T_1 & Magnetization Transfer

Peter van Gelderen
AMRI, LFMI, NINDS, National Institutes of Health,
Bethesda, MD, United States

Outline

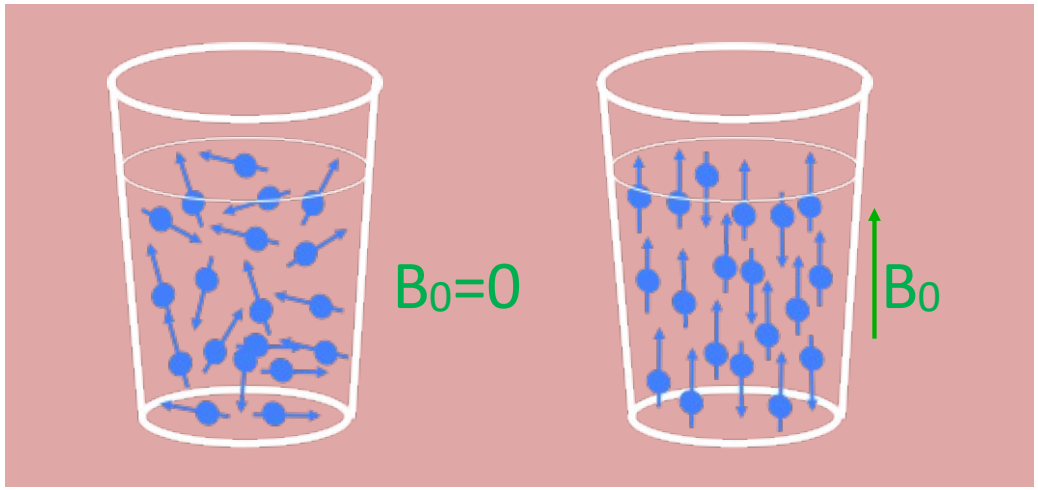
- T_1 and T_2
- Relevance for MRI
- Measuring T_1
- Magnetization Transfer (MT)
- Measuring MT
- Sources of T_1 contrast: T_1 & MT

Magnetization

Nuclear spins polarize in a magnetic field

Magnetization

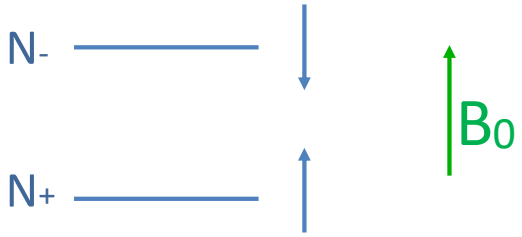
Nuclear spins polarize in a magnetic field



Magnetization

Nuclear spins polarize in a magnetic field

Energy:



$$N_-/N_+ = e^{-h\gamma B_0/k_b T} \cong 1 - h\gamma B_0/k_b T = 1 - 6.5\times10^{-6} B_0$$

Magnetization

Nuclear spins polarize in a magnetic field, but how fast?

Change in polarization requires energy transfer to different species.

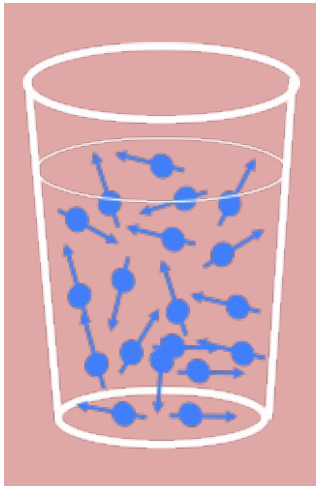
Pure water: little energy transfer -> slow (change in) polarization

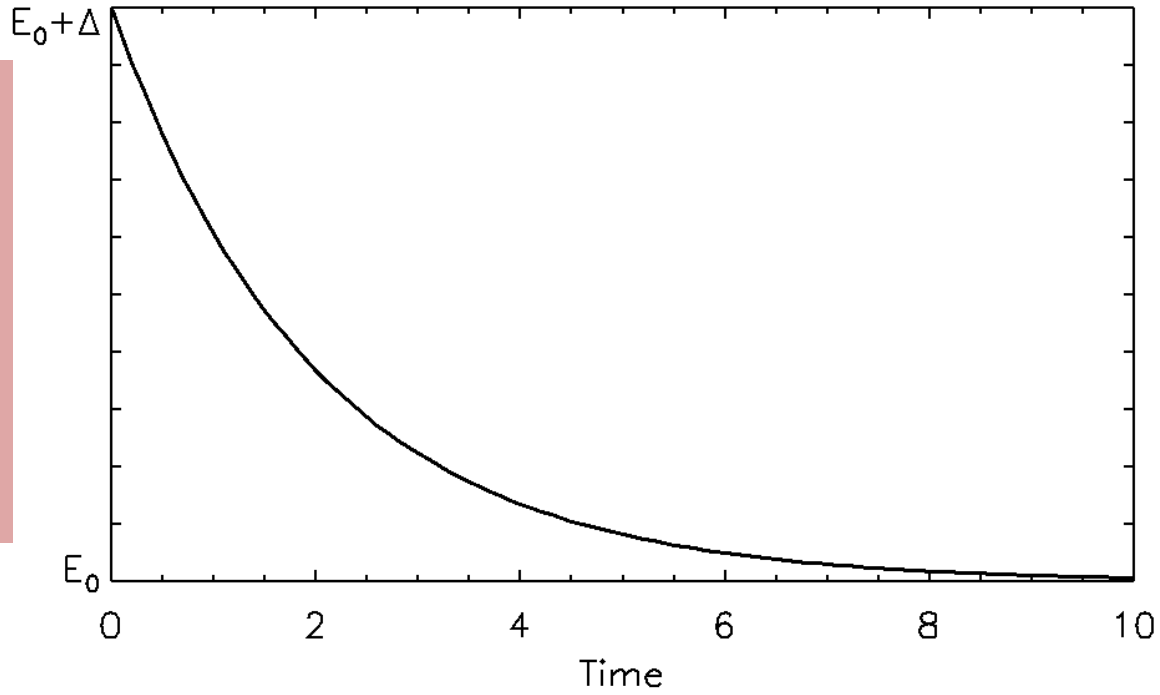
Magnetization

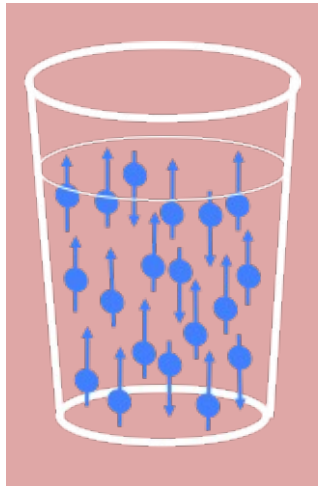
Time course:

- every spin has certain probability to transition
- P_- for ↓↑ P_+ for ↑↓ where P_- slightly higher than P_+ (due to ΔE)
- # spins ↓↑ : N_-P_-, ↑↓ : N_+P_+
- $M= N_+ -N_-$
- change in $M= dM= (N_-P_- -N_+P_+)$
- $dM= 0$ for equilibrium (M_0), $N_{+0}/N_{-0}= P_-/P_+$
- $M= M_0 + \Delta$, $N_-= N_{-0} - \Delta/2$, $N_+= N_{+0} + \Delta/2$,
- $dM= ((N_{-0} - \Delta/2)P_- -(N_{+0} + \Delta/2)P_+)= N_{-0}P_- -N_{+0}P_+ - \Delta/2(P_-+P_+)=- \Delta/2(P_-+P_+)$
- $dM/dt= -k(M-M_0)$, $k= R_1=1/T_1$

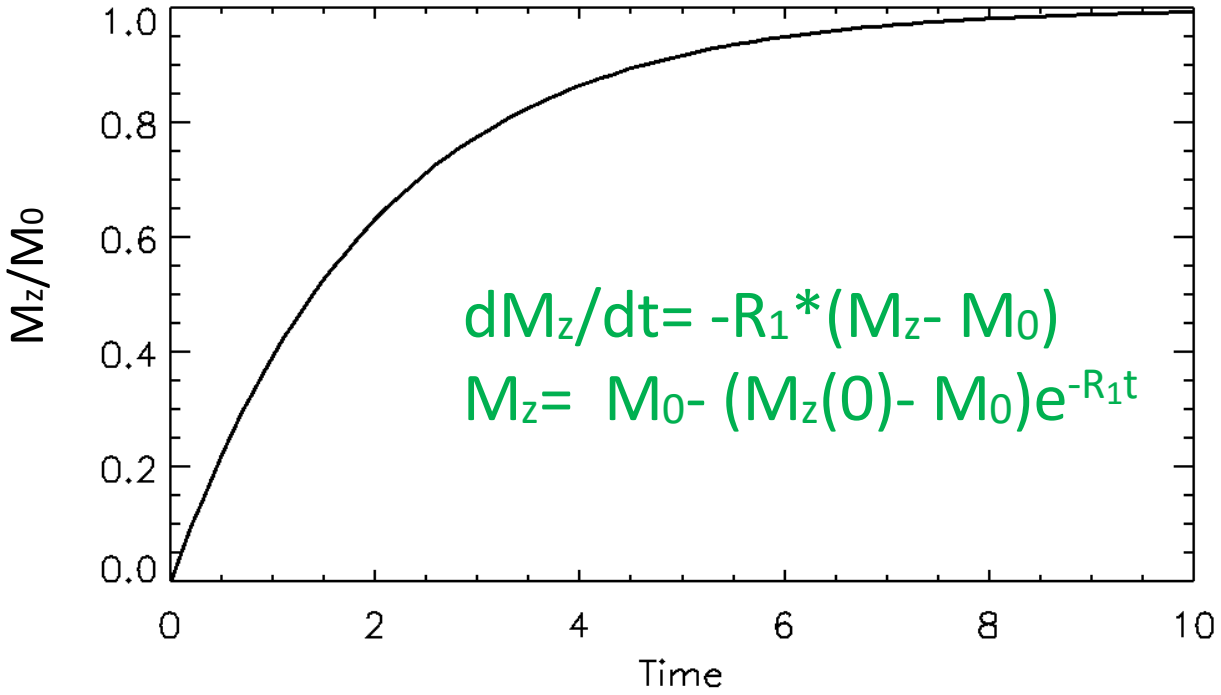
Magnetization



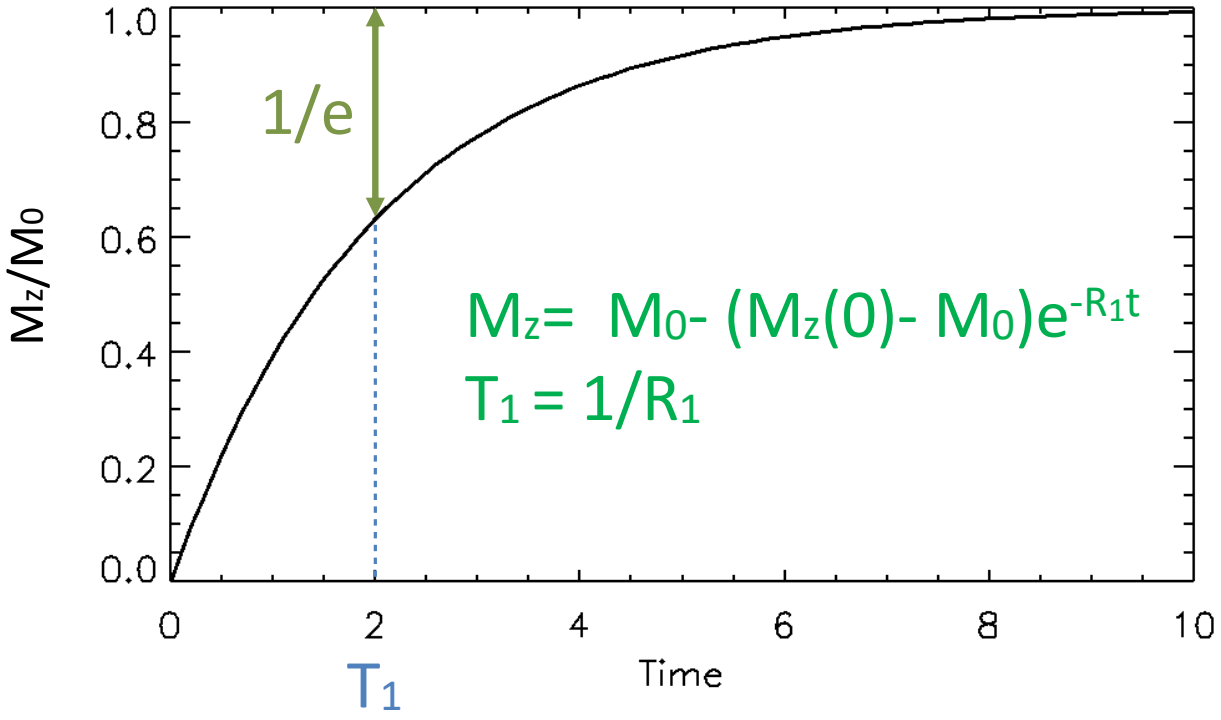




Magnetization

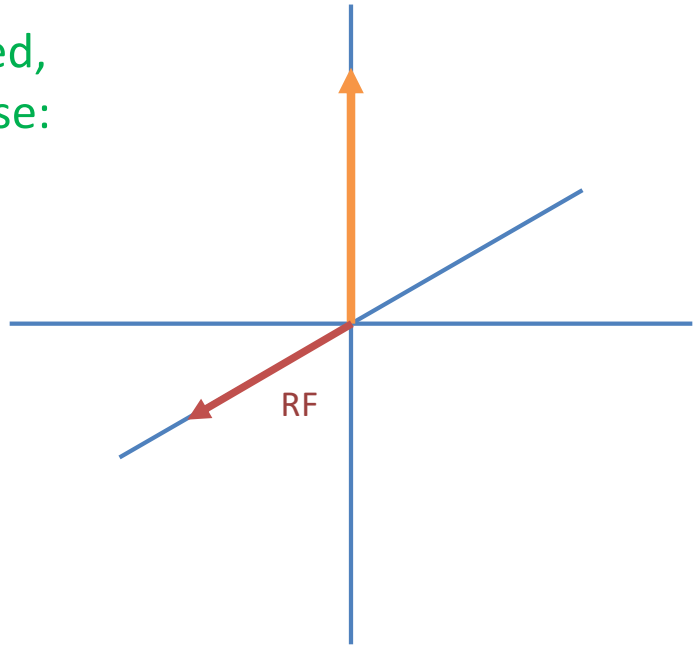


Magnetization



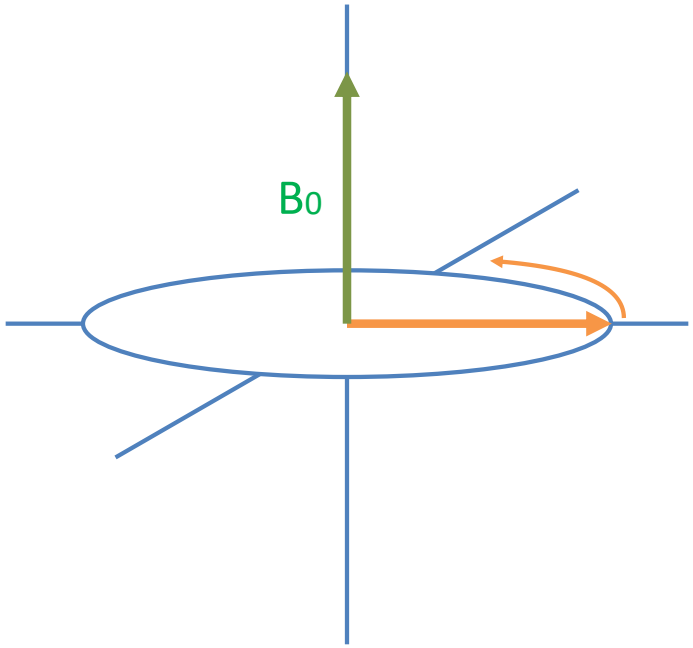
T_1-Relaxation in MRI

M_z not directly measured,
M needs to be transverse:



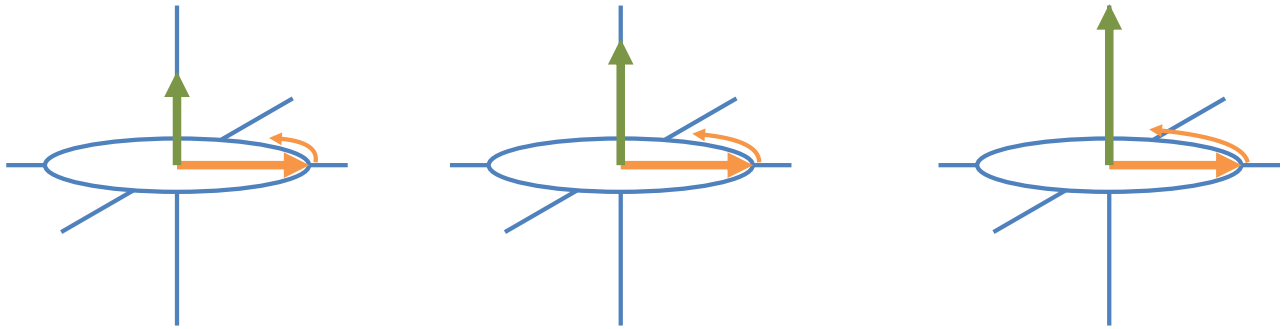
T_2-Relaxation

M rotates around B_0
Frequency: γB_0



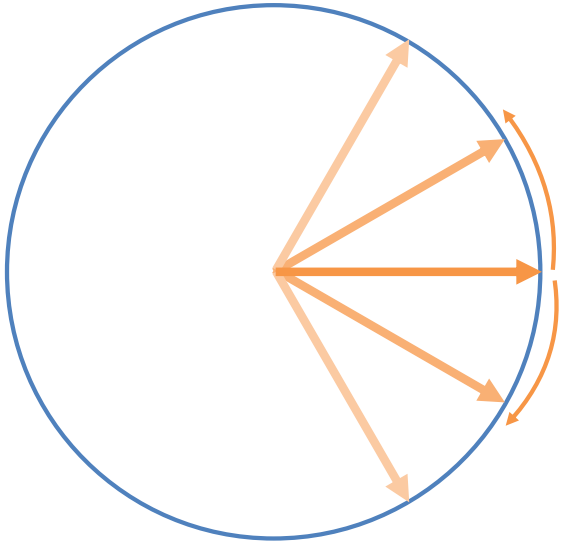
T_2-Relaxation

M rotates around B_0
Frequency: γB_0
B_0 not the same everywhere:
dispersion

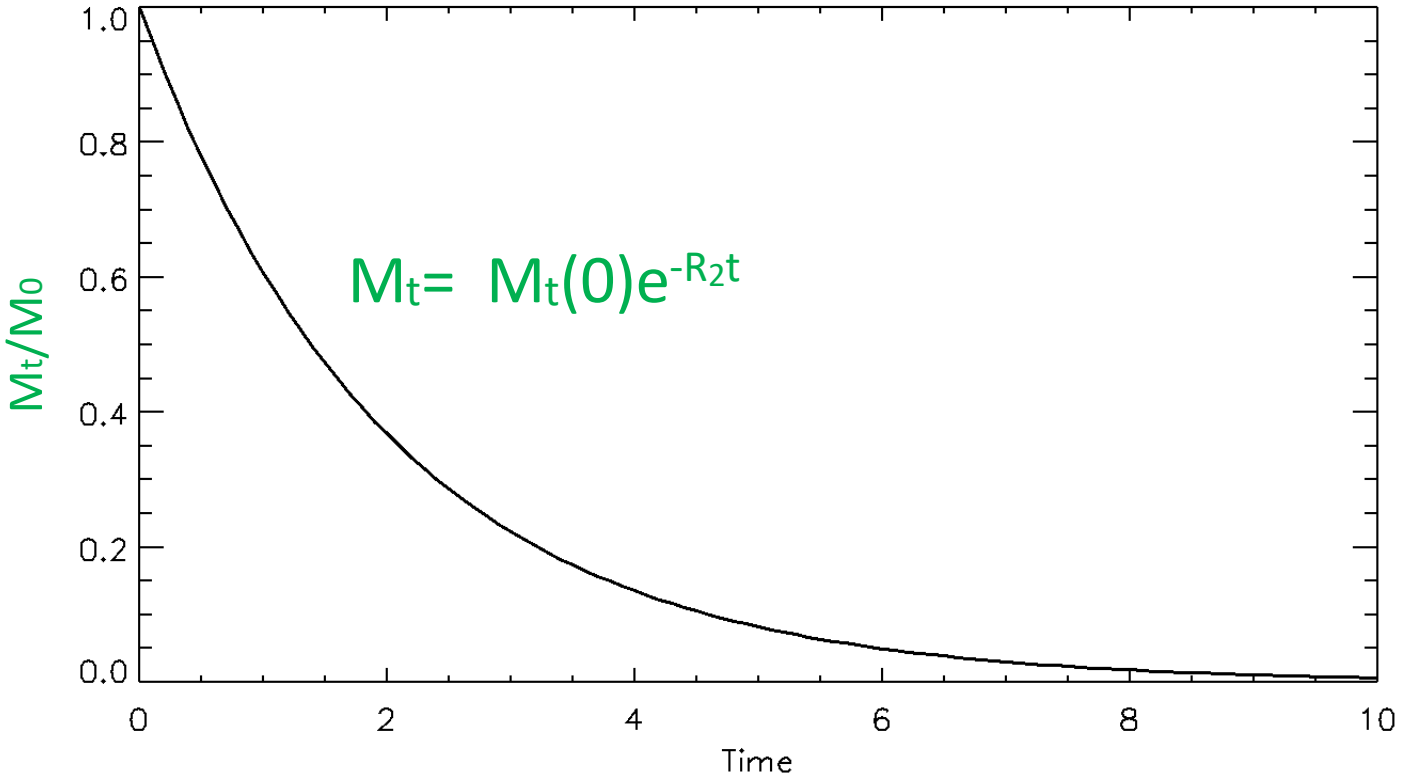


T_2-Relaxation

M_t in rotating frame:



