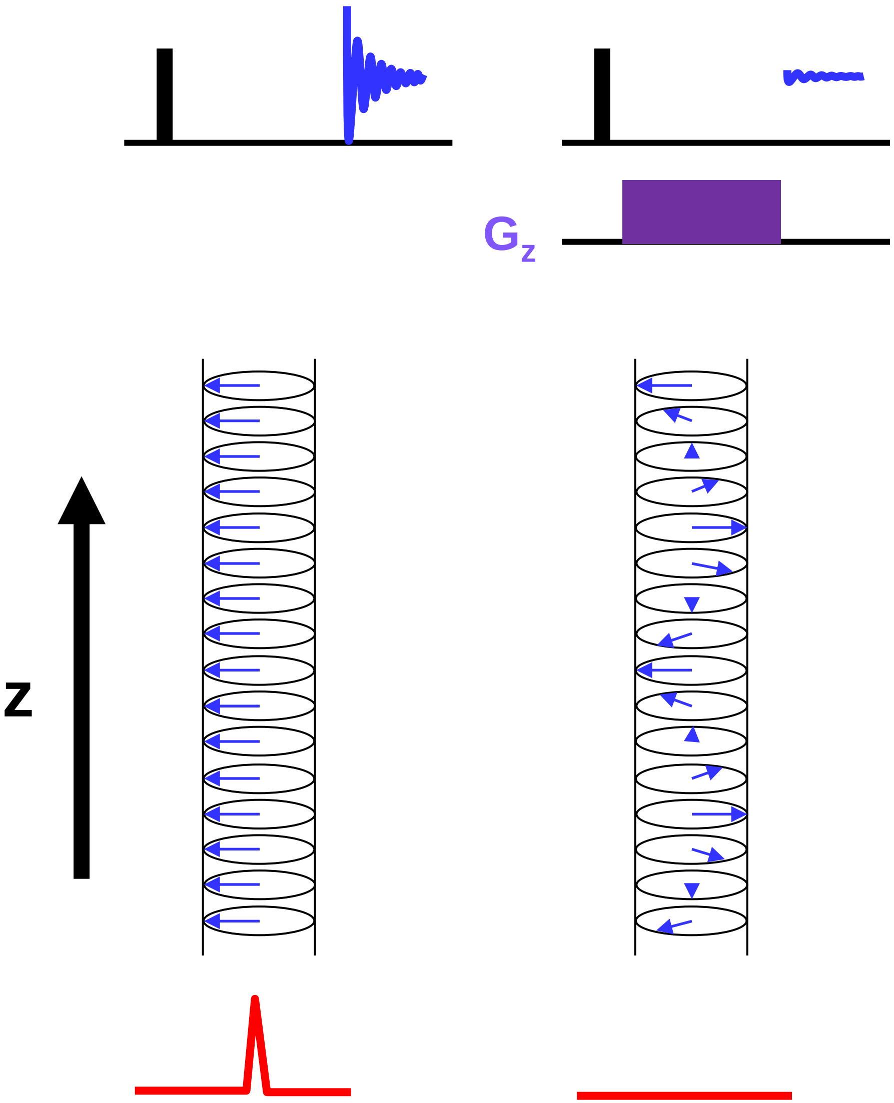
Figures courtesy of Joseph Hornak, The Basics of MRI http://www.cis.rit.edu/htbooks/mri

