

Bloch Equation

$$\frac{d\vec{M}}{dt} = \underbrace{\vec{M} \times \gamma \vec{B}}_{\text{precession}} - \underbrace{\frac{M_x \hat{i} + M_y \hat{j}}{T_2}}_{T_2 \text{ relaxation}} - \underbrace{\frac{(M_z - m) \hat{k}}{T_1}}_{T_1 \text{ relaxation}}$$

consider $\vec{B} = B_0 \hat{k}$ $\omega_0 = \gamma B_0$

$$\begin{bmatrix} \dot{M}_x \\ \dot{M}_y \\ \dot{M}_z \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 \\ -\omega_0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} \quad \star$$

$$\vec{M}(t) = R_z(\omega_0 t) \vec{M}(0)$$

↪ left handed rotation about z axis
by angle $\omega_0 t$

$$\begin{bmatrix} \cos \omega_0 t & \sin \omega_0 t & 0 \\ -\sin \omega_0 t & \cos \omega_0 t & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

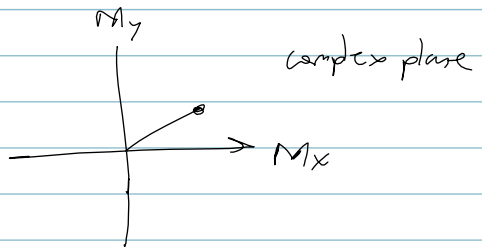
now lets include T_2 & T_1

$$\vec{M}(t) = \begin{bmatrix} e^{-t/T_2} & 0 & 0 \\ 0 & e^{-t/T_2} & 0 \\ 0 & 0 & e^{-t/T_1} \end{bmatrix} R_z(\omega_0 t) \vec{M}(0) + \begin{bmatrix} 0 \\ 0 \\ M_0 (1 - e^{-t/T_1}) \end{bmatrix}$$

referred $M_z(t) = M_z(0) e^{-t/T_1} + M_0 (1 - e^{-t/T_1})$
 T_1 recover

Lets focus on the received signal, comes from X, y components
FID

~~M~~ $M \triangleq M_x + i M_y$



Bloch Eqn

$$\frac{dM}{dt} = \frac{dM_x}{dt} + i \frac{dM_y}{dt}$$

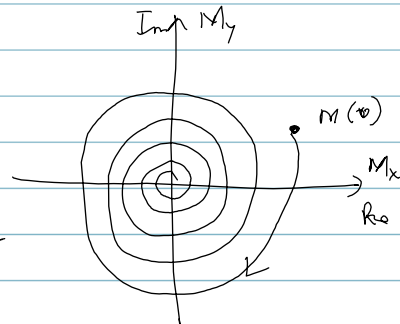
$$= \underbrace{\omega_0 M_y - i \omega_0 M_x}_{\text{precession}} - \underbrace{\frac{1}{T_2} (M_x + i M_y)}_{\text{relaxation}}$$

↗ PVS PAGE
★

$$-i \omega_0 (M_x + i M_y)$$

$$\frac{dM}{dt} = - \left(i \omega_0 + \frac{1}{T_2} \right) M$$

$$M(t) = M(0) e^{-i \omega_0 t} e^{-\frac{1}{T_2} t}$$



lets be more general

$$M(x, y, z, t) = M_x(x, y, z, t) + i M_y(x, y, z, t)$$

\uparrow \uparrow \uparrow
 x component of
 the magnetization
 x position

$$\vec{r} = x, y, z$$

$$M(\vec{r}, t)$$

$$B(\vec{r}, t), T_2(\vec{r})$$

$$\frac{dM(\vec{r}, t)}{dt} = - \left[i(\omega_0 + \Delta\omega(\vec{r}, t)) + \frac{1}{T_2(\vec{r})} \right] M(\vec{r}, t)$$



$$B_z(\vec{r}, t) = B_0 + \Delta B(\vec{r}, t)$$

$$M(\vec{r}, t) = M(\vec{r}, 0) e^{-t/T_2(\vec{r})} e^{-i\omega_0 t} e^{-i \int_0^t \Delta\omega(\vec{r}, t) dt}$$

same as before

time dependent
phase

$$M_a(\vec{r}, t)$$



$$\Delta w(\vec{r}, t) = \begin{cases} \gamma G_{xx} & \text{linear } G_{xx} \text{ on} \\ \gamma \vec{G} \cdot \vec{r} = \gamma(G_{xx}x + G_{yy}y + G_{zz}z) & \text{arbitrary linear gradient} \\ \gamma \vec{G}(t) \cdot \vec{r} & \text{time varying} \end{cases}$$