T2-Relaxation



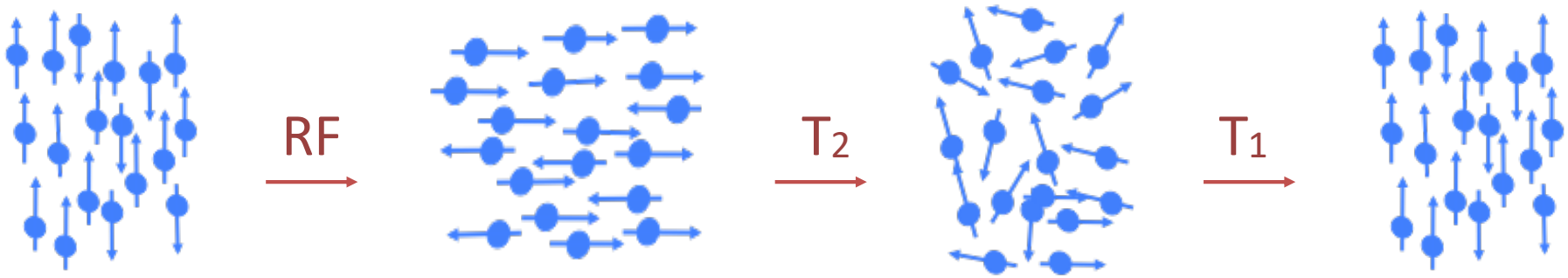
T_2-Relaxation

T_2 is dispersion of M in transverse plain
caused by frequency differences, from
- spin-spin interactions (true T_2)
- field inhomogeneity from magnet or local susceptibility (T_2^*)

No energy transfer, can be (much) faster then T_1

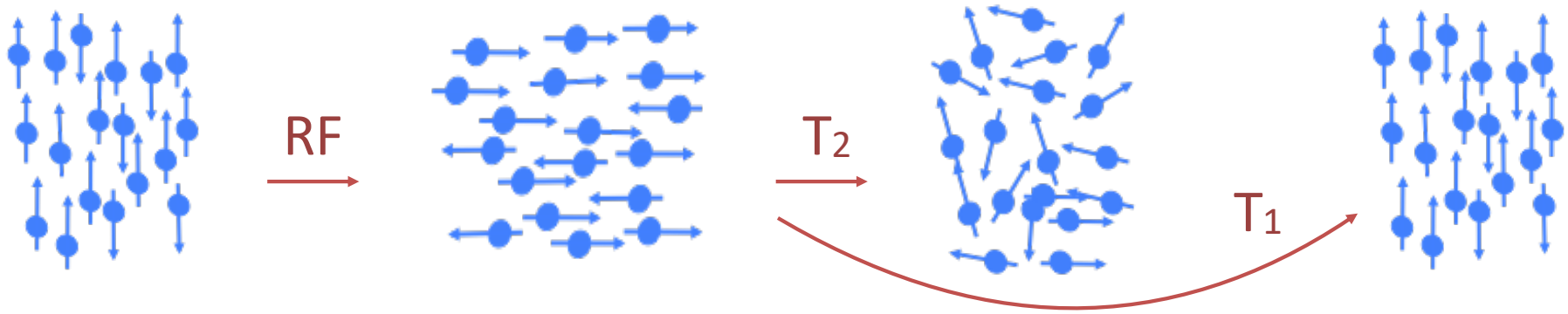
T1-Relaxation

MR measurement:



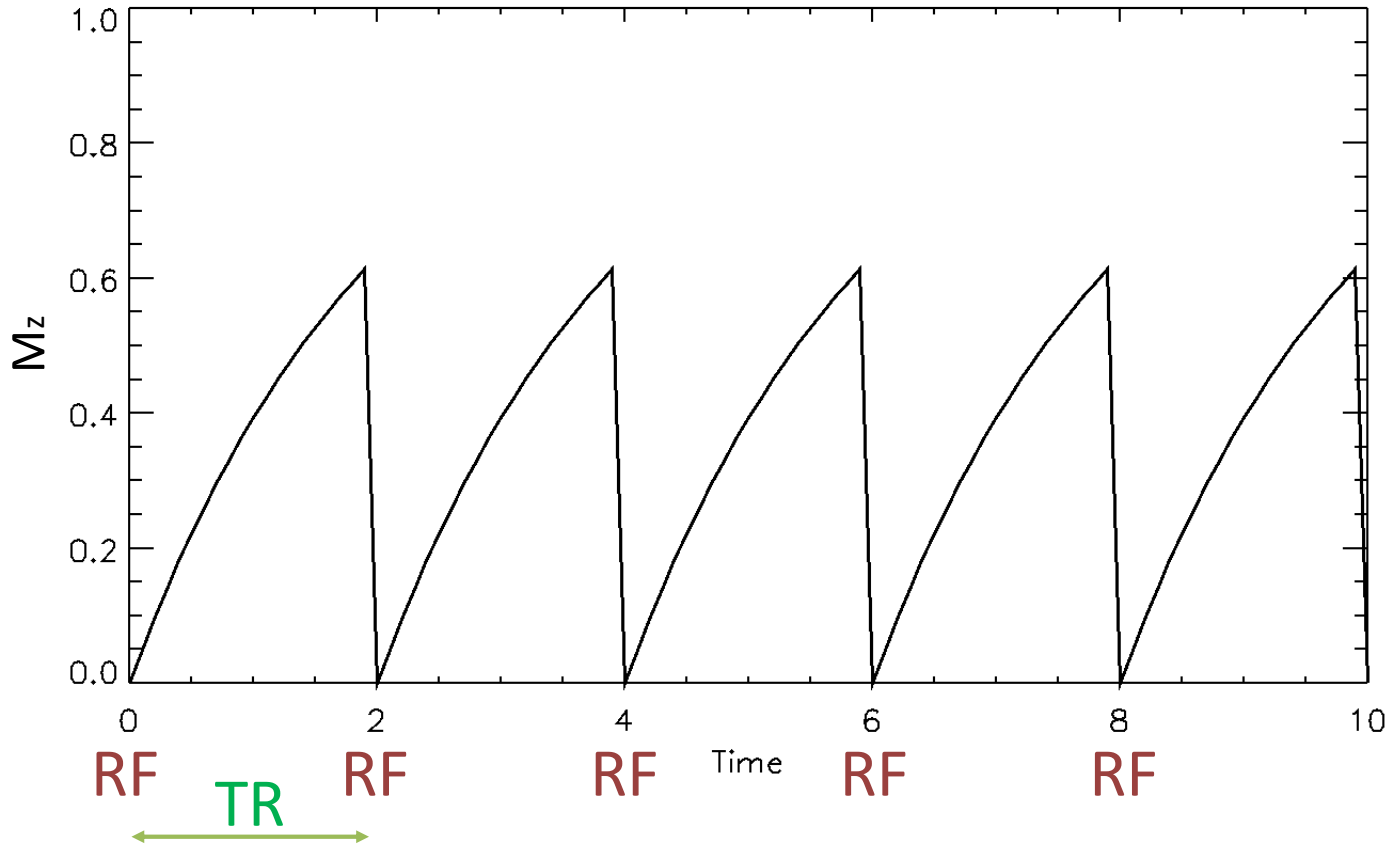
T1-Relaxation

Relevance for MR Imaging

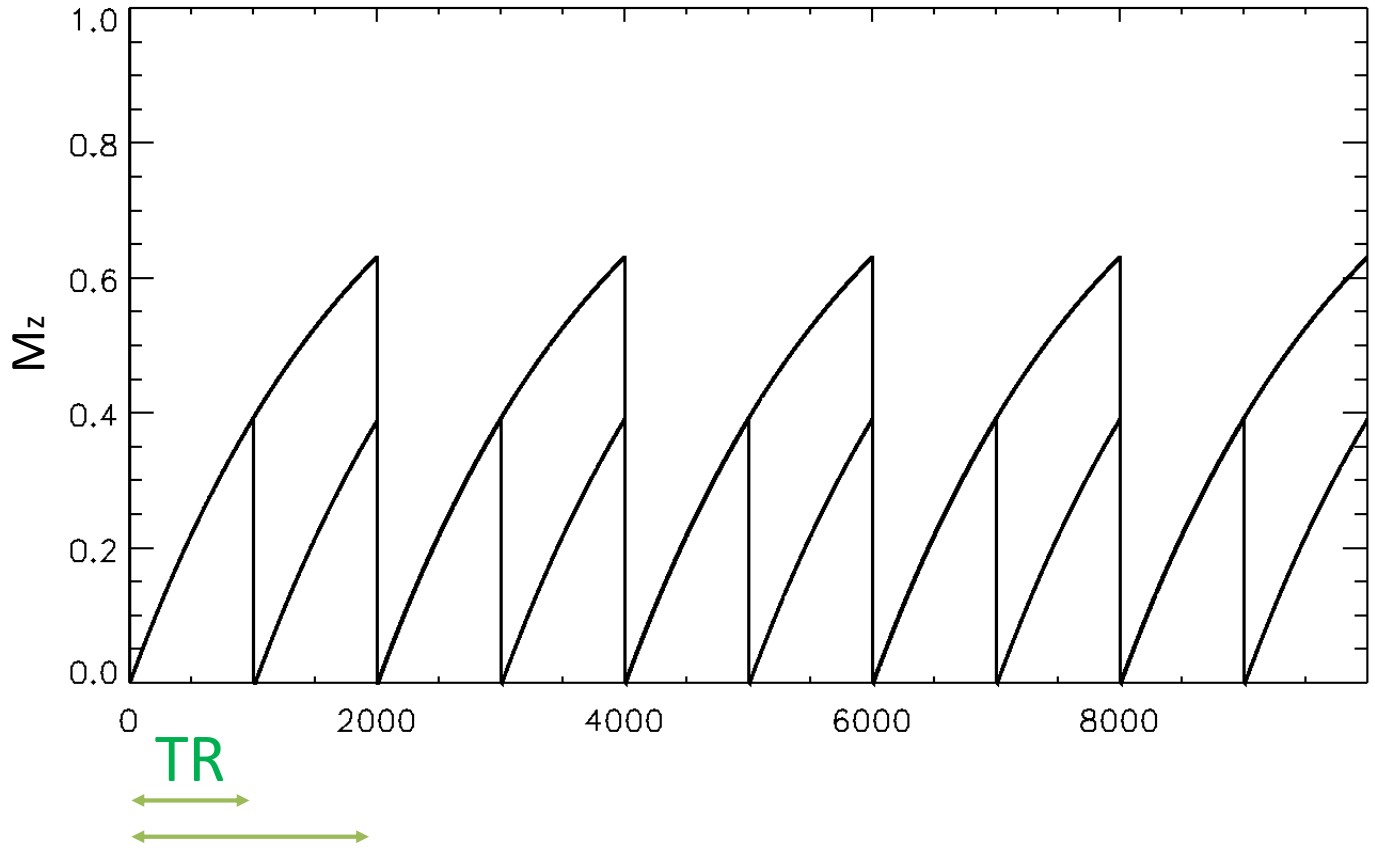


$M_t=0, M_z= 1$ $M_t=1, M_z= 0$ $M_t=0, M_z= 0$

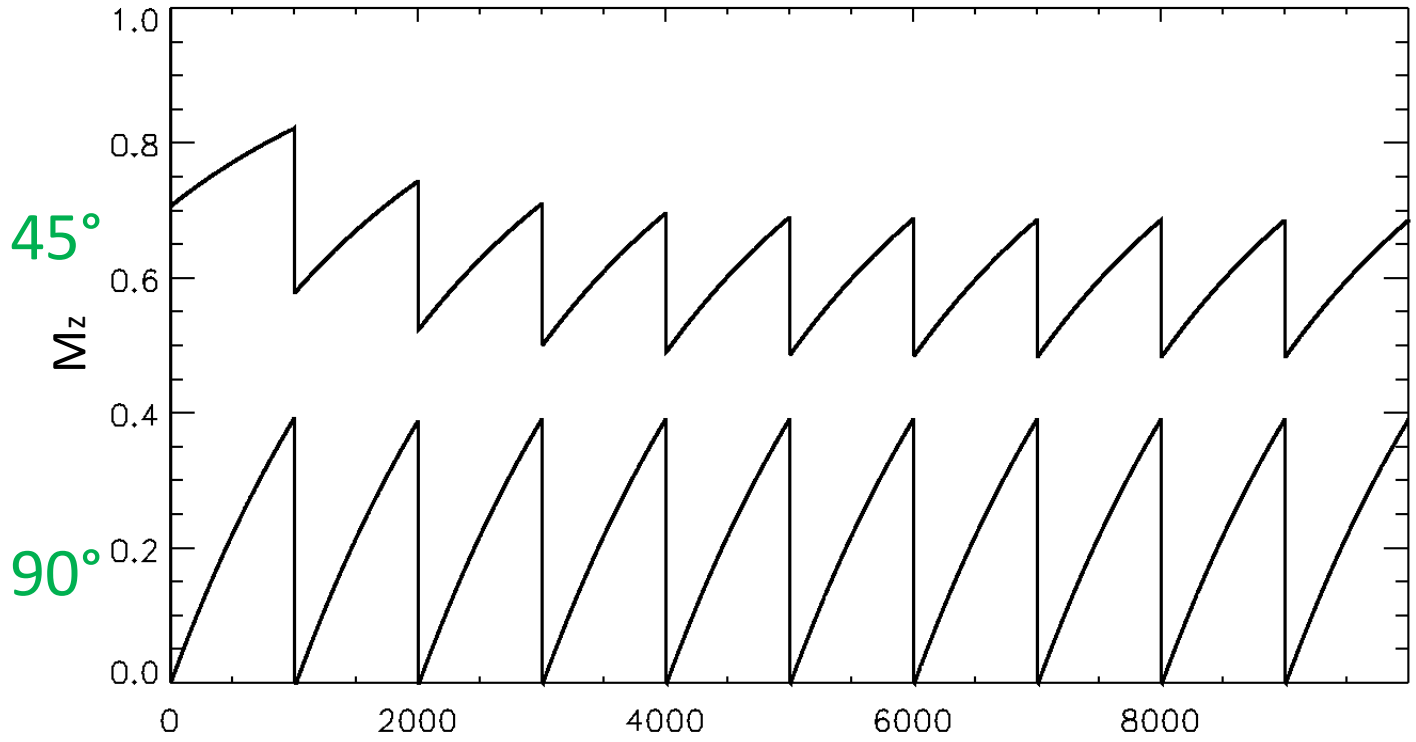
T1-Relaxation & MRI



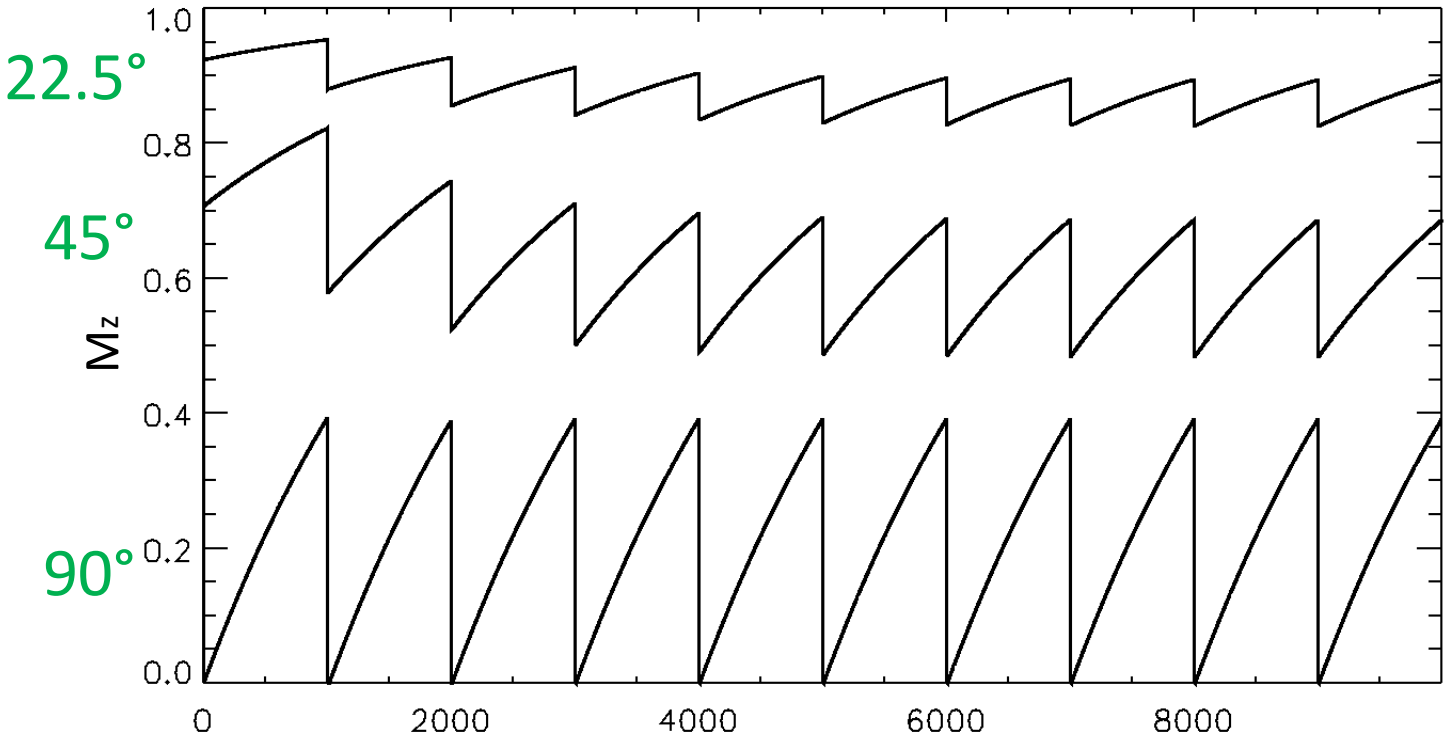
T1-Relaxation & TR



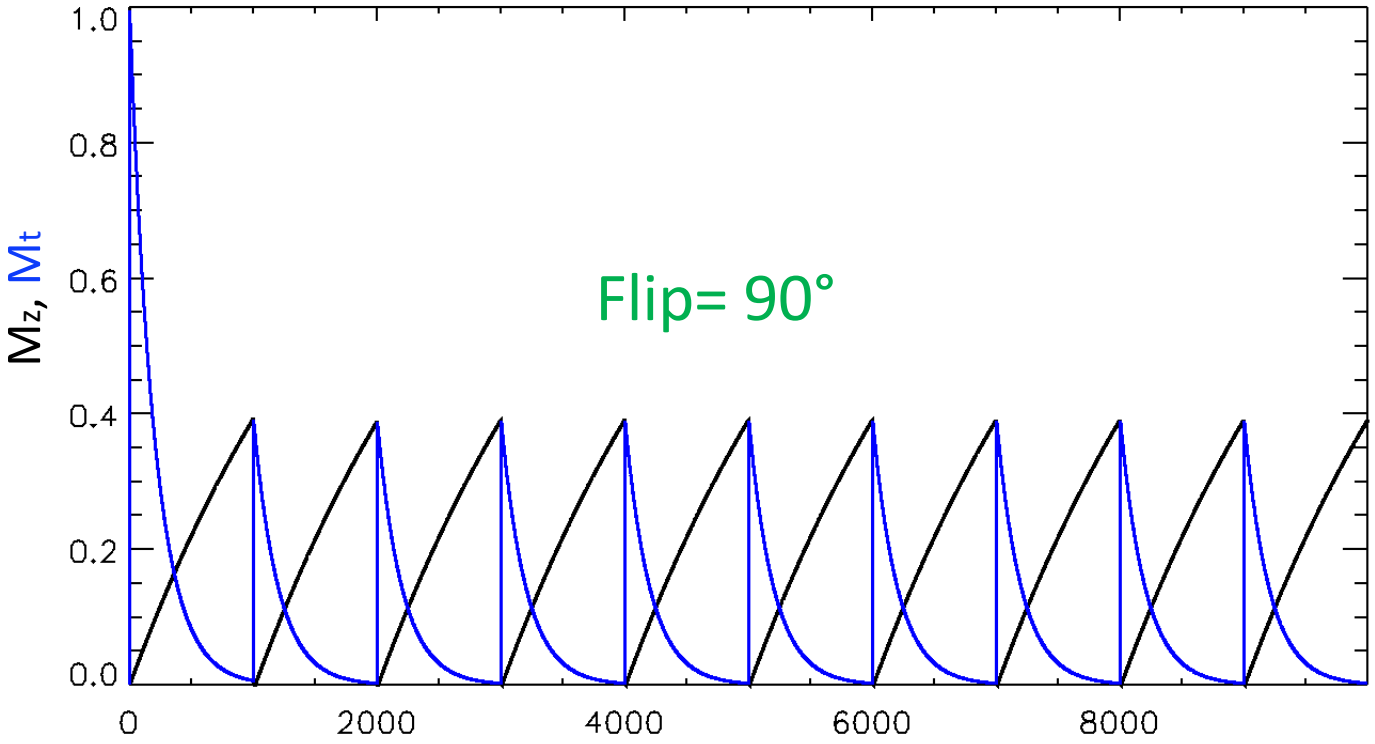
T1-Relaxation & Flip Angle



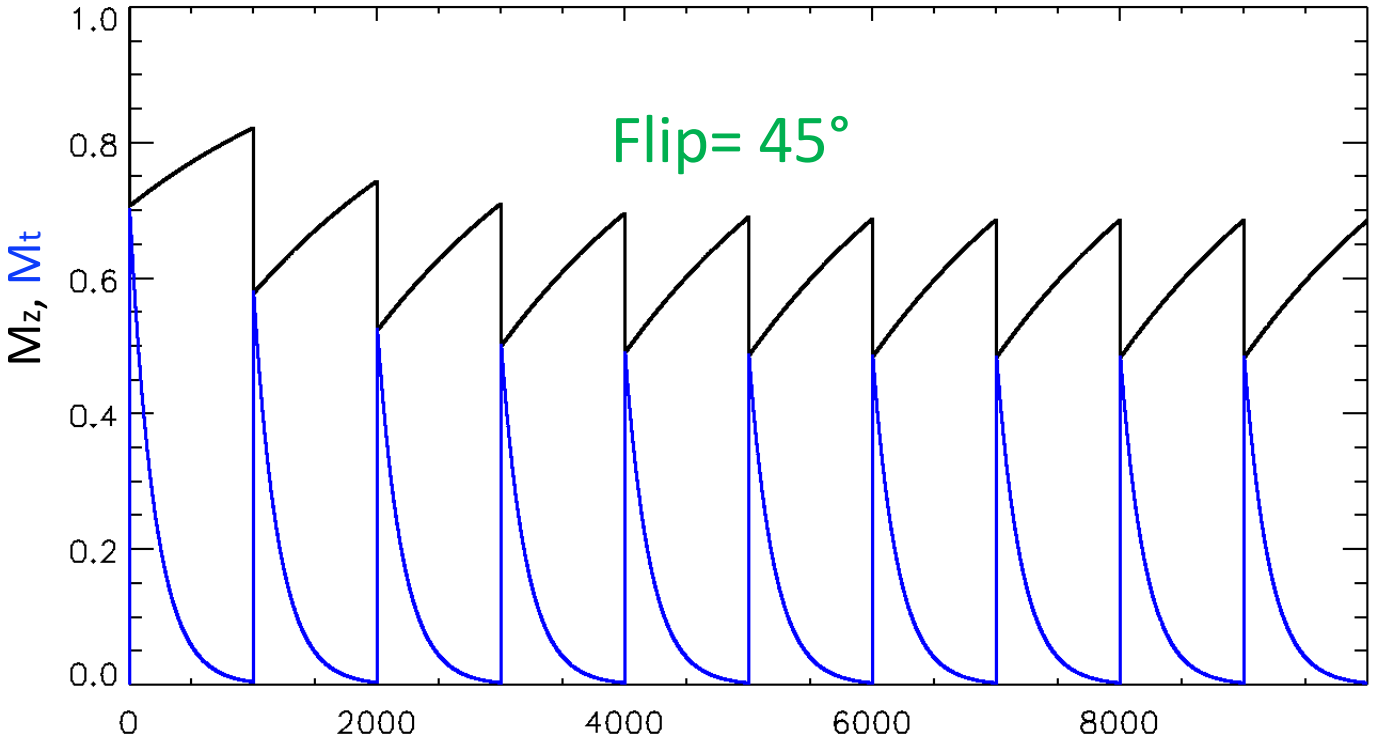
T1-Relaxation & Flip Angle



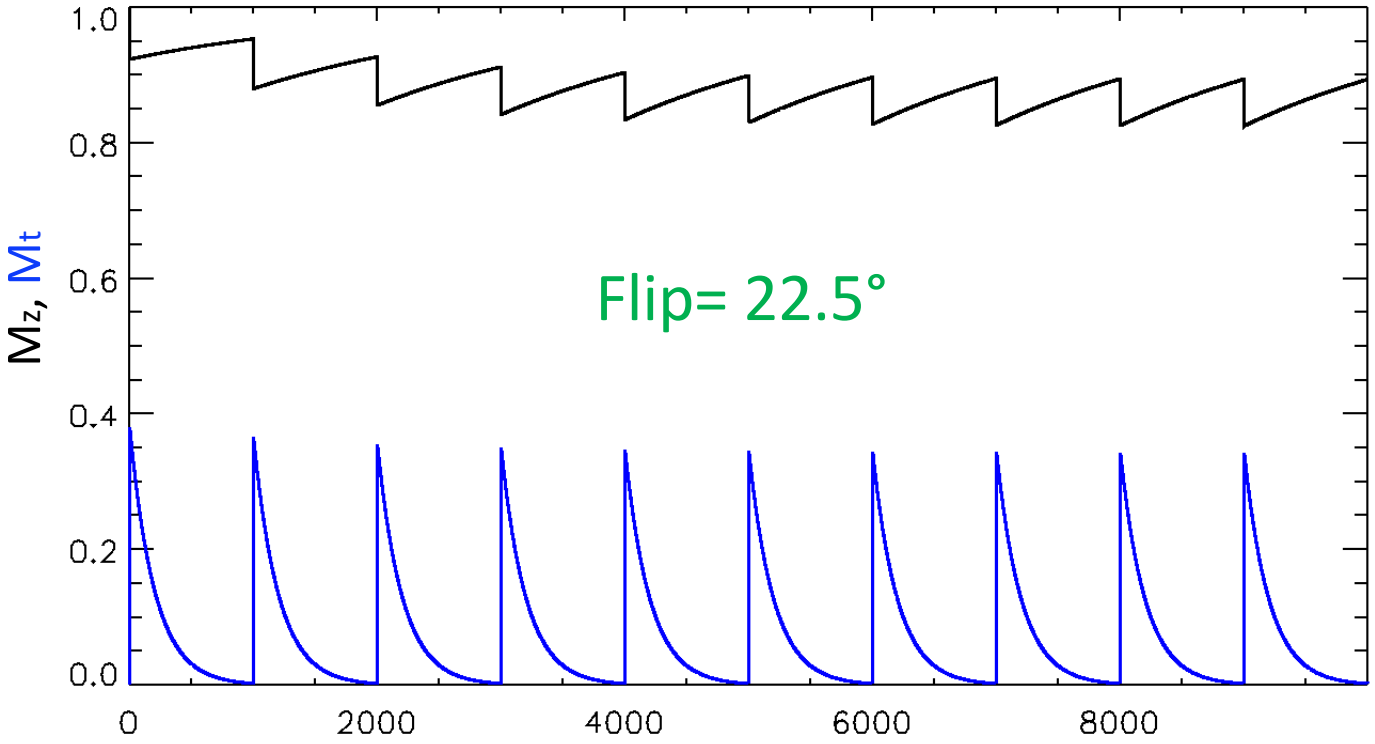
T1-Relaxation & Signal



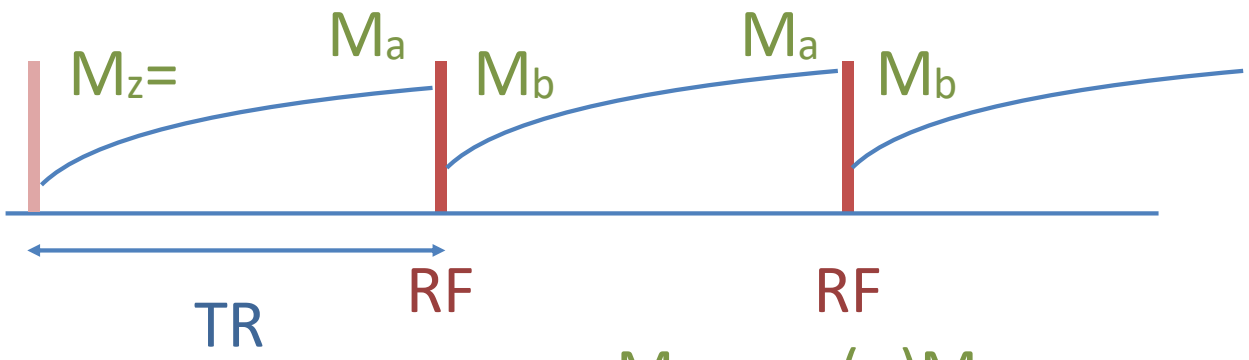
T1-Relaxation & Signal



T1-Relaxation & Signal



T_1-Relaxation: Signal Calculation



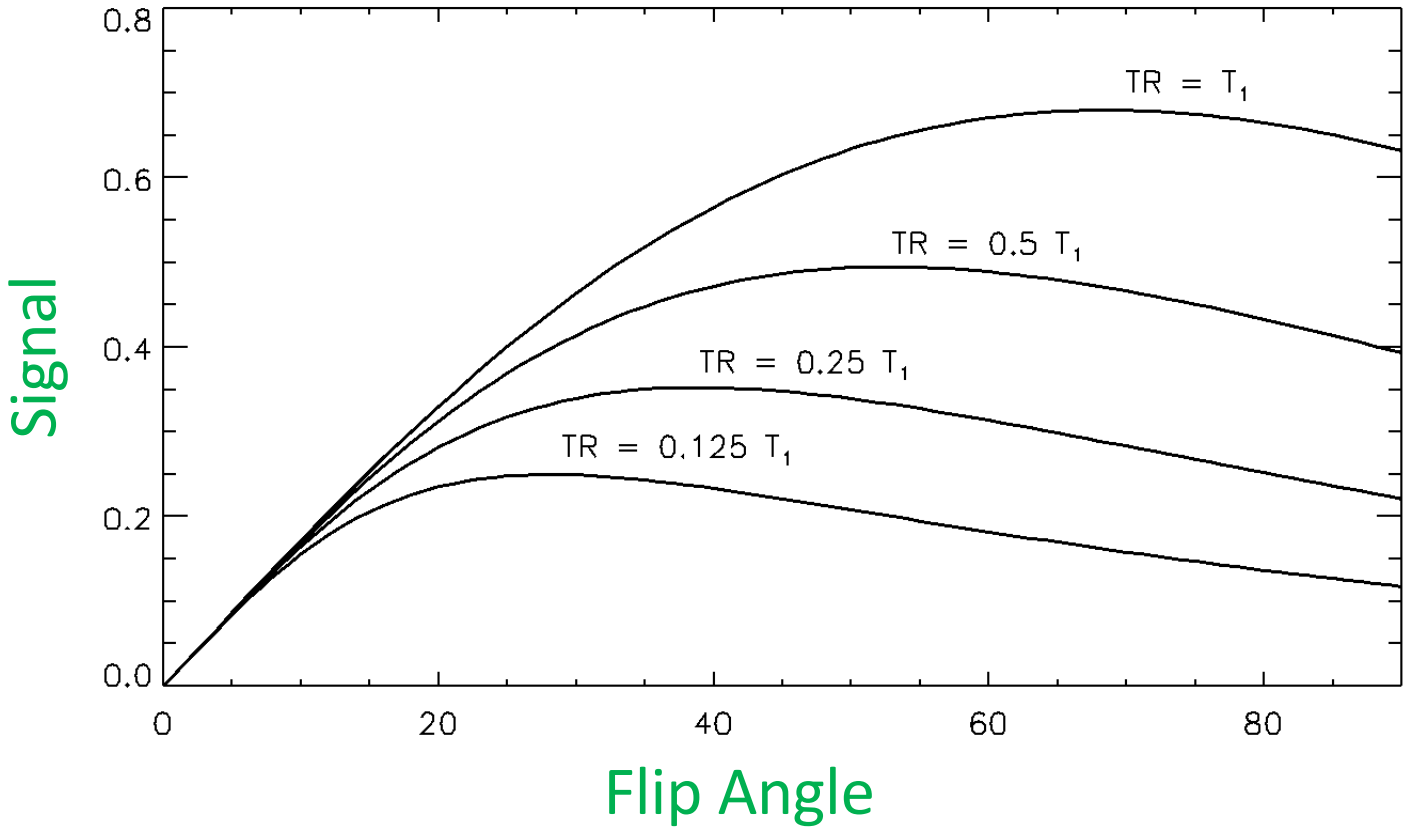
$M_b = \cos(\alpha) M_a$

$M_a = 1-(1-M_b)e^{-TR/T_1} = 1-(1-M_b)E_1$

Solution: $M_a = (1-E_1)/(1-\cos(\alpha)E_1)$

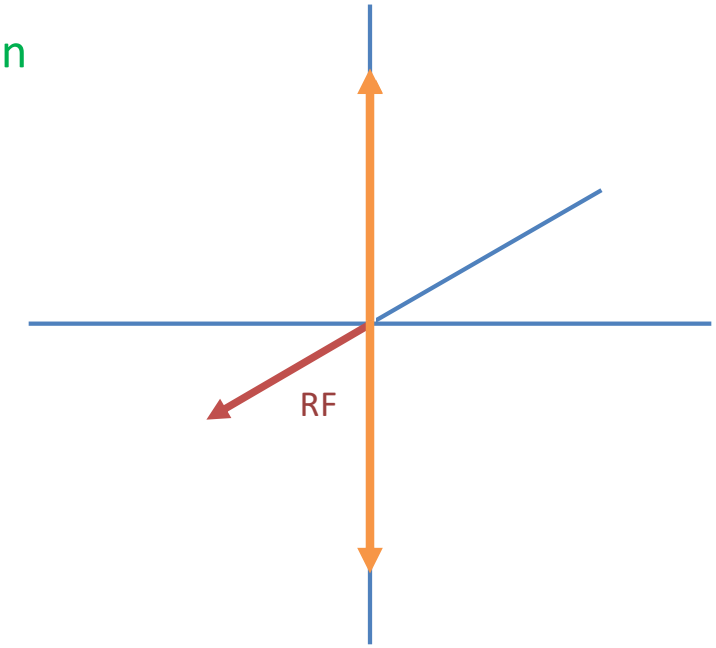
Signal: $M_t = \sin(\alpha) M_a$

T1-Relaxation & Signal

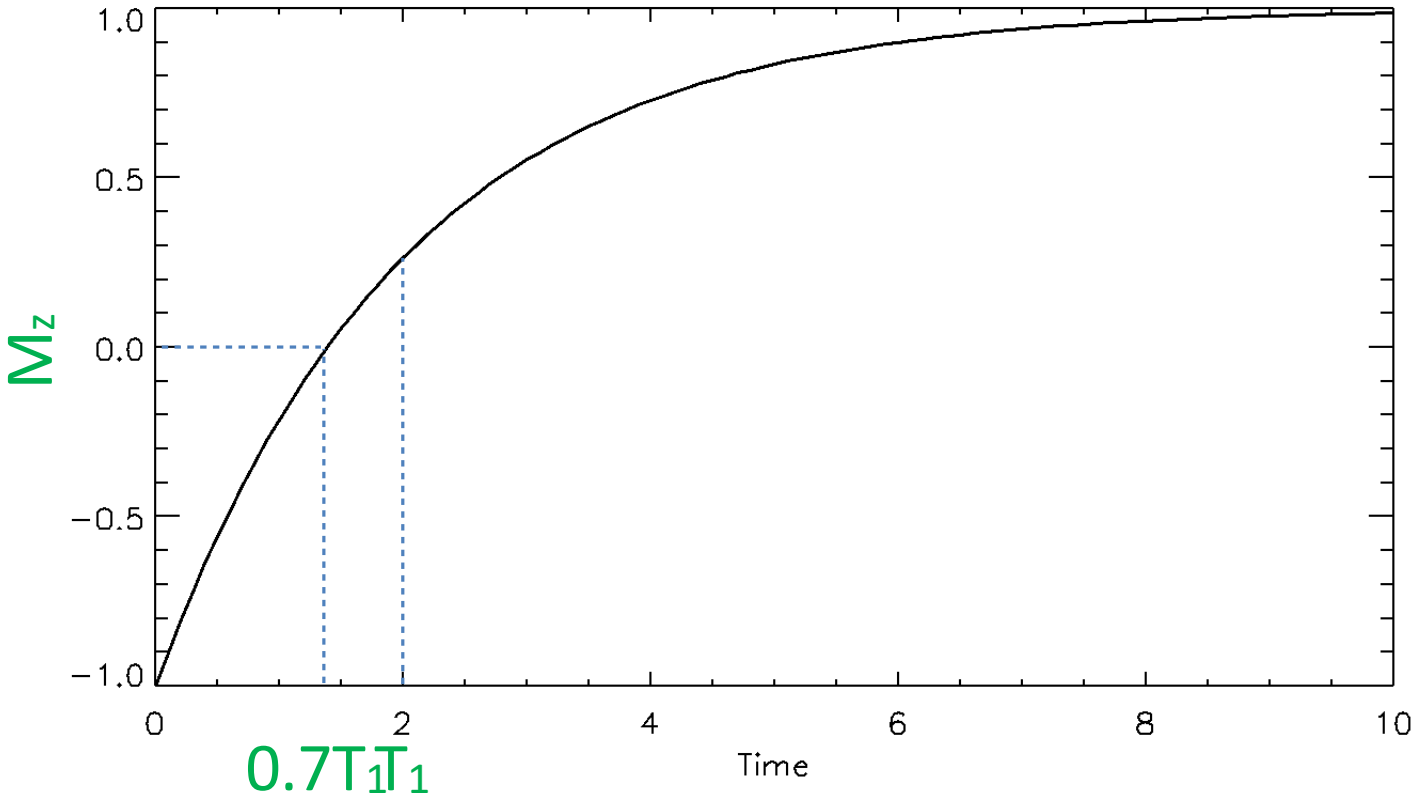


Inversion

More RF than excitation



Inversion Recovery



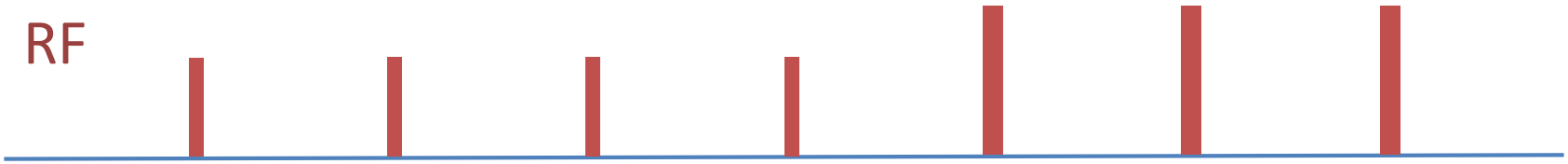
T_1 Measurement

T_1 can be measured in two ways:

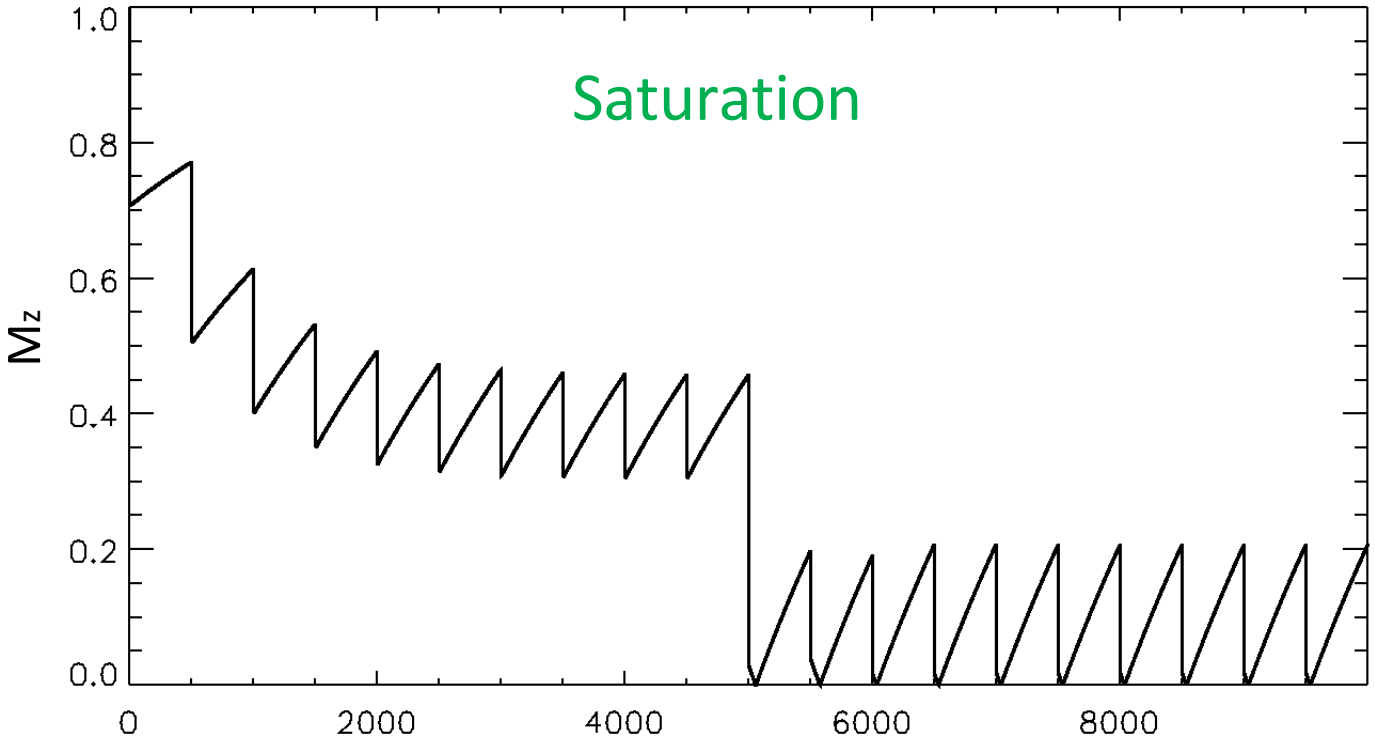
- saturation
- inversion recovery

T_1 Measurement

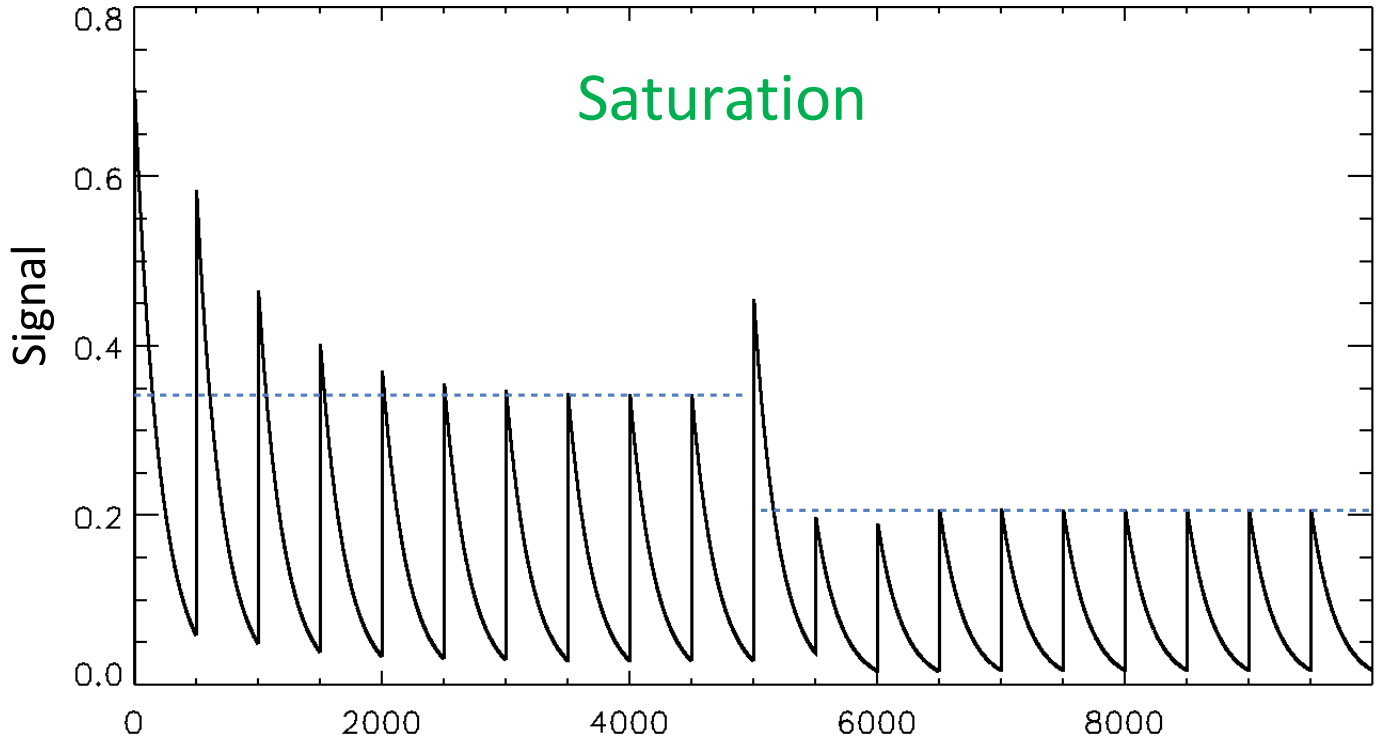
Saturation



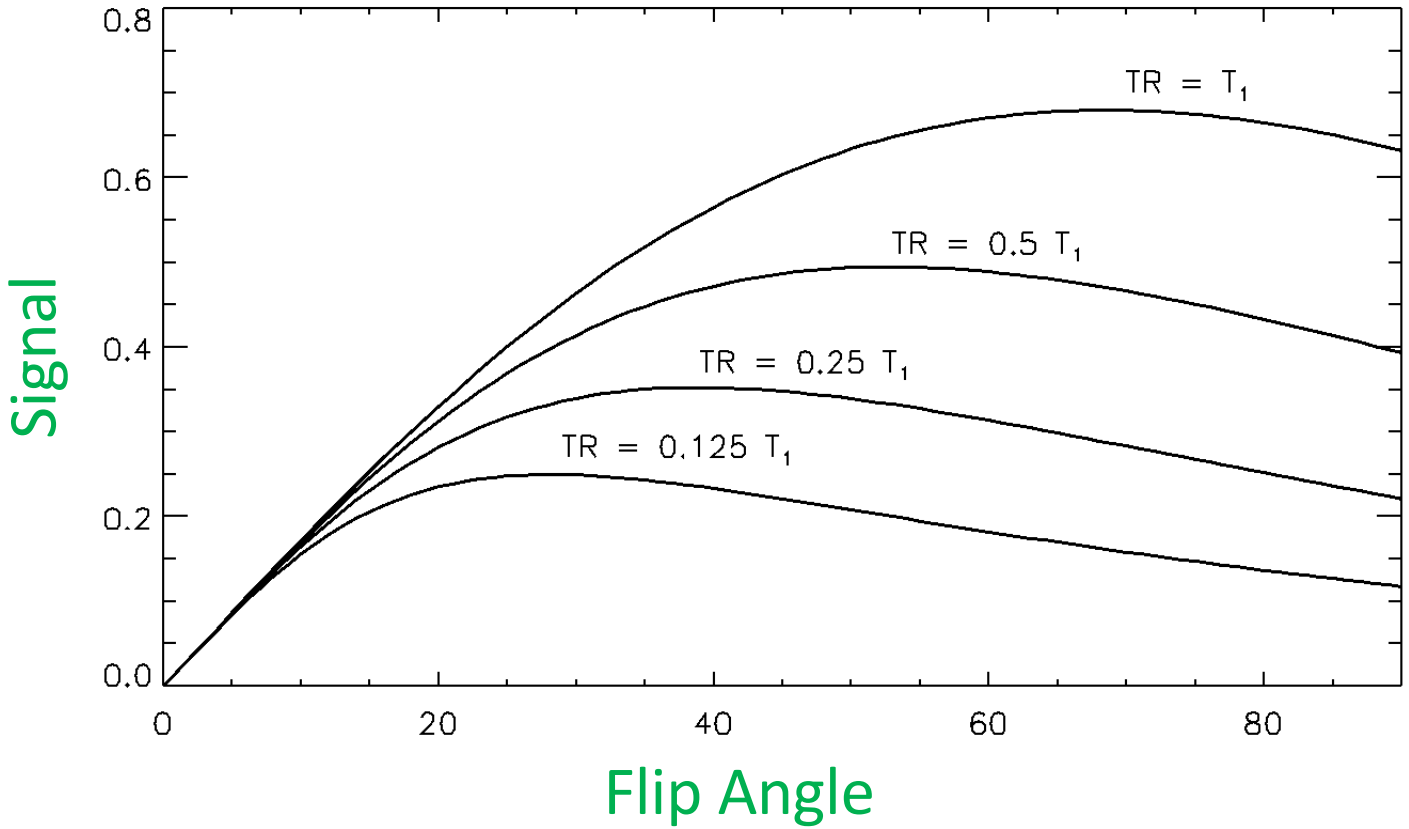
T_1 Measurement



T_1 Measurement

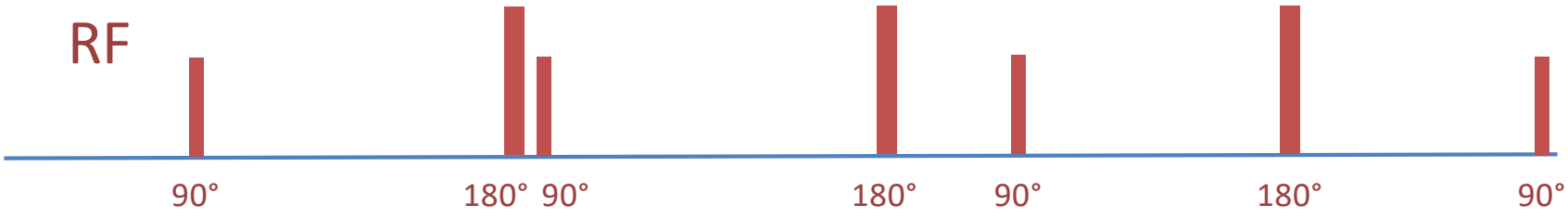


T1-Relaxation & Signal

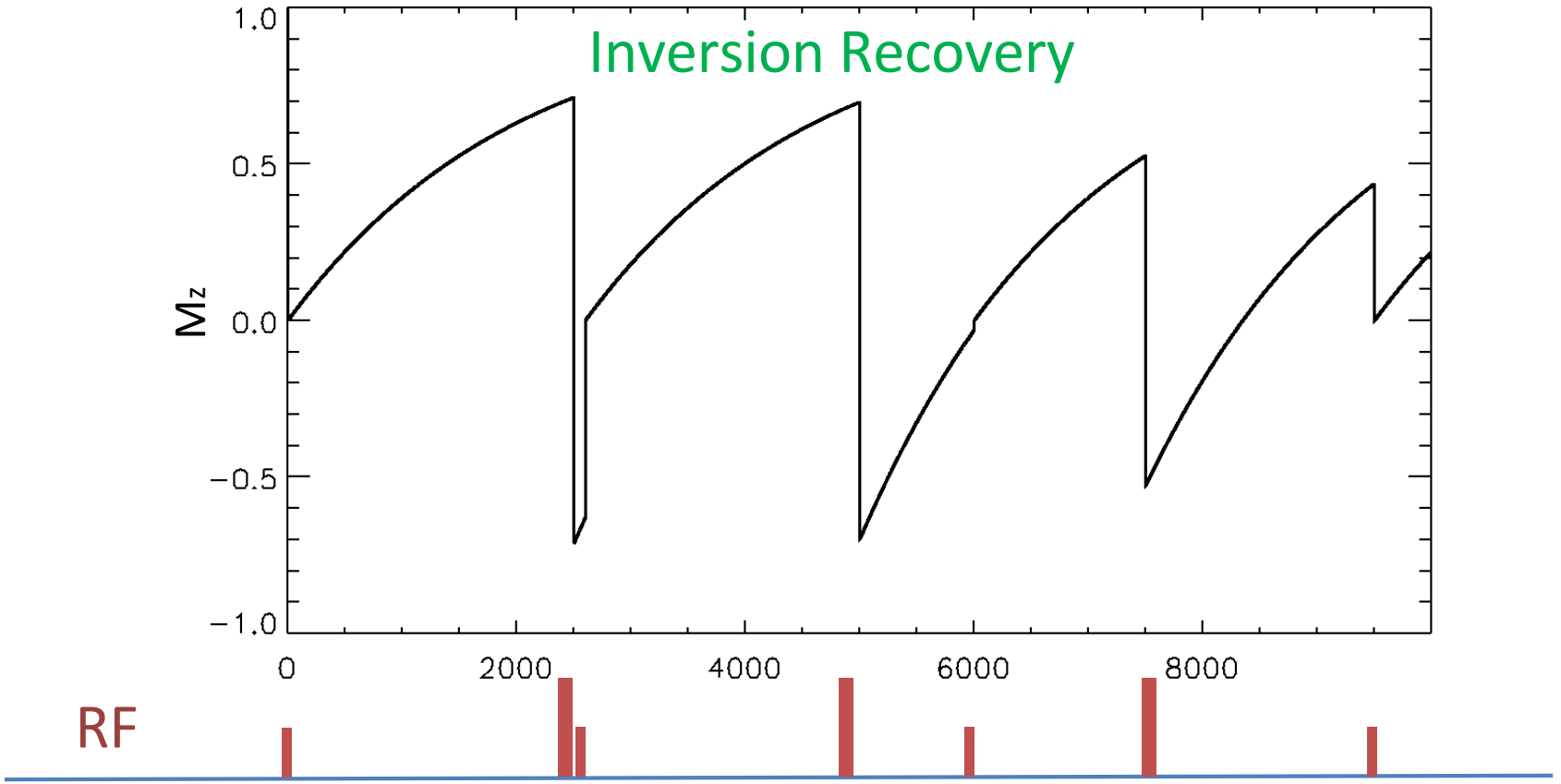


T_1 Measurement

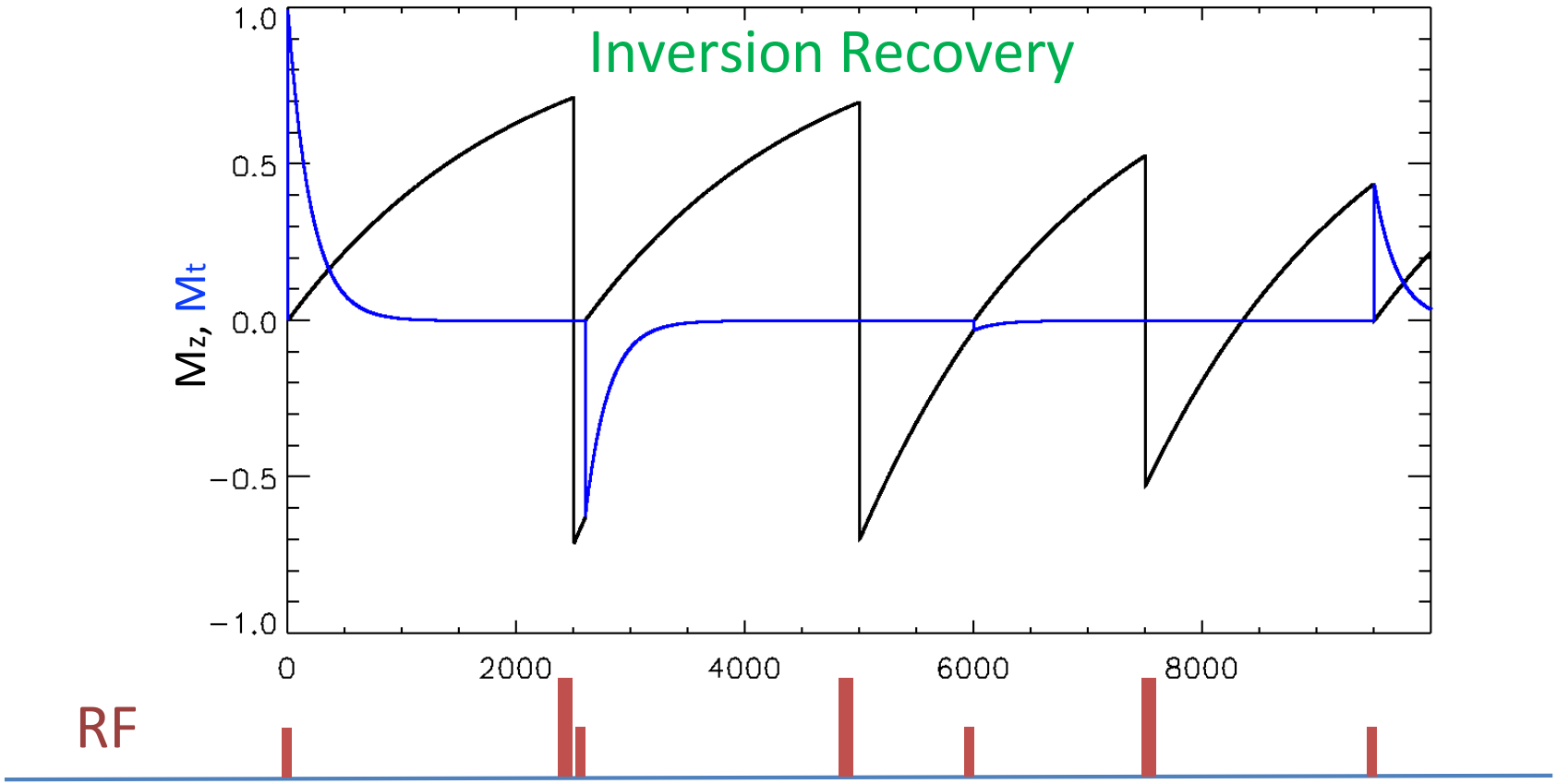
Inversion Recovery



T_1 Measurement

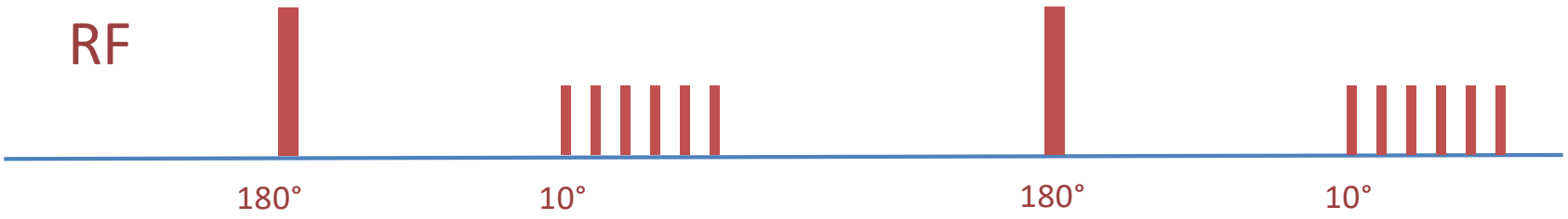


T_1 Measurement

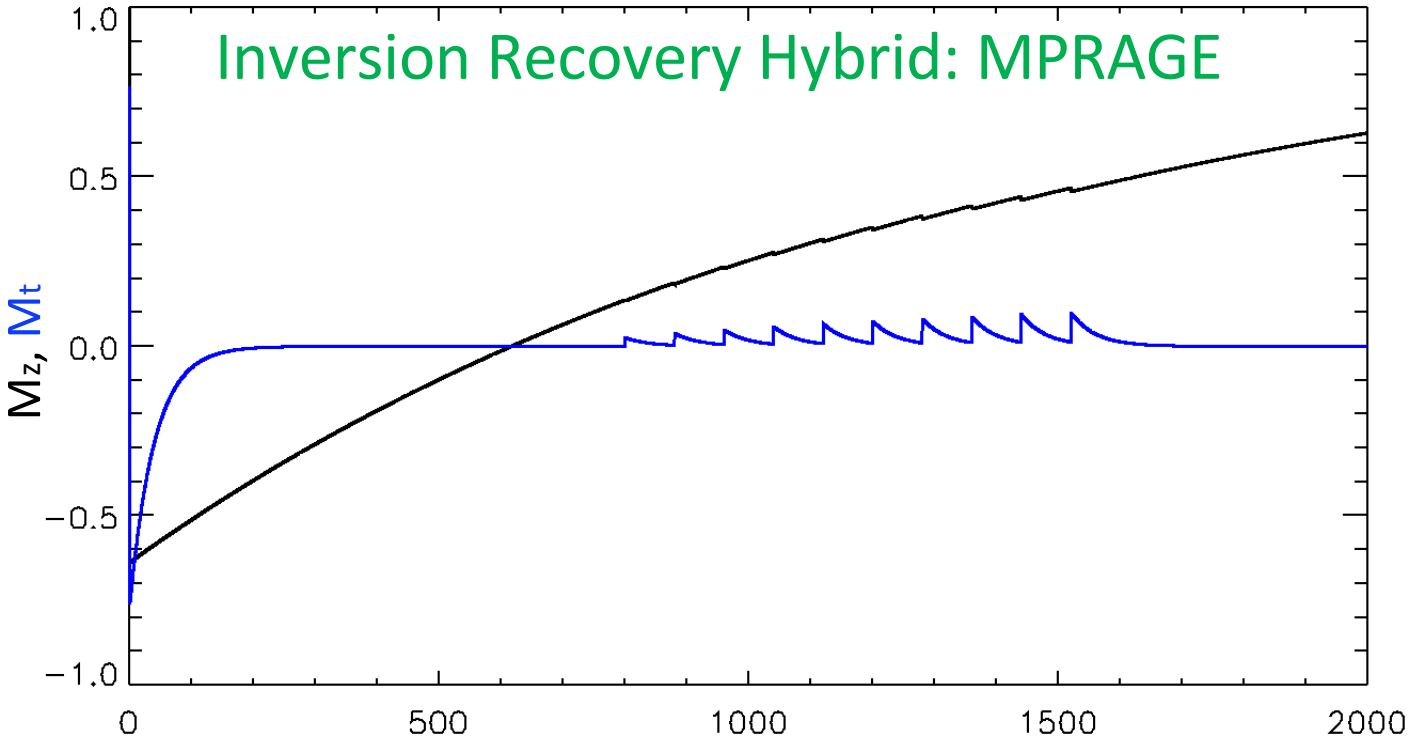


T_1 Measurement

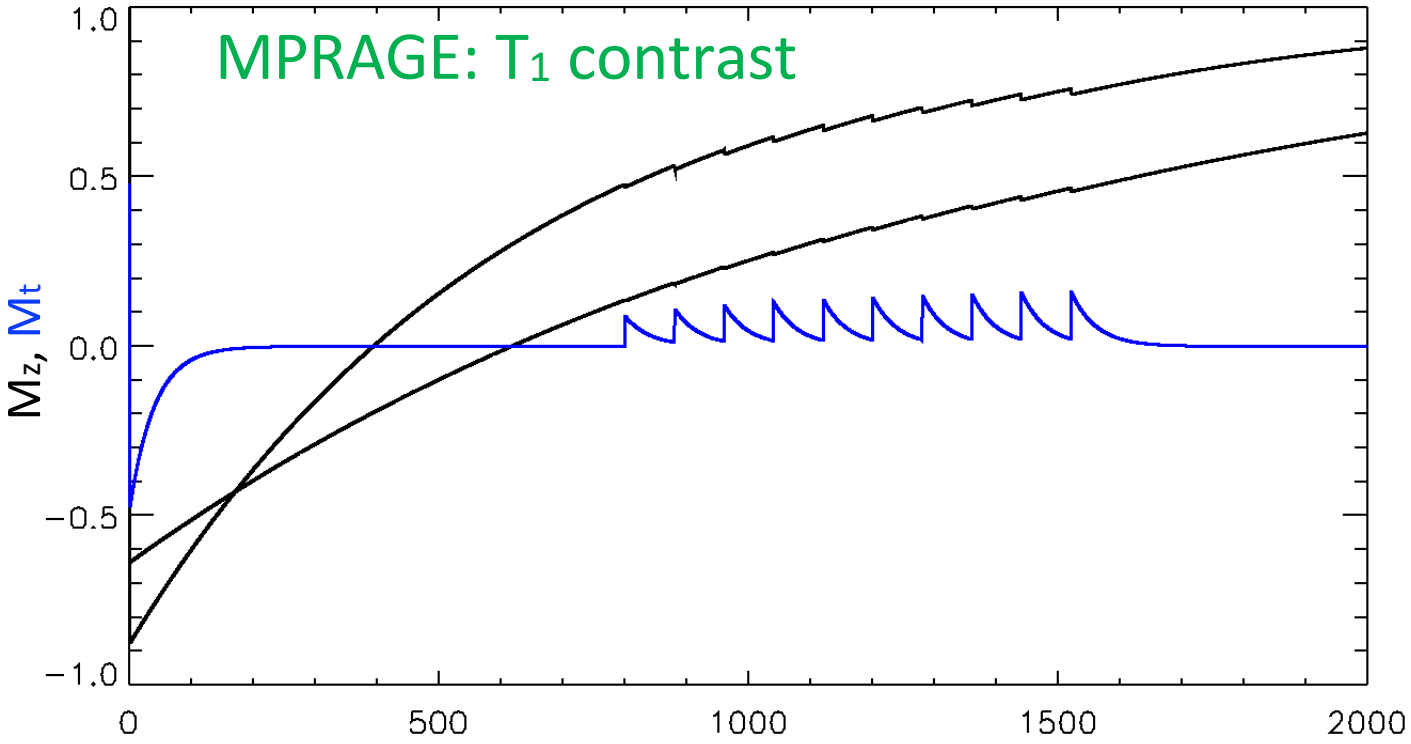
Inversion Recovery Hybrid: MPRAGE



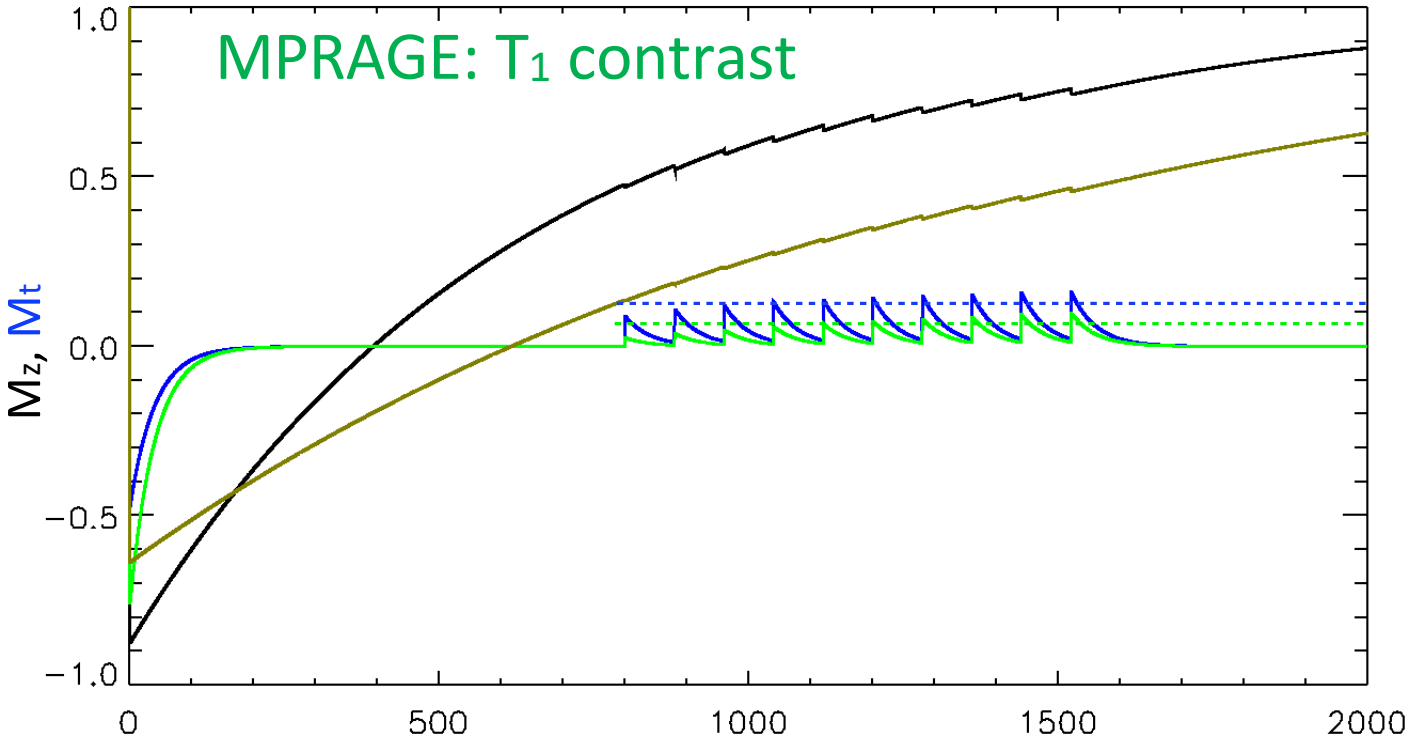
T_1 Measurement



T_1 Measurement



T_1 Measurement



T_1 Measurement

Complications

Signal depends on T_1, but also on:

- $T_2^{(*)}$
- RF (flip angle): Transmit coil, Dielectric effects, Calibration
- Receive sensitivity: Coils, System amplification
- Proton density

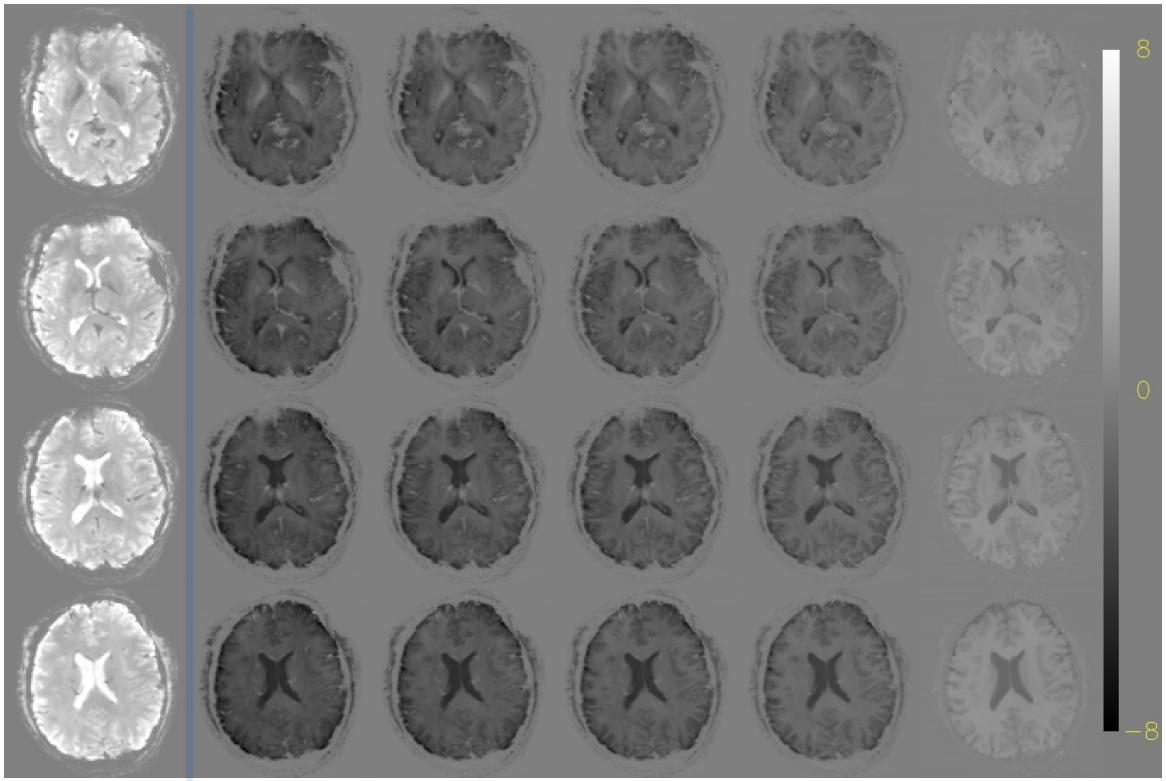