Slice Selected 2D Back projection MRI



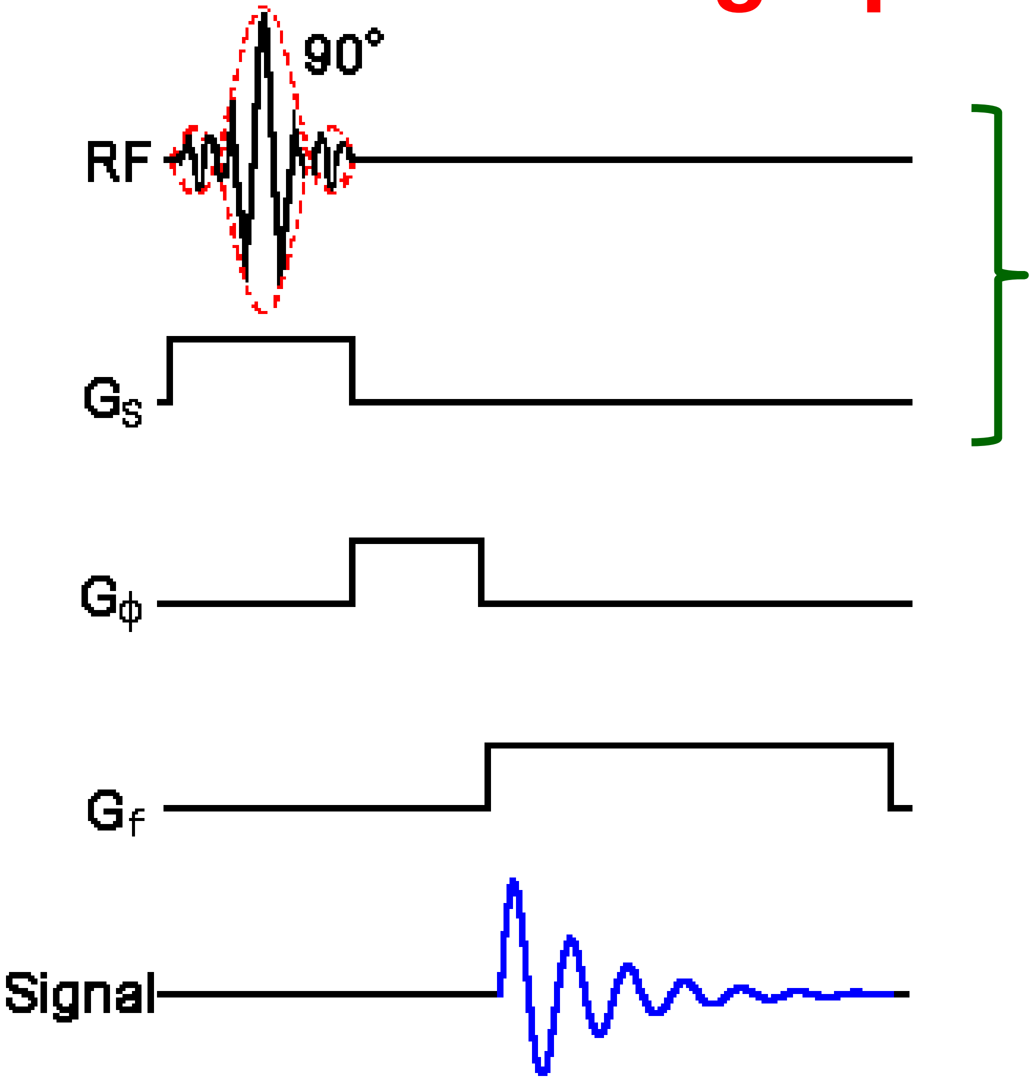
Figures courtesy of Joseph Hornak, The Basics of MRI http://www.cis.rit.edu/htbooks/mri

Phase Encoding Gradients



After the phase encoding gradient, each position of the sample on the z axis has a phase angle related to its position.

