MULTISLICE RF PULSES

CONVENTIONAL MULTISLICE

3D MULTISLICE

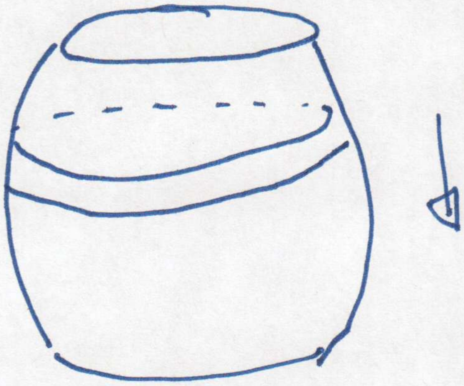
HADAMARD

POMP

SIMULTANEOUS MULTISLICE

CONVENTIONAL MULTISLICE

IMAGE ONE SLICE AT A TIME



OFFSET z_0
SLICE WIDTH
Δz

RF PULSE IS

$$B_1(t, z_0) = B_1(t, 0)\, e^{-i\gamma G z_0 t}$$

LET $n = z_0/\Delta z$, OFFSET IN SLICE WIDTHS

$$B_{1,n}(t) = B_{1,0}(t)\, e^{-i\gamma G \Delta z \frac{z_0}{\Delta z} t}$$

$$= B_{1,0}(t)\, e^{-i2\pi \underbrace{\left(\frac{\gamma}{2\pi} \gamma G \Delta z\right)}_{BW} n t}$$

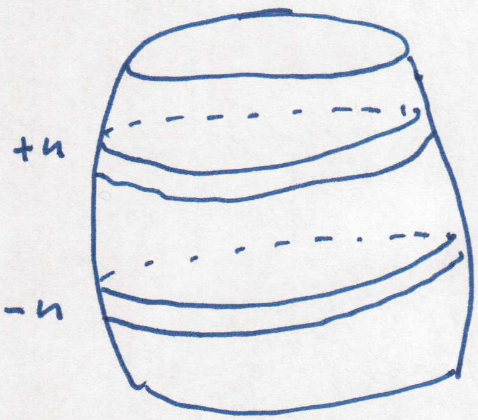
$$= B_{1,0}(t)\, e^{-i2\pi (T(BW)) n t/T}$$

LET $\tau = t/T$

$$B_{1,n}(t) = B_{1,0}(t)\, e^{-i2\pi (TBW) n \tau}$$

WE NEED TBW CYCLES OF PHASE OVER THE PULSE TO OFFSET ONE SLICE WIDTH

WE CAN EXCITE MULTIPLE SLICES AT ONCE BY ADDING RF PULSES



$$B_1(t) = B_{1,n}(t) + B_{1,-n}(t)$$

THEN

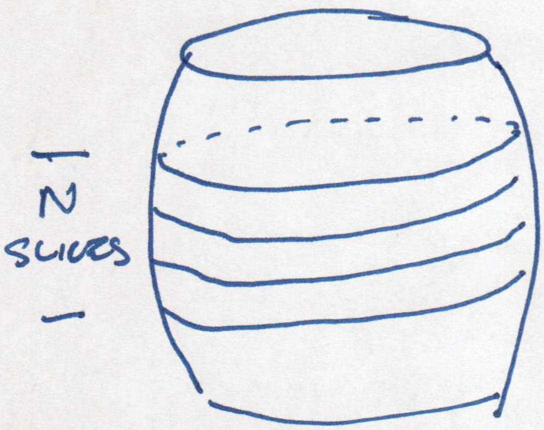
$$B_1(t) = B_{1,0}(t)\, e^{-i2\pi(TBW)n\tau} + B_{1,0}(t)\, e^{-i2\pi(TBW)(-n)\tau}$$

$$= B_{1,0}(t)\left(e^{-i2\pi(TBW)n\tau} + e^{-i2\pi(TBW)(-n)\tau}\right)$$

$$= B_{1,0}(t)\left(2\cos 2\pi(TBW)n\tau\right)$$

<u>TWICE</u> THE AMPLITUDE!