T_1 Measurement

Choosing a method

Inversion Recovery: best quantification, slow
Saturation: fast, but mixed with RF and some T_2
MPRAGE: fast and useful contrast, hard to quantify,
and potential for spatial blurring.
MPRAGE with second scan (MP2RAGE) can compensate some of the coil contrast etc.

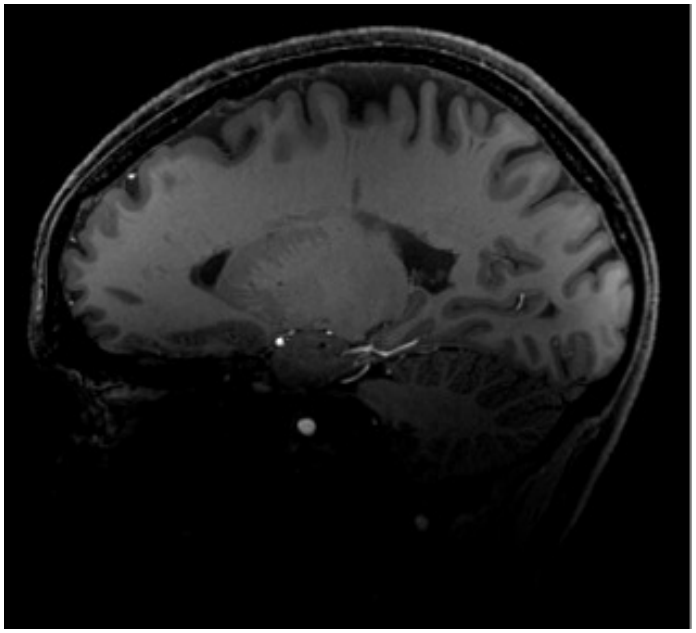
T_1 Measurement

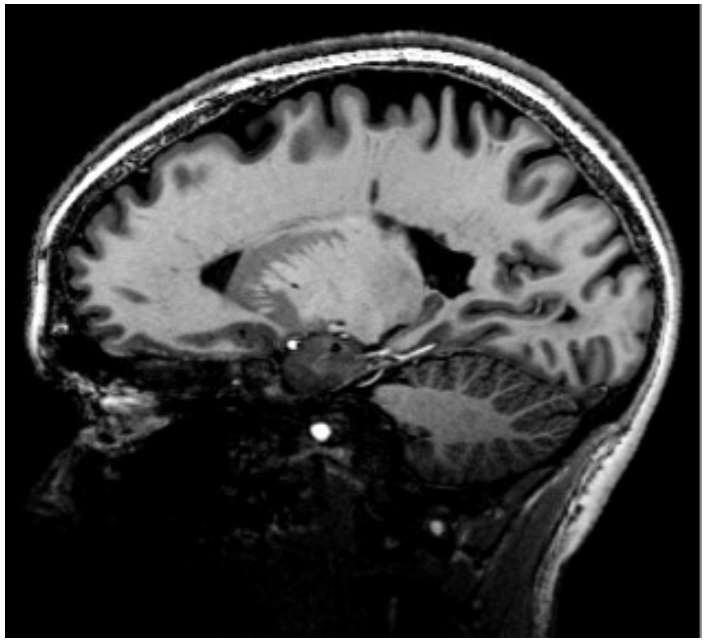
Examples: 7T IR with EPI



T_1 Measurement

Examples: MPRAGE, MP2RAGE

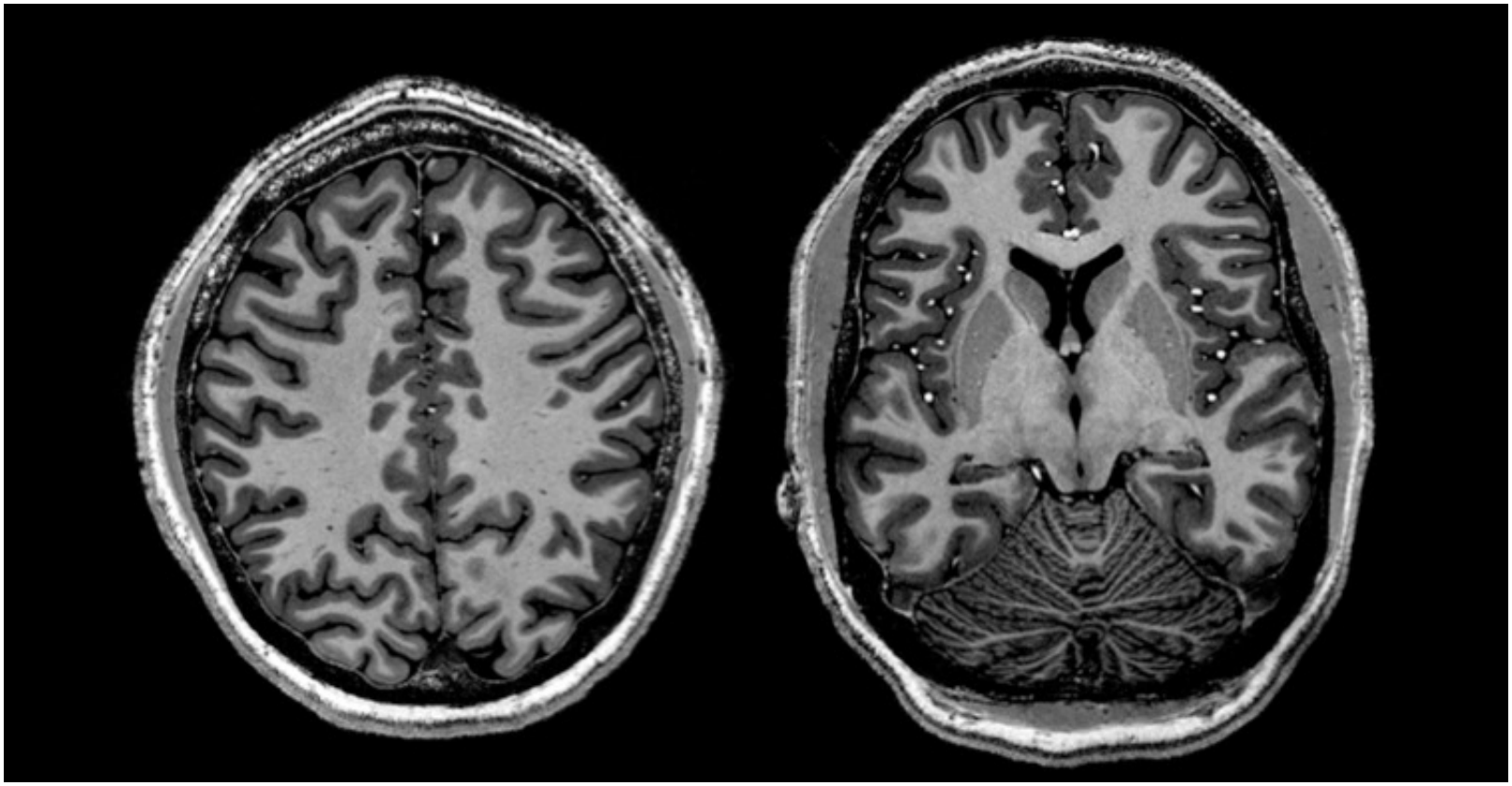




Curtesy of Pascal Sati, NINDS

T_1 Measurement

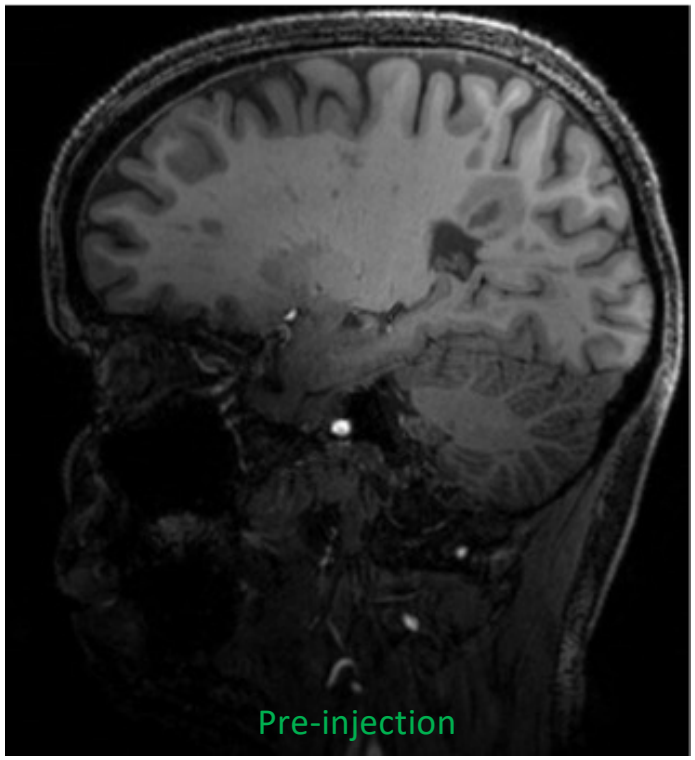
Examples: 7T 0.5mm MP2RAGE

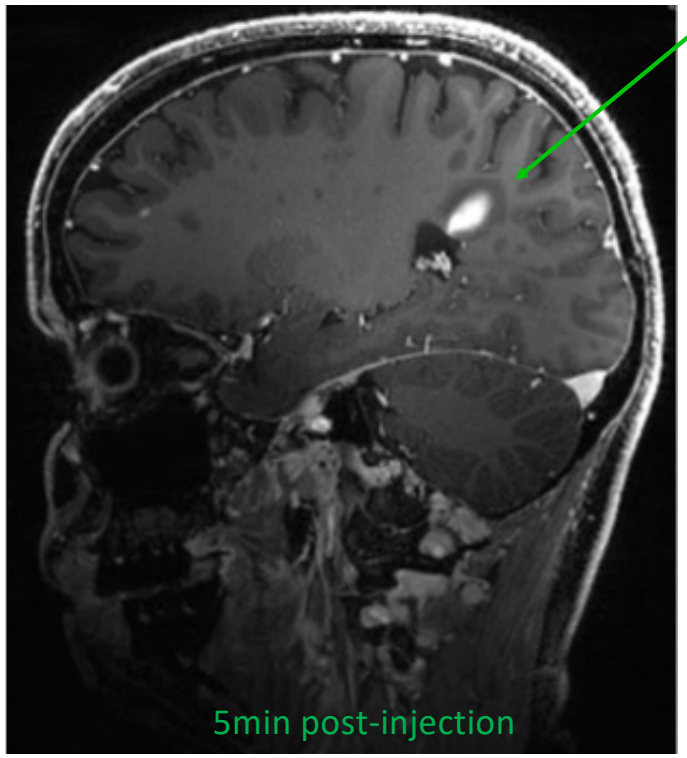


Curtesy of Pascal Sati, NINDS

T_1 Measurement

Examples: 7T, MPRAGE, Gd-injection





Curtesy of Pascal Sati, NINDS

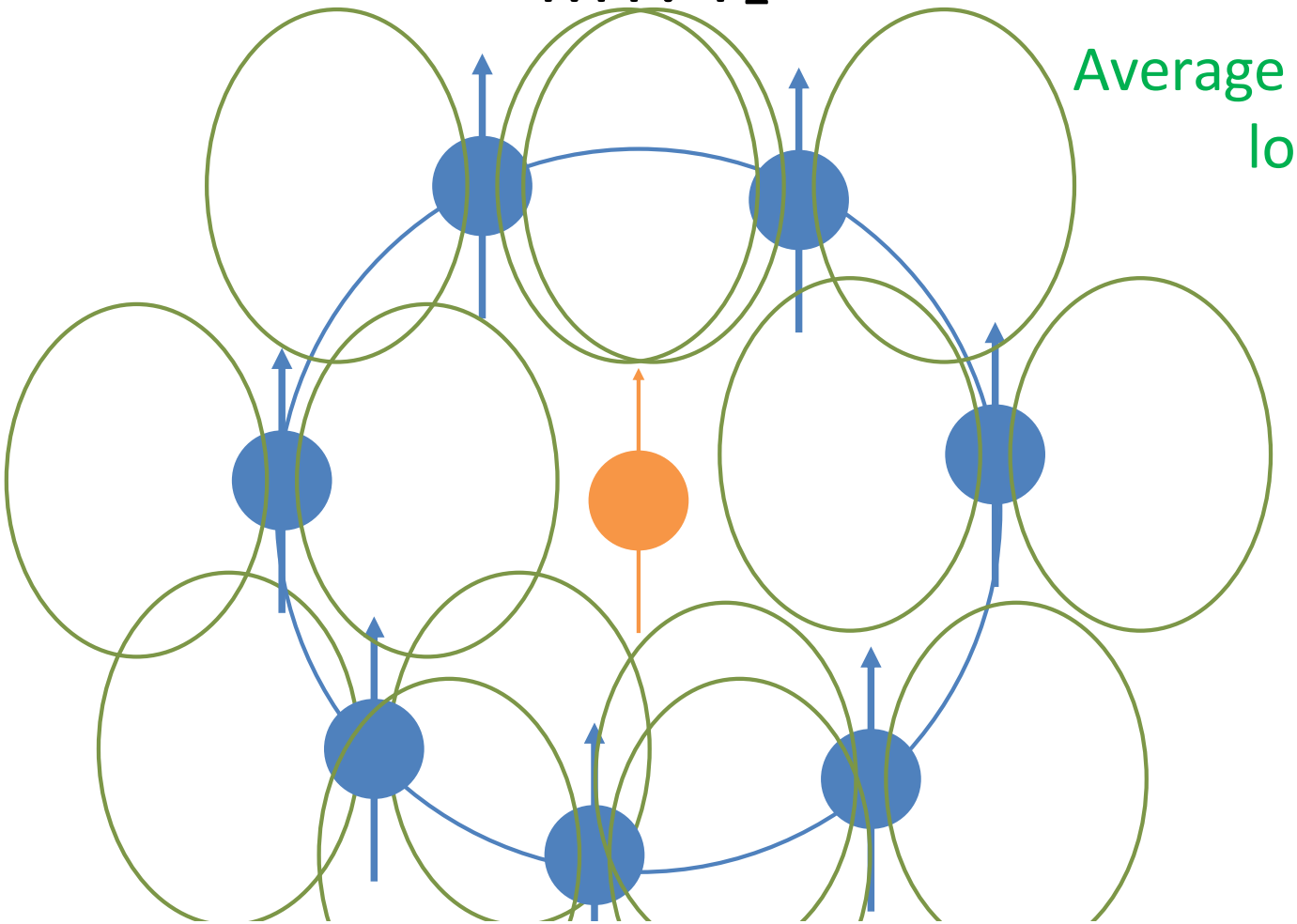
T_1: Sources

Pure water: very little energy transfer -> slow relaxation

Interaction with other molecules required:
in the brain, mostly lipids and protein