$$M(\vec{r}, t) = \begin{cases} M_a(\vec{r}, t) e^{-i \gamma G_{xx} x t} \\ M_a(\vec{r}, t) e^{-i \gamma (\vec{G} \cdot \vec{r}) t} \\ M_a(\vec{r}, t) e^{-i \gamma \int_0^t \vec{G}(\tau) \cdot \vec{r} d\tau} \end{cases} \quad * \leftarrow$$

$$\downarrow$$

$$e^{-i 2\pi \left(\frac{\gamma}{2\pi} \int_0^t \vec{G}(\tau) \cdot \vec{r} d\tau \right) \cdot \vec{r}}$$

consider signal received by RF coil

Faraday's law

$$\text{EMF } \mathcal{E} = - \frac{d\Phi}{dt} \quad \mathcal{E} \propto - \frac{dM(\vec{r}, t)}{dt}$$

FCV signal

$$S_r(t) = -K \int_{\text{volume}} - [i\omega_0 + \gamma \vec{G}(t) \cdot \vec{r}] M(\vec{r}, t) dV$$

$\approx i\omega_0$

ignore T_z

use ps expansion * ←

$$s_r(t) = \underbrace{(k_i \omega_0)}_{\text{const}} \int_{\text{slice}} m_0(\vec{r}) e^{-i\omega_0 t} e^{-i 2\pi \left(\frac{\delta}{2\pi} \int_0^t \tilde{u}(r) dr \right) \cdot \vec{r}} dV$$

Three simplifications

1) continue ignoring T_2

2) assume 2D imaging, excite thin slice Δz

$$\text{define } m_0(x, y) = \int_{\Delta z} m_0(x, y, z) dz$$



3) demodulate by ω_0

$$s(t) \hat{=} s_r(t) e^{+i\omega_0 t} \quad \text{"baseband"}$$

$$s(t) = \iint_{x, y} m_0(x, y) e^{-i 2\pi \left[\underbrace{\left(\frac{\delta}{2\pi} \int_0^t \tilde{u}_x(r) dr \right)}_{k_x(t)} x + \underbrace{\left(\frac{\delta}{2\pi} \int_0^t \tilde{u}_y(r) dr \right)}_{k_y(t)} y \right]} dx dy$$

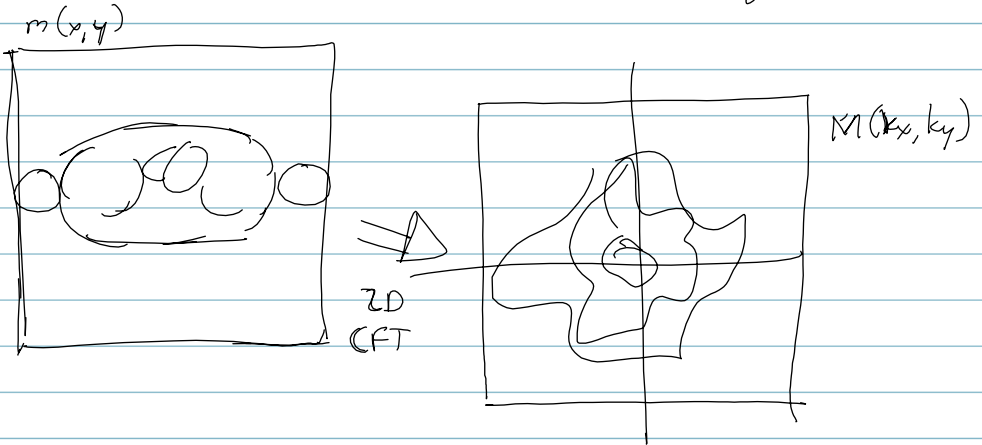
$$= \iint_{x, y} m(x, y) e^{-i 2\pi (k_x(t) x + k_y(t) y)} dx dy$$

$$\Rightarrow \int \left\{ m(x, y) \right\} \downarrow \begin{matrix} \text{spatial freq} \\ k_x(t), k_y(t) \end{matrix}$$

$$s(t) = M(k_x(t), k_y(t))$$

$$k_x(t) = \frac{\gamma}{2\pi} \int_0^t u_x(\tau) d\tau$$

$$k_y(t) = \frac{\gamma}{2\pi} \int_0^t u_y(\tau) d\tau$$



sampling $M(k_x, k_y)$

map of trajectories in the spatial frequency domain
 u_x, u_y control