3D MULTISLICE (2½ D IMAGING)



EXCITE ALL N SLICES AT ONCE

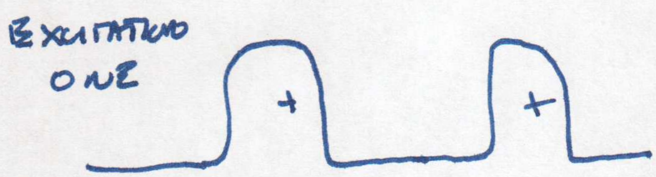
CONTIGUOUS OR SPACED

HOW DO WE SORT THEM OUT?

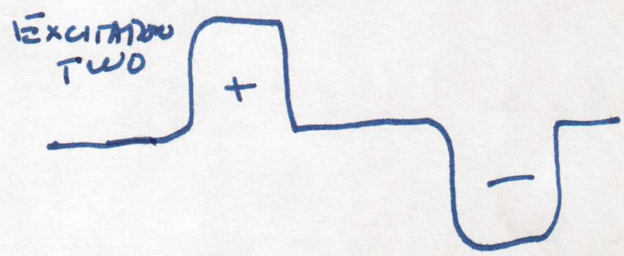
KEY IDEA WE CAN EXCITE EACH SLICE WITH ANY PHASE TO ENCODE THE SLICES

EXAMPLE TWO SLICES

$B_{1,n}(t) + B_{1,-n}(t)$



$B_{1,n}(t) - B_{1,-n}(t)$



ACQUIRE TWO SIGNALS, $S_p(t)$ AND $S_m(t)$. THEN

$S_p(t) + S_m(t)$ 2x SLICE 1 SIGNAL

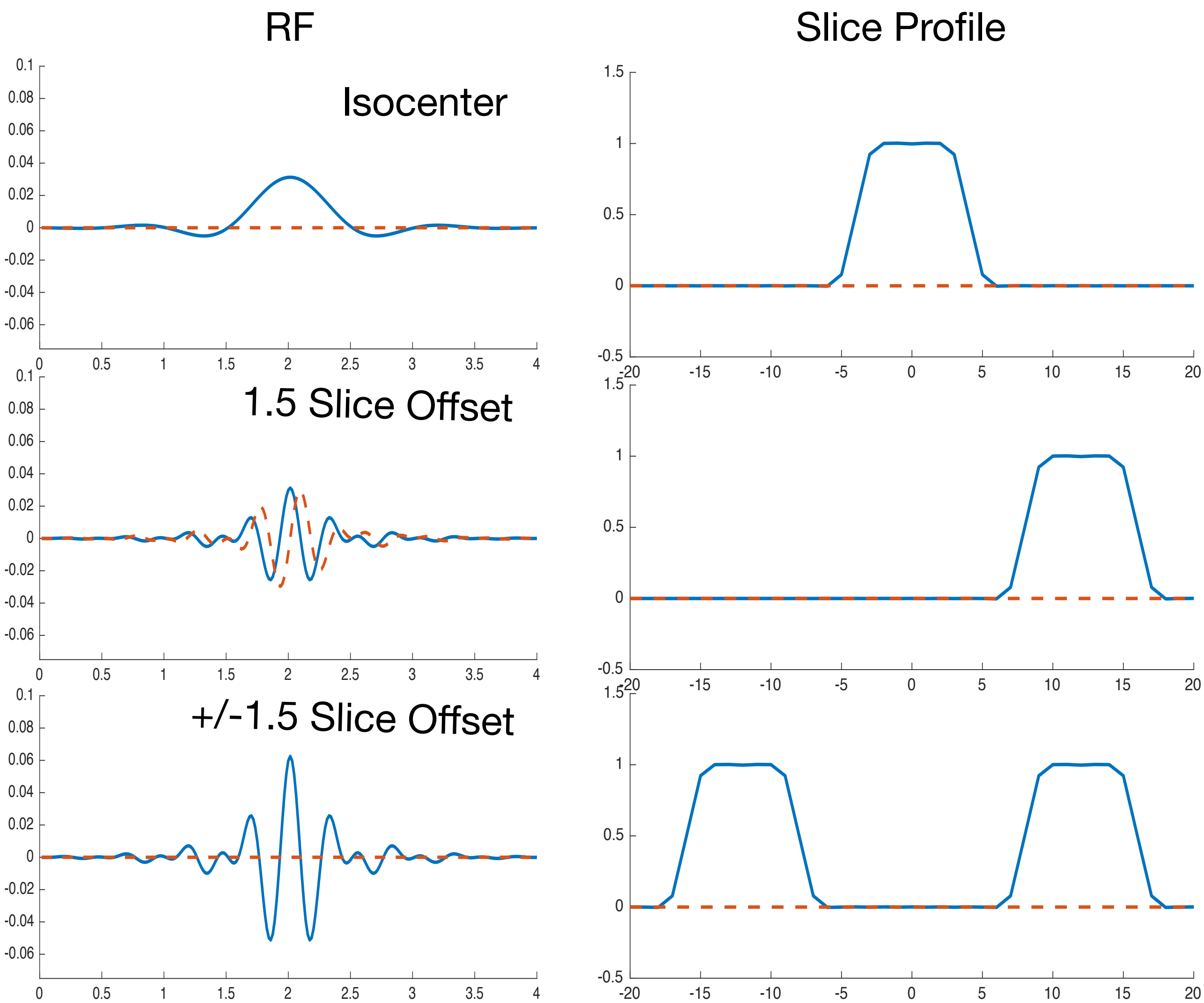
$S_p(t) - S_m(t)$ 2x SLICE 2 SIGNAL

SCAN TIME TWICE AS LONG

SNR $\sqrt{2}$ LARGER

Multislice Excitation

TBW = 4, T = 4 ms, BW = 2 kHz



Two slices doubles the amplitude
Four times the peak RF power

MORE GENERALLY, N SLICES

HADAMARD ENCODING

ENCODE SLICES WITH ± 1'S

$$\begin{pmatrix} B^{H}_{1,1}(t) \\ B^{H}_{1,2}(t) \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} B_{1,n}(t) \\ B_{1,m}(t) \end{pmatrix}$$

SAME AS EXAMPLE ABOVE

HADAMARD MATRIX

$$H_2 = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

FOR HIGHER ORDER

$$H_4 = \begin{pmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{pmatrix}$$

$$= \begin{array}{cc} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} & \begin{array}{c} 1 \\ 4 \\ 2 \\ 3 \end{array} \end{array}$$

USUALLY WRITTEN IN "SEQUENCY" ORDER, LIKE SINES AND COSINES

$$H_8 = \begin{pmatrix} H_4 & H_4 \\ H_4 & -H_4 \end{pmatrix}$$

AND SO ON ....

IN GENERAL

$$\underline{B}_1^H = H_N \underline{B}$$

WHERE $\underline{B}$ IS A VECTOR OF THE MULTISLICE PULSES, AND $\underline{B}_1^H$ ARE THE HADAMARD ENCODED PULSES. IF $\underline{S}$ ARE THE MULTISLICE SIGNALS AND $\underline{S}^H$ ARE THE SIGNALS FROM THE HADAMARD ENCODED PULSES