Interaction: Magnetization Transfer (= part 2)

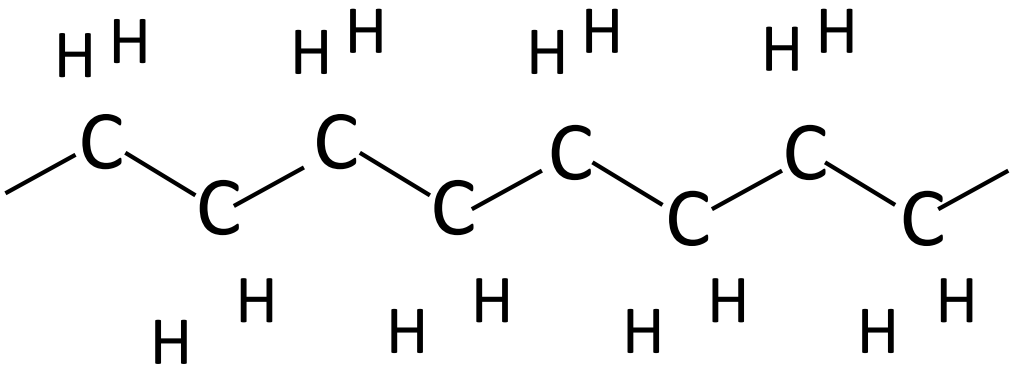
MT: T_2



Average field = 0 :
long T_2

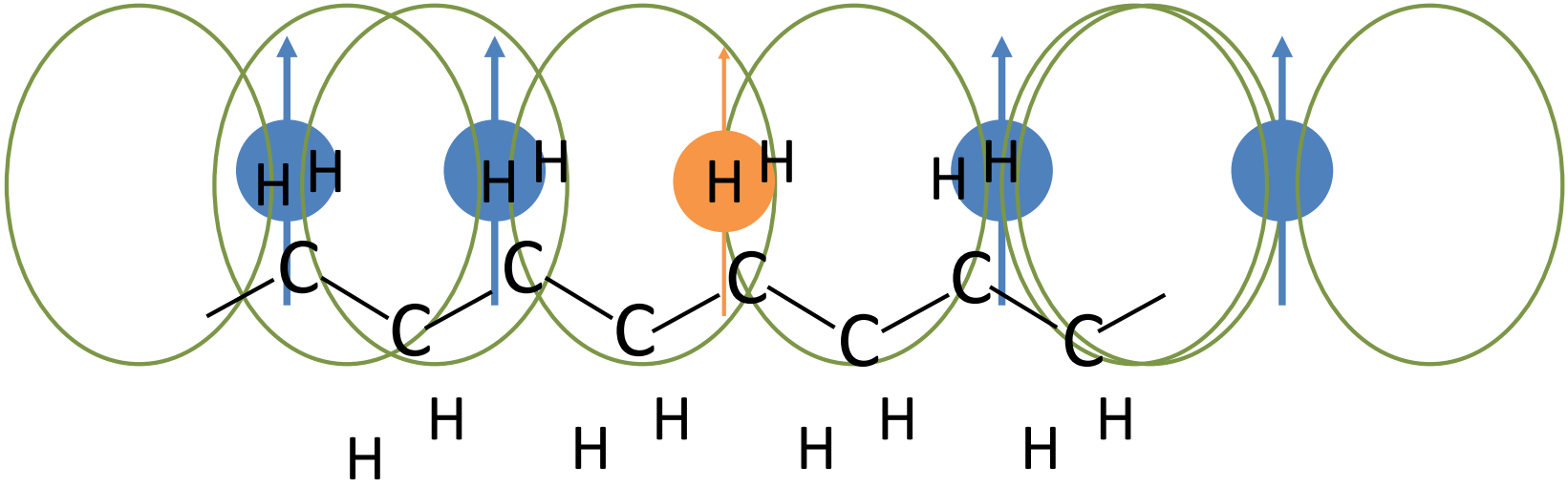
MT: T_2

Lipid has more structure



MT: T_2

Average field ≠ 0: short T_2



MT: T_2

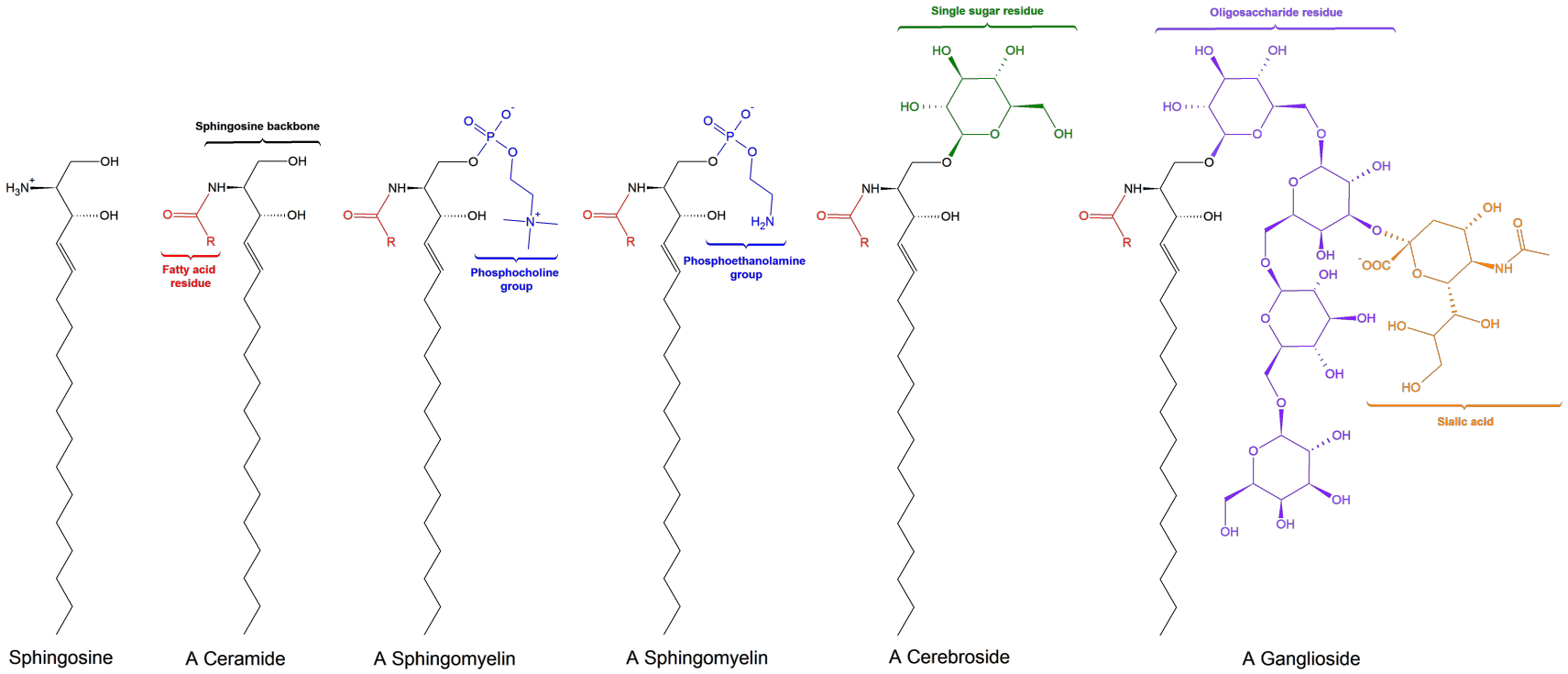
Short T_2

$T_2 << 1$ ms : not visible in MRI

But: ‘hidden’ magnetization interacts with water

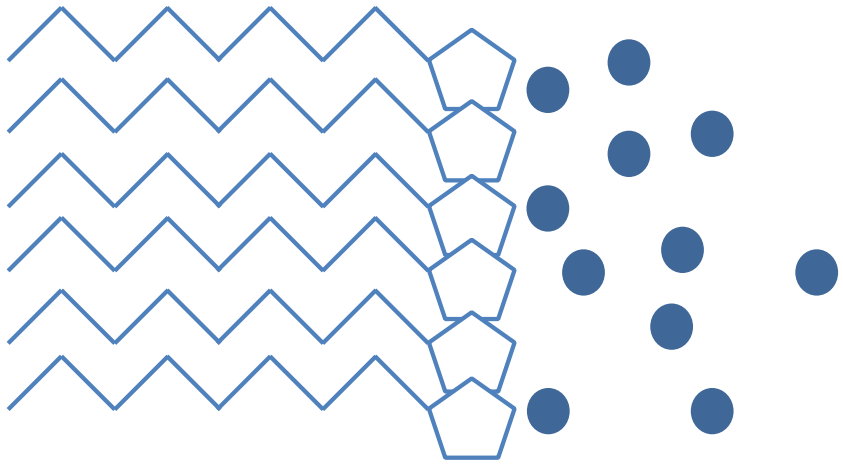
MT: T_2

Lipid and Exchange



MT: T_2

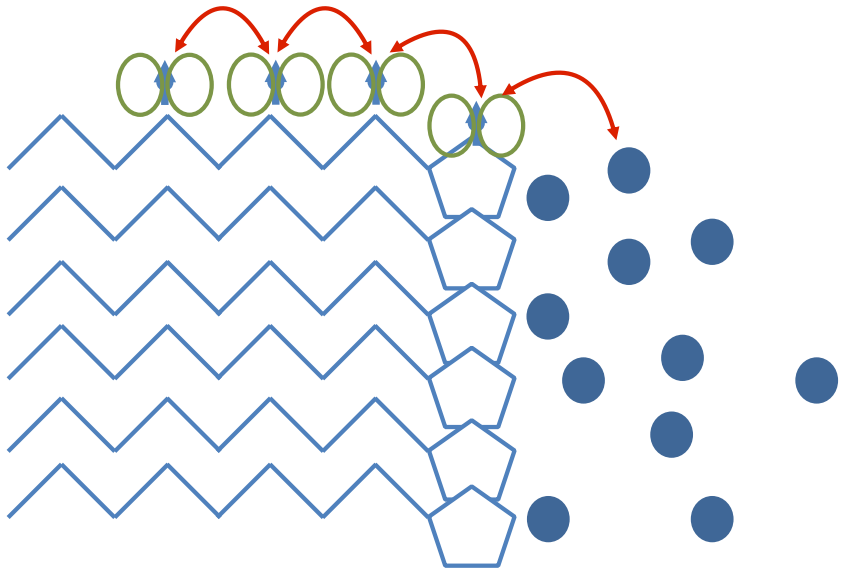
Lipid and Exchange



Lipid Membrane Water

MT

Lipid and Exchange

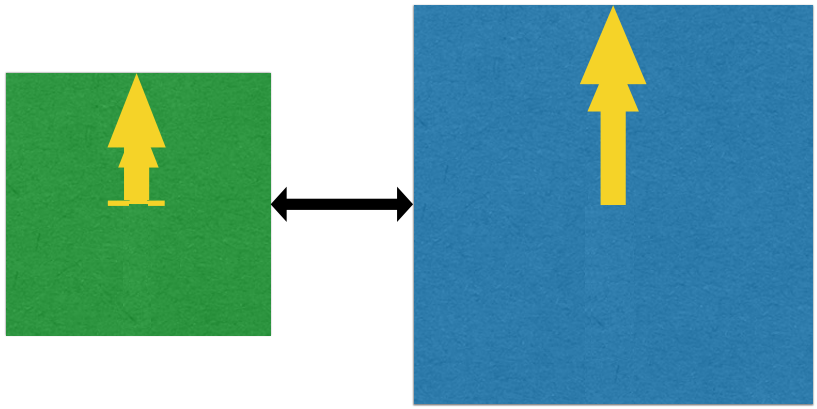


Lipid Membrane Water

Exchange:
- Magnetic
- Chemical

MT

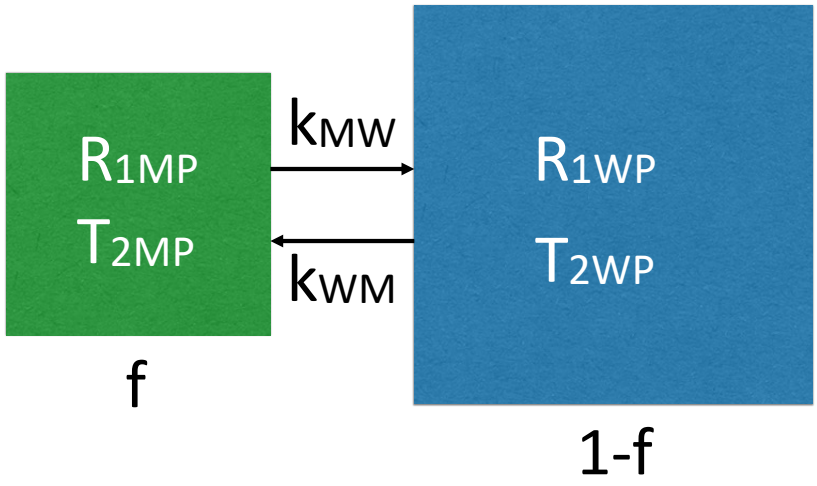
Lipid and Exchange



Macro Molecular Protons Water Protons

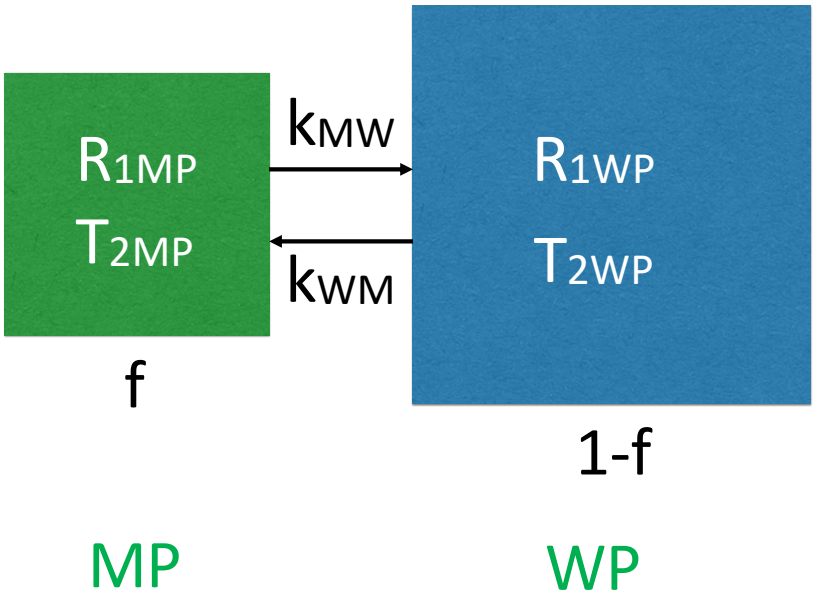
MT

Parameters



MT

Equations



saturation: $S = 1 - M_z$

$$d S_{WP} / dt = -R_{1wp} S_{WP} - k_{WM} S_{WP} + k_{WM} S_{MP}$$

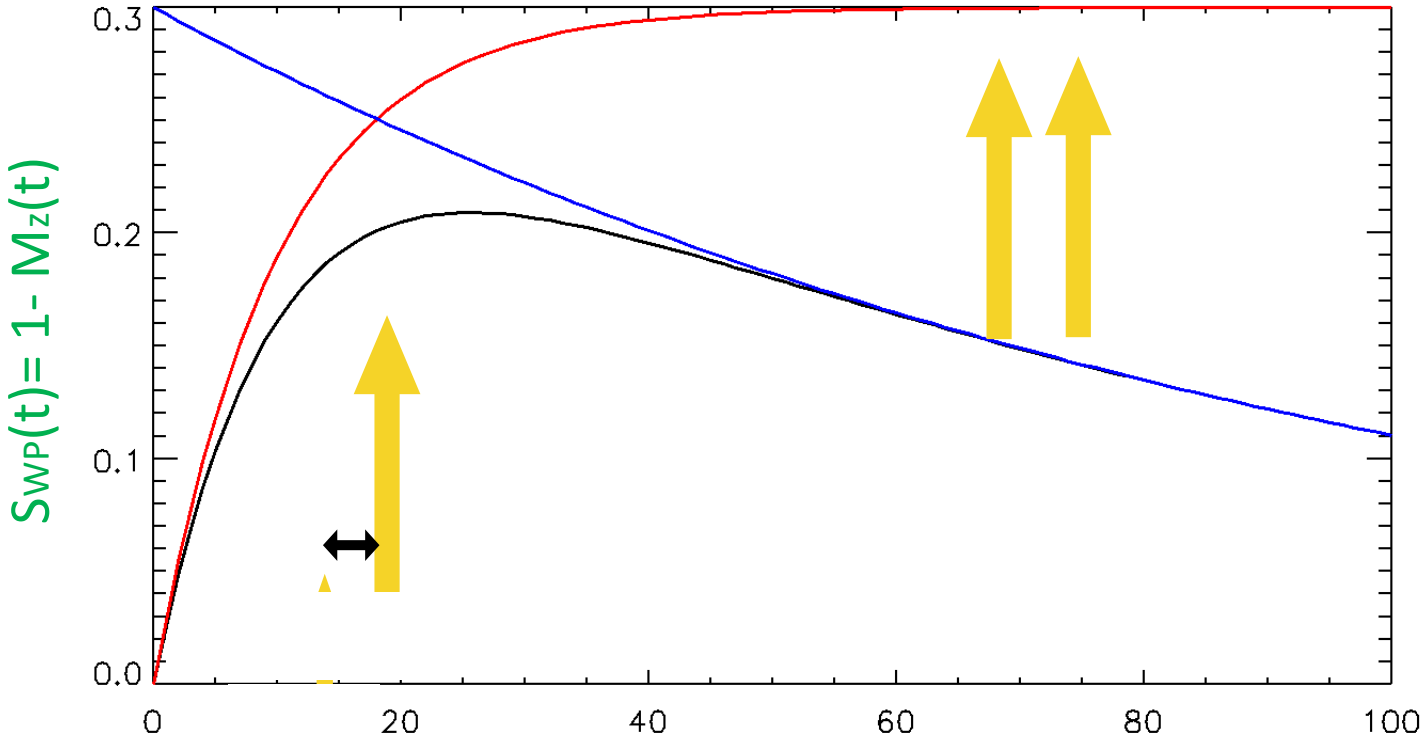
$$d S_{MP} / dt = -R_{1mp} S_{MP} - k_{MW} S_{MP} + k_{MW} S_{WP}$$

$$f k_{MW} = (1-f) k_{WM}$$

$$S_{WP}(t) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$$

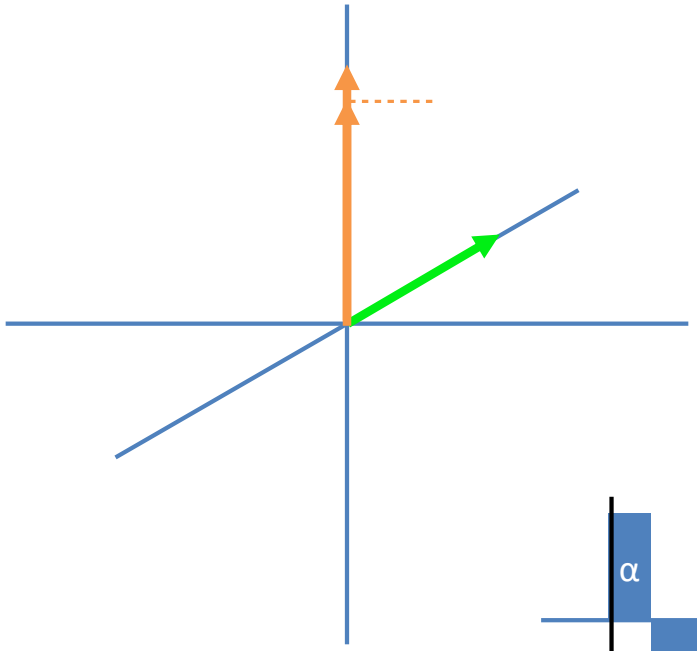
MT

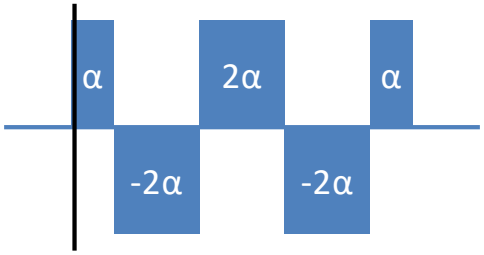
Saturation $S_{WP}(t) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$