Tomographic MRI



Slice selection about the z axis

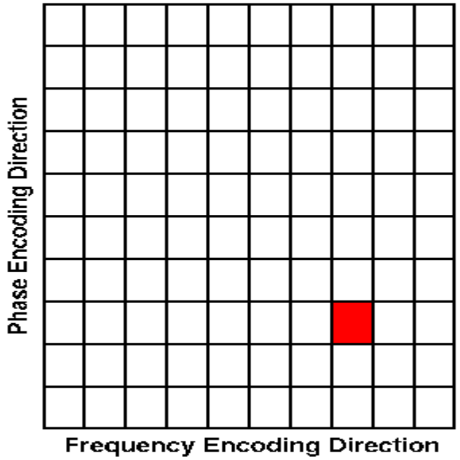
Phase encoding about the x axis

Frequency encoding about the y axis

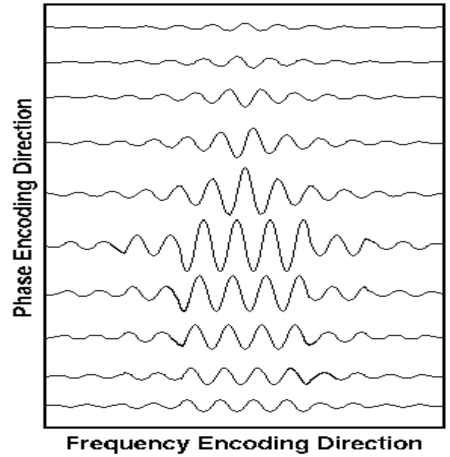
MRI time domain signal

The sequence is repeated with a series of phase encoding gradients with varying amplitude.