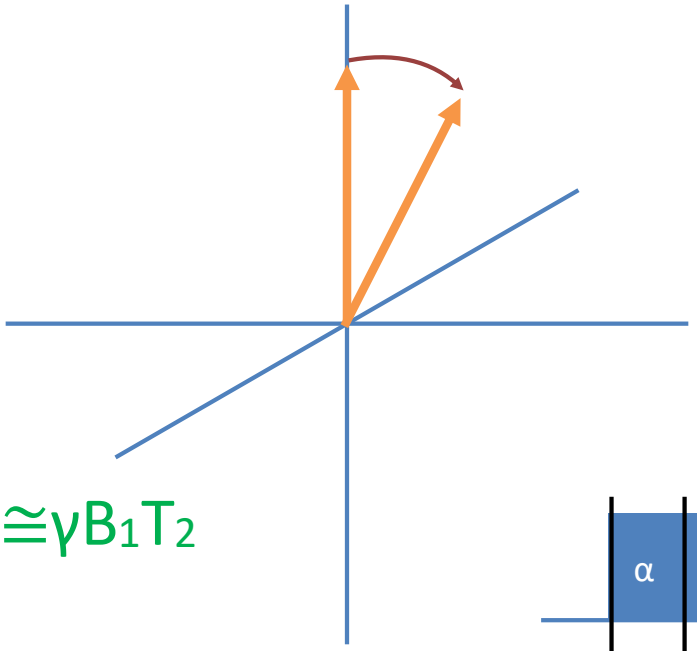
Pulse Design

Short T_2





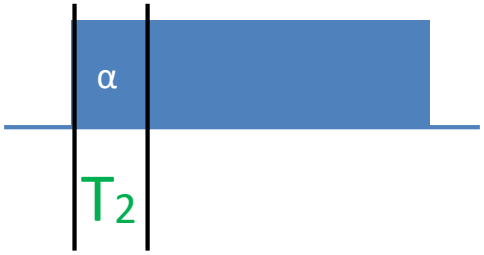
Pulse Design



Effective flip angle $\alpha \cong \gamma B_1 T_2$

$M_z = \cos(\alpha) = 1 - \alpha^2/2$

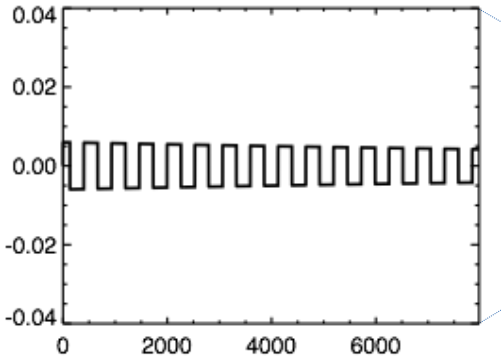
PW/T_2 times

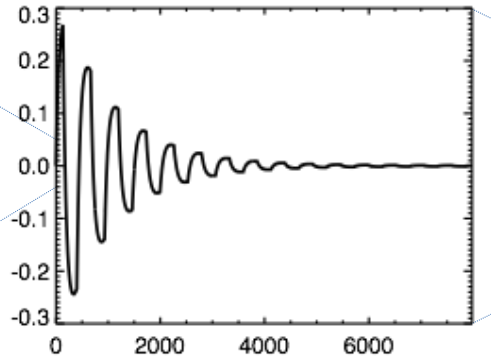


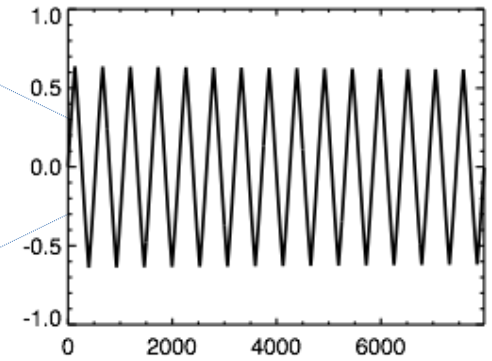
Pulse Effect

Short T2 | Intermediate T2 | Long T2

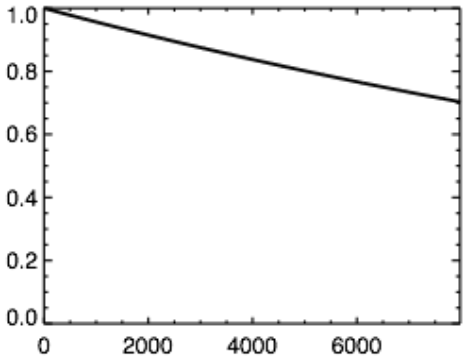
My

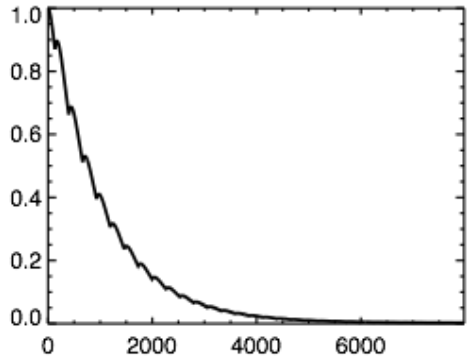


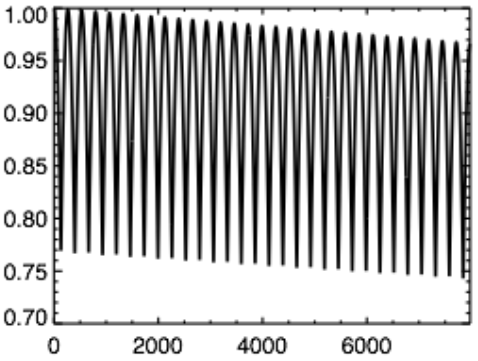




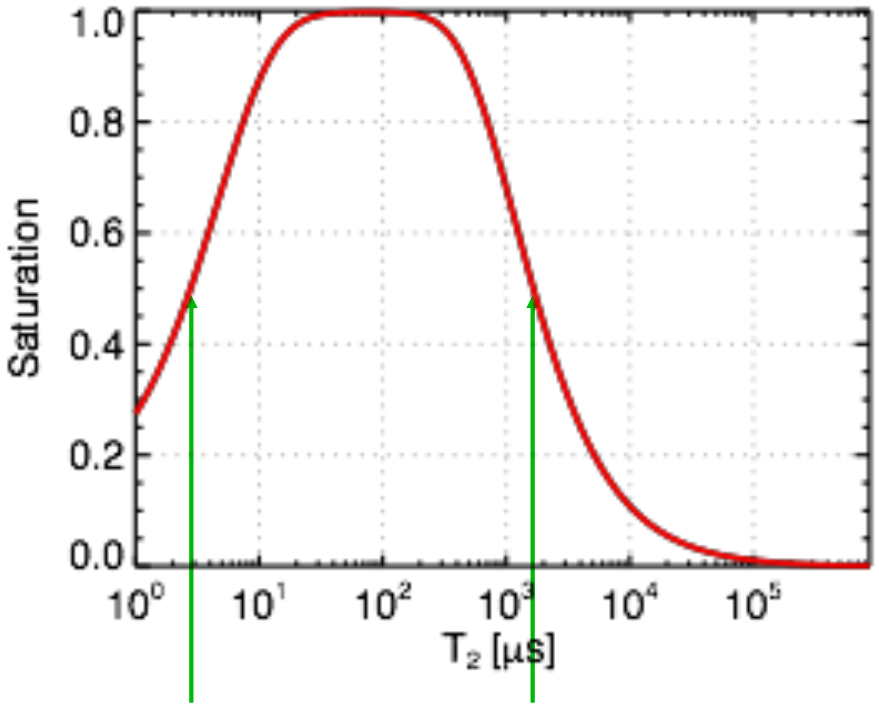
Mz







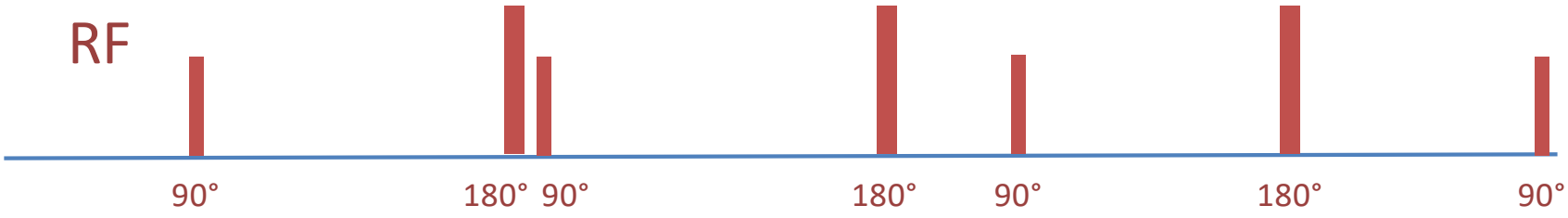
Pulse Design



Approximate Transitions:	Short T_2: $(\gamma B_1)^2 PW/2$	Long T_2: $\sin(\alpha)^2 PW/2$

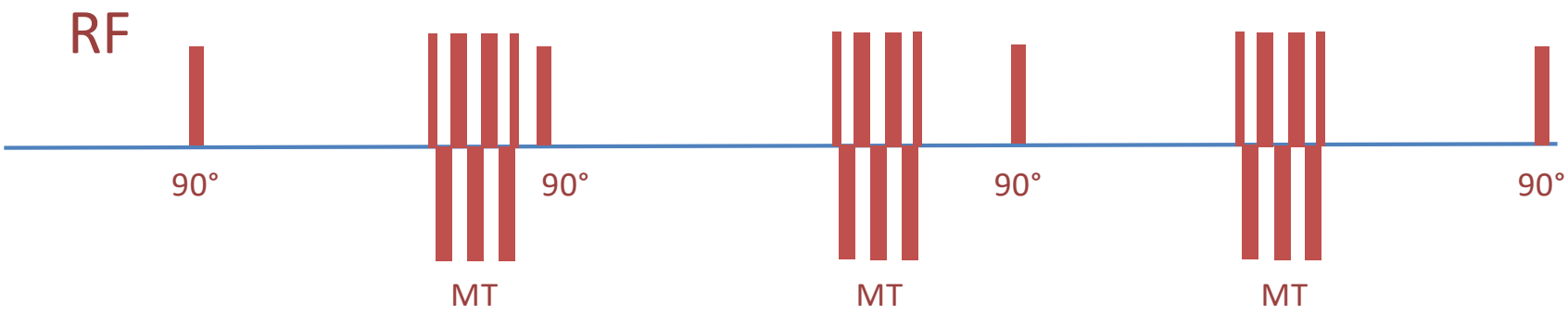
T_1 Measurement

Inversion Recovery

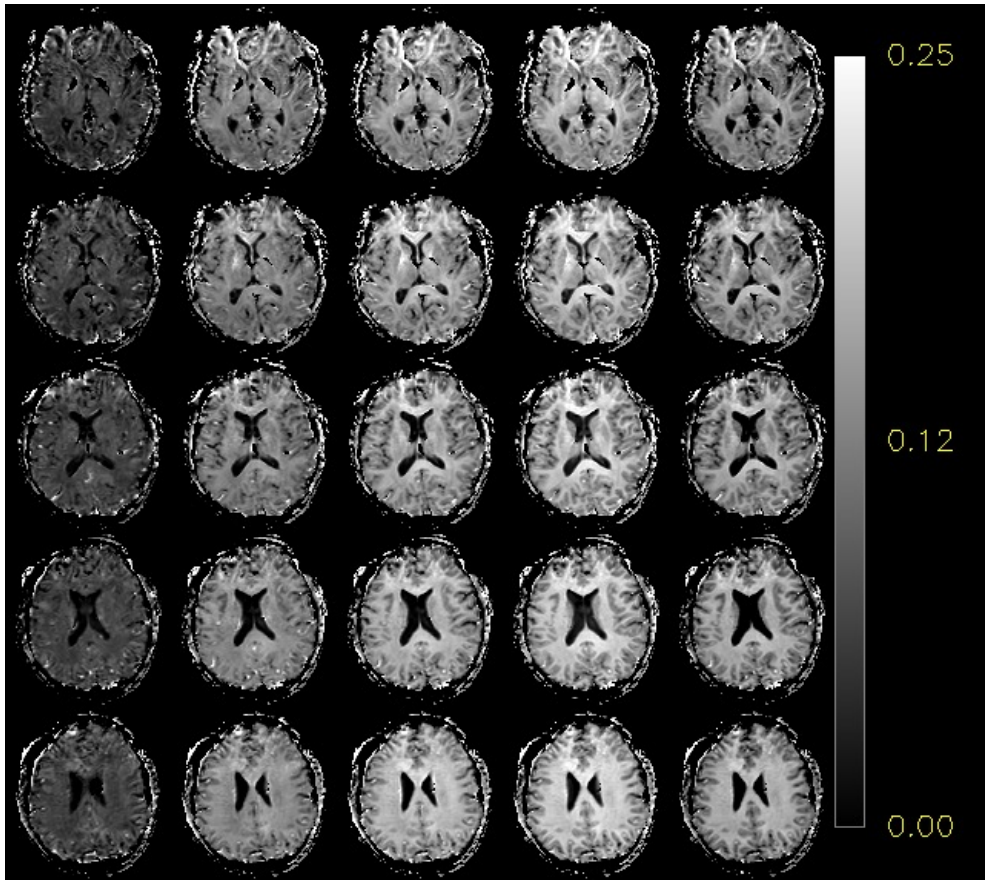


MT Measurement

MT Saturation Recovery



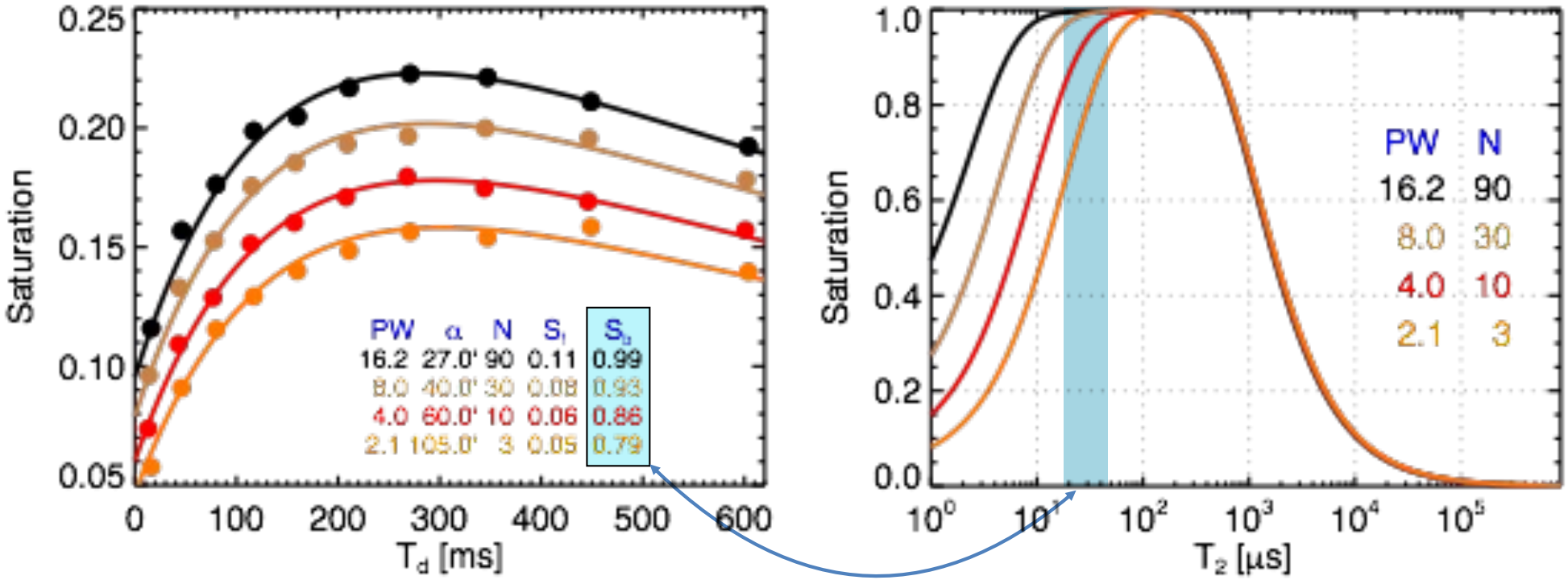
MT Recovery



TI: 7 64 145 256 380 ms

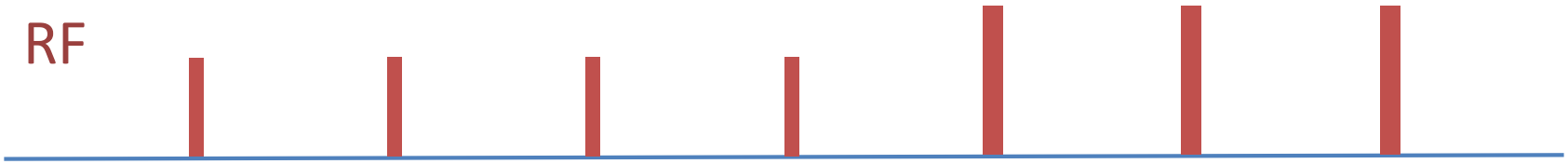
Normalized difference with reference

MT measurements



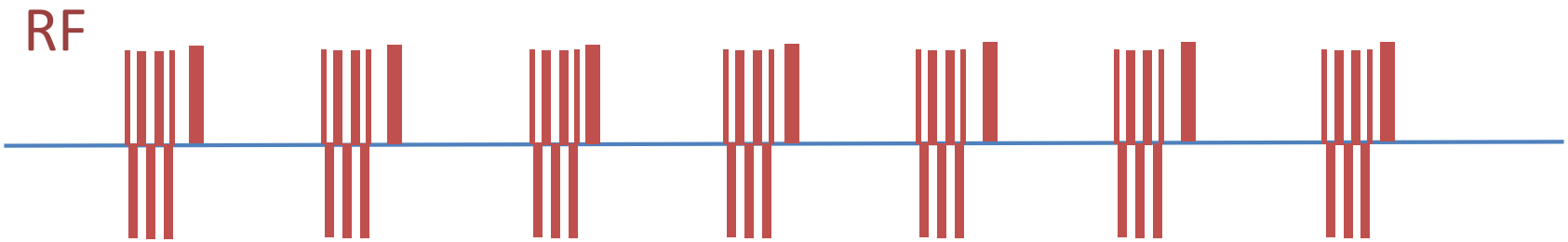
T_1 Measurement

Saturation



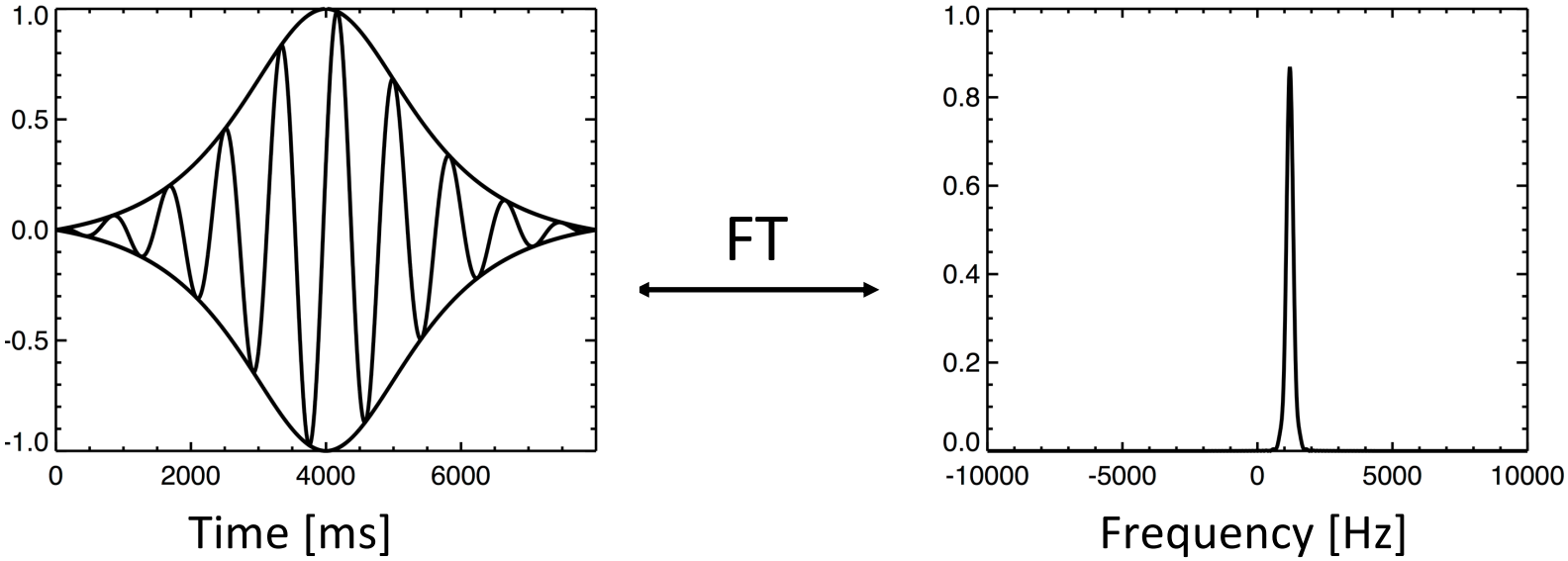
MT Measurement

MT Saturation Equilibrium

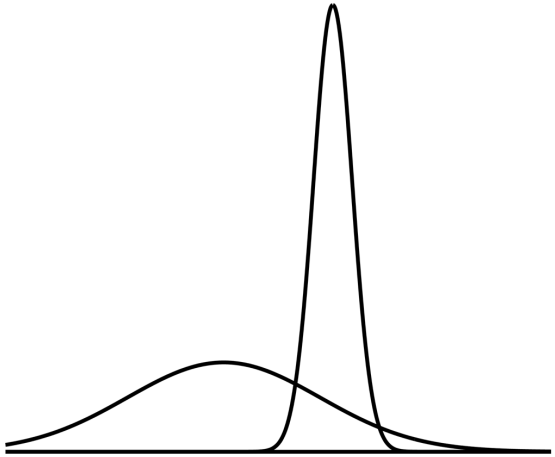


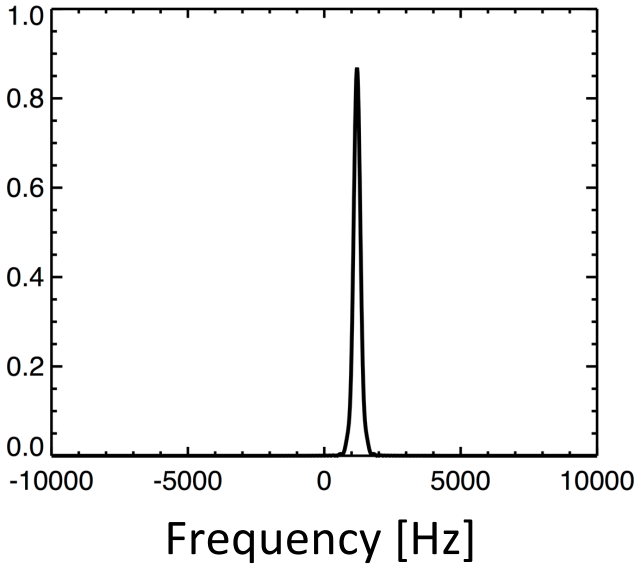
MT Saturation in balance with T_1

Saturation by off-resonance RF



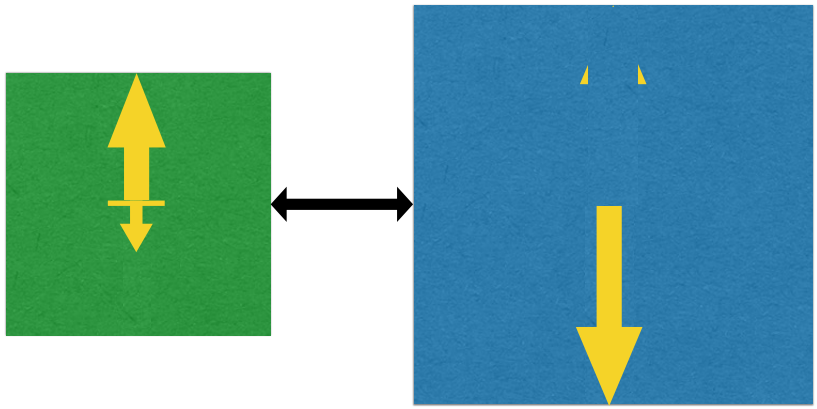
Saturation by off-resonance RF





Inversion & MT

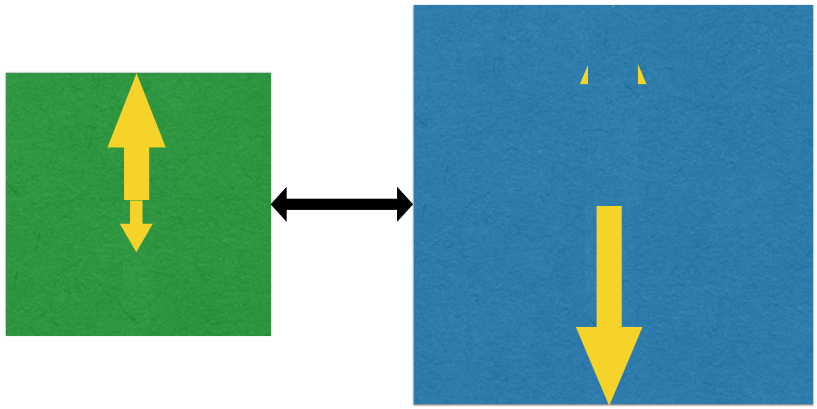
IR and Exchange



MP WP

Inversion & MT

IR and Exchange



MP WP

Inversion & MT

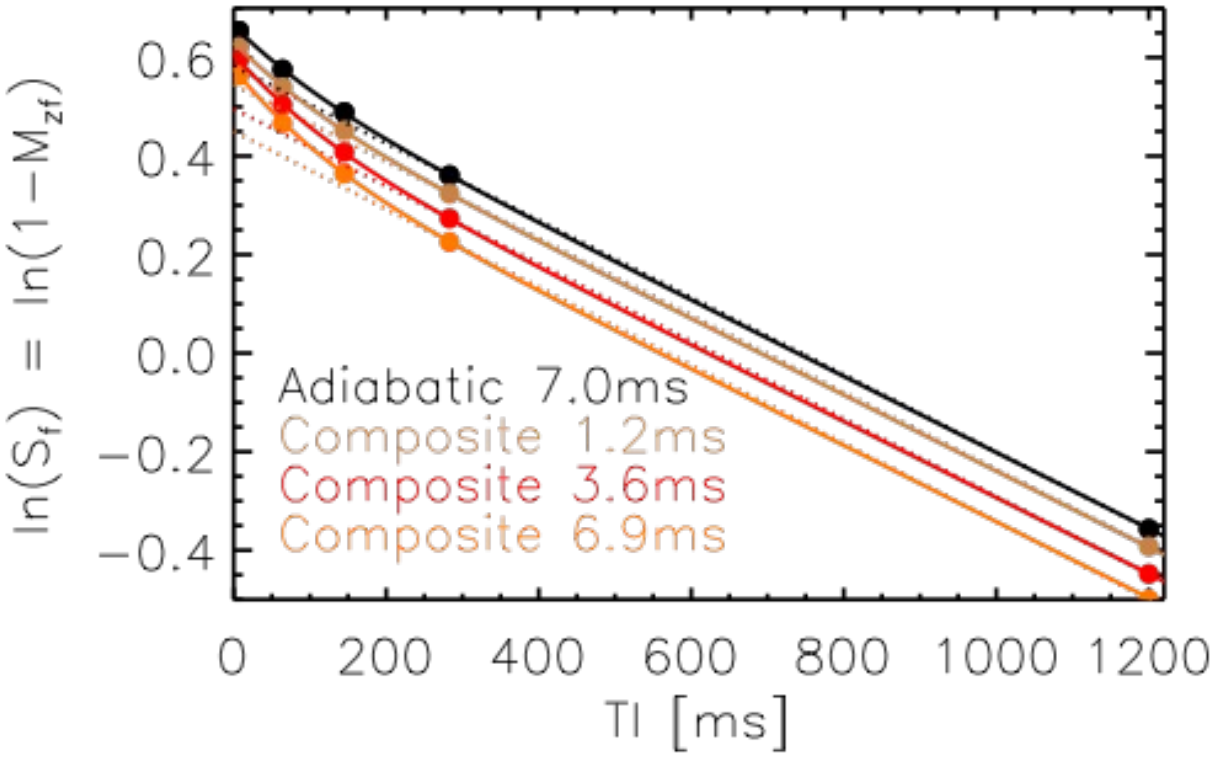
IR and Exchange

In an IR experiment initial saturation of MP depends on RF power

Early part of IR dominated by exchange

Inversion & MT

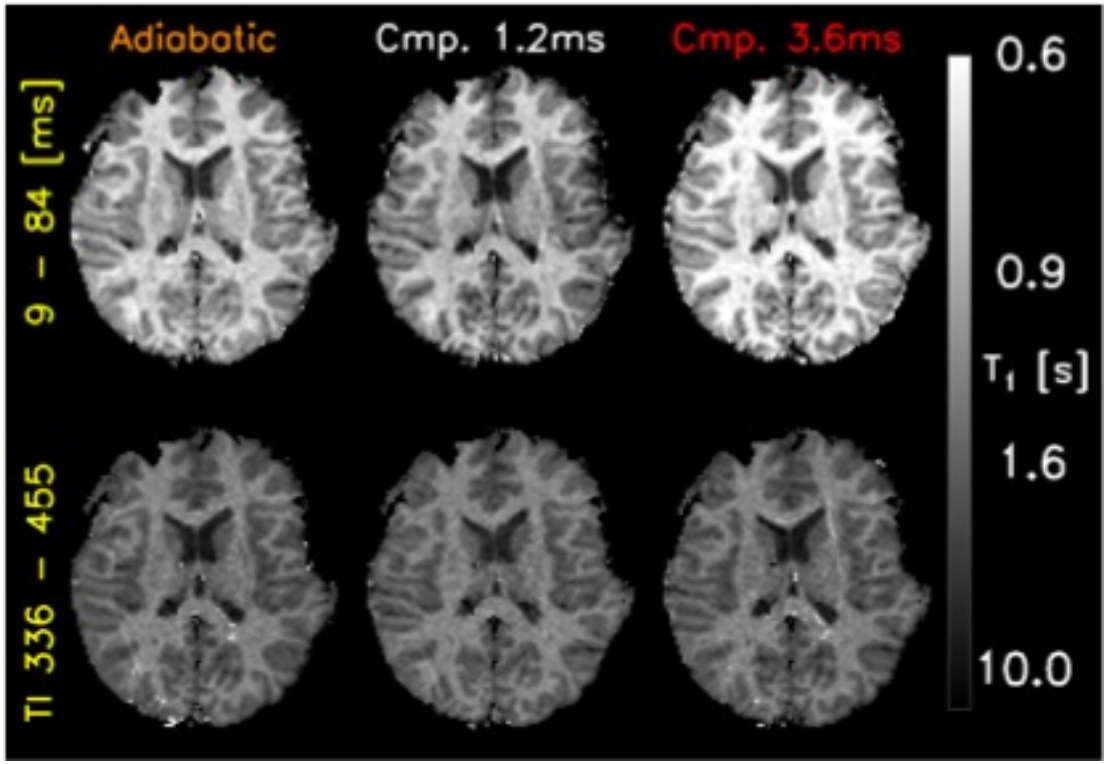
IR double exponential and RF dependent



Inversion & MT

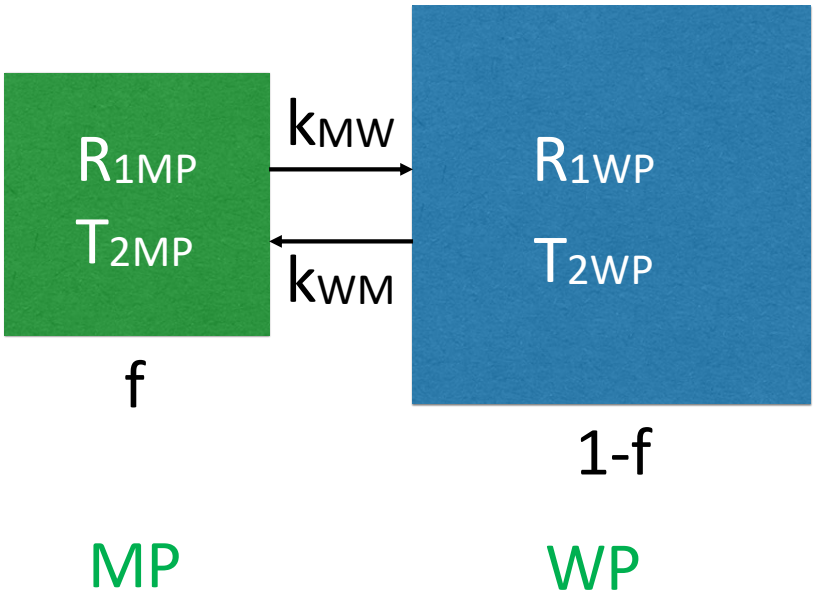
Calculated T_1 as function of TI

High RF Low RF



MT

Equations



$$d S_{WP} / dt = -R_{1WP} S_{WP} - k_{WM} S_{WP} + k_{WM} S_{MP}$$

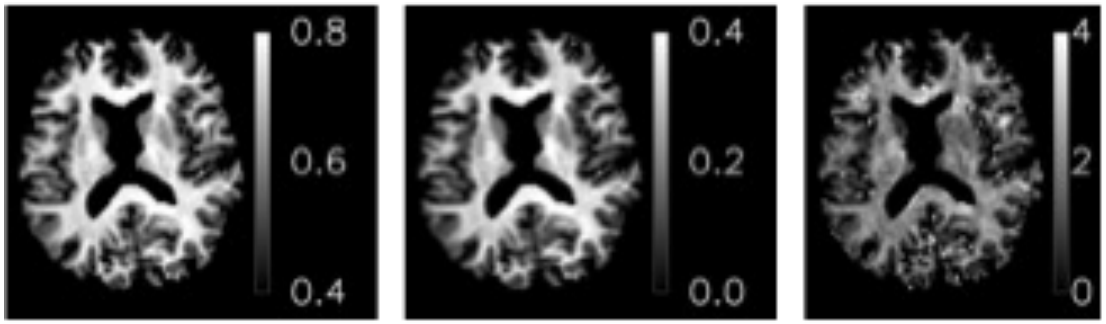
$$d S_{MP} / dt = -R_{1MP} S_{MP} - k_{MW} S_{MP} + k_{MW} S_{WP}$$

$$f k_{MW} = (1-f) k_{WM}$$

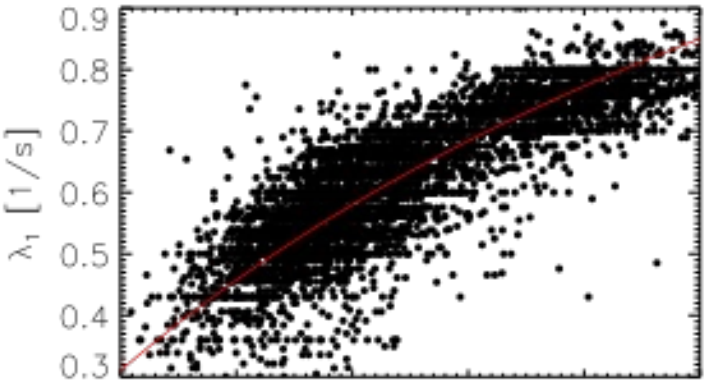
$$S_{WP}(t) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$$

$$\lambda_1 ? (1-f)R_{1WP} + fR_{1MP}$$

Inversion & MT



λ_1 f k_{wm}



$$R_{1eff} = \lambda_1 (1-f)R_{1WP} + fR_{1MP}$$

T_1 & MT

Summary

- Pure water has a very long T_1
- Main source of T_1 relaxation is semi-solid lipids & other macro molecules through MT between water and MP
- Consequences:
  :: MT and T_1 contrast both measure MP
  :: T_1 relaxation (at least) bi-exponential

T_1 & MT

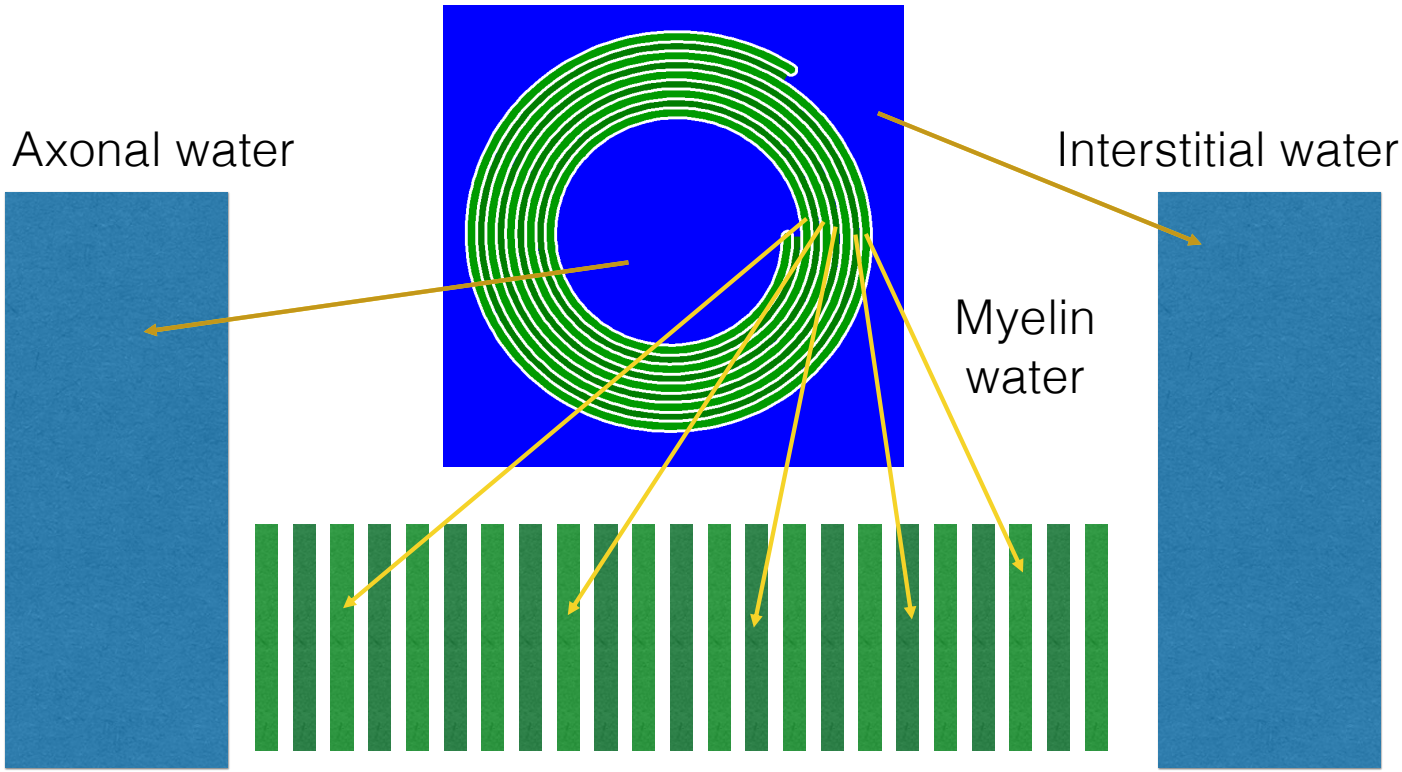
Summary

Reality more complex:

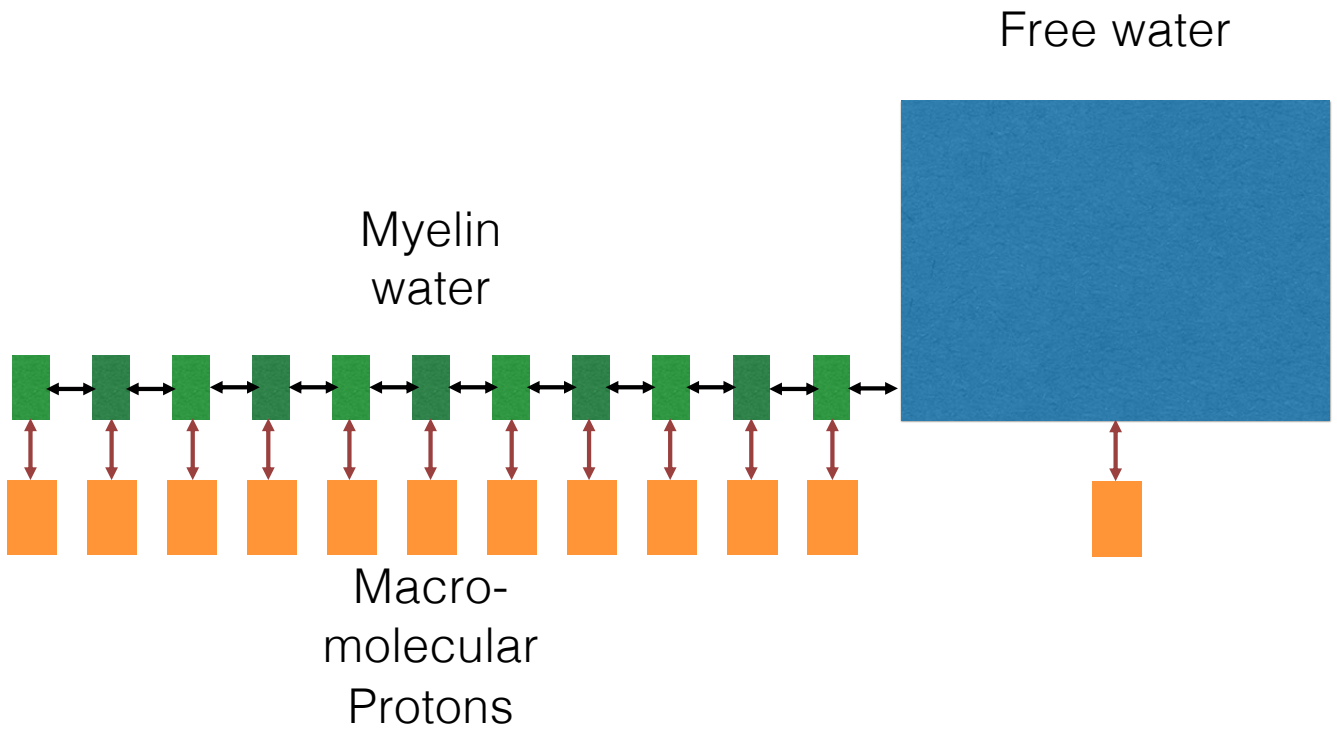
- multiple pools of water (intra-, extra- cellular, myelin)
- multiple kinds of MP, each with R_1, T_2 etc.

Two pool T_1 generally sufficient, fast component more important at higher field

Many compartments



Many compartments



T1 & MT

The End