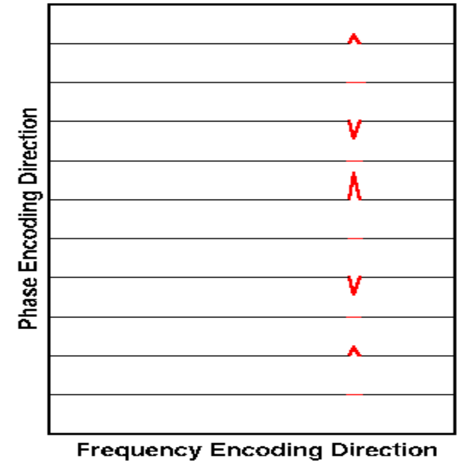
Tomographic MRI – Signal Processing



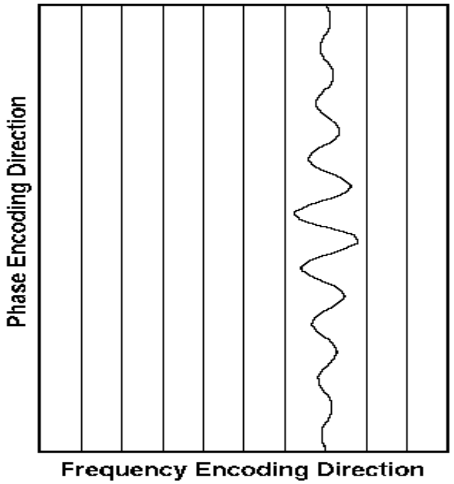
selected slice



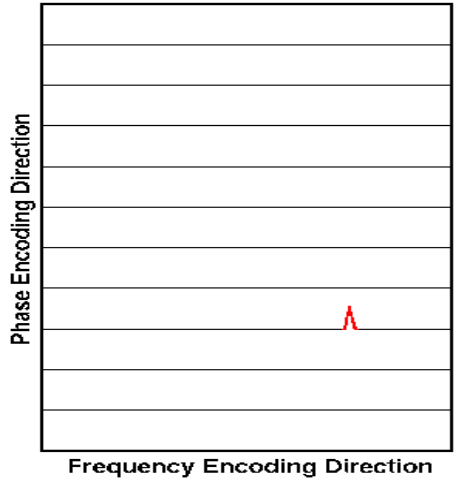
signal from each phase gradient



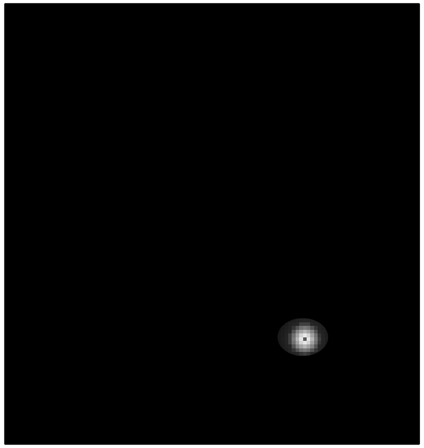
FT of phase encoded signals



intensity of transformed signals

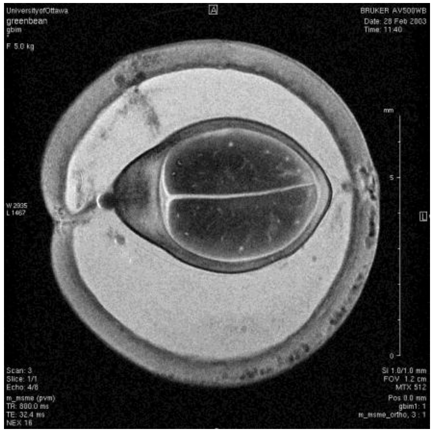


FT along phase encoded axis

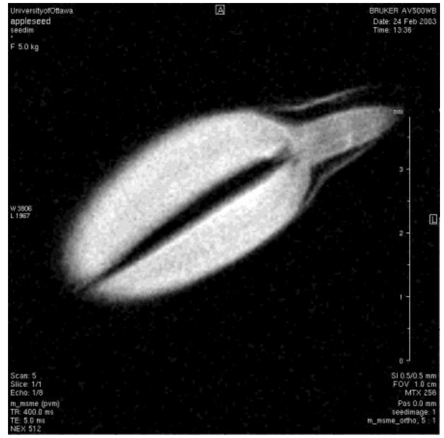


MRI

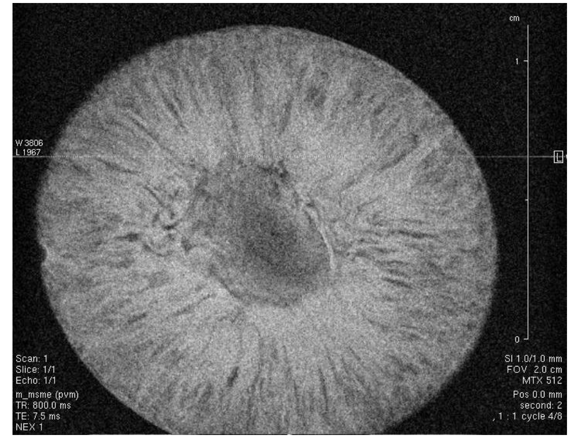
Magnetic Resonance Images



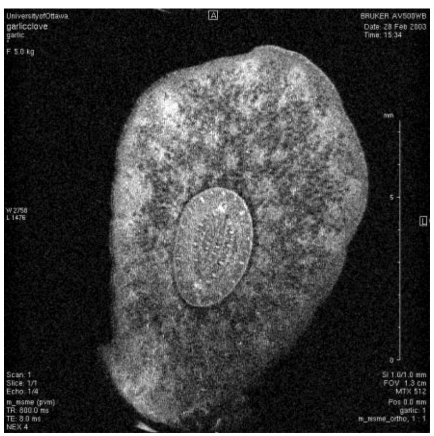
Green Bean



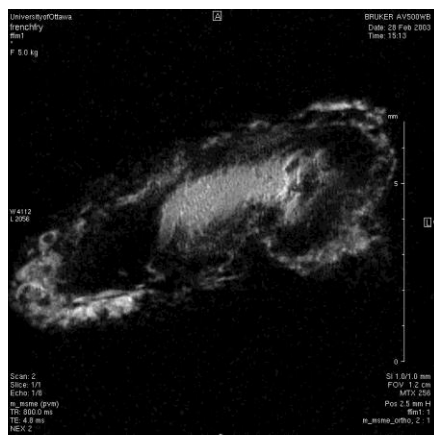
Apple Seed



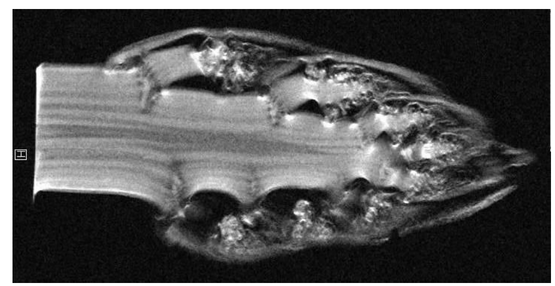
Seedless Grape



Garlic Clove



French Fry



Asparagus Tip