$$\underline{S}^H = H_N \underline{S}$$

AND WE CAN RECOVER THE SIGNALS OF THE INDIVIDUAL SLICES

$$\underline{S} = H_N^{-1} \underline{S}^H$$

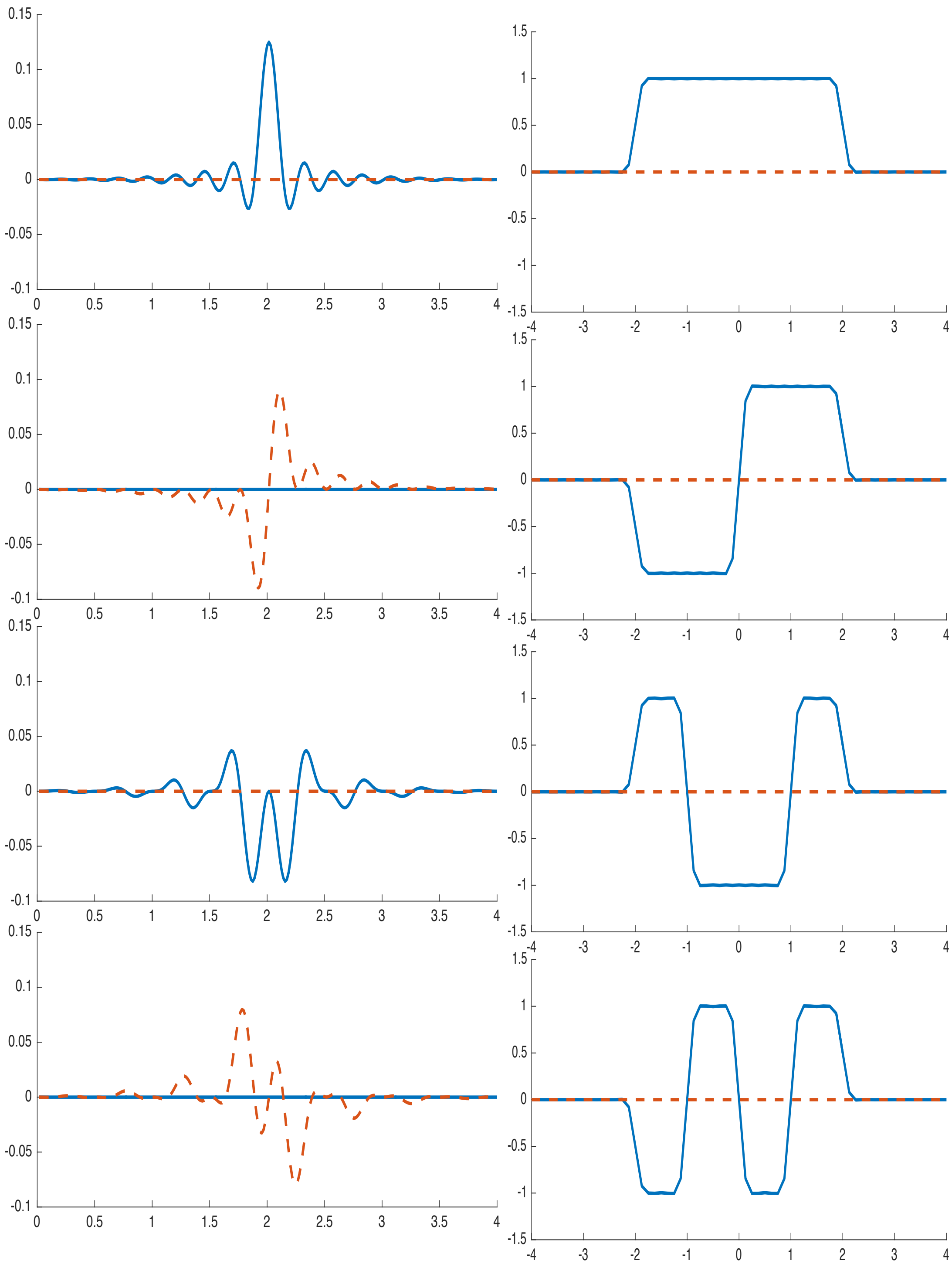
N EXCITATIONS FOR EACH PHASE ENCODE

N TIMES LONGER SCAN TIME

$\sqrt{N}$ BETTER SNR ($\sqrt{\text{AIDTIME}}$)

<u>ADVANTAGE</u>: WELL DEFINED SLICES, PLACED ANYWHERE. NEED NOT BE CONTIGUOUS, LIKE 3DFT.

Hadamard N=4 Pulses and Slice Profiles



POMP ENCODING (PHASE OFFSET MULTIPLANAR)

M_{xy} SUPPORTS PHASE NOT JUST ± 1!

USE A FOURIER BASIS (DFT)

LET

$$P_N = \left[e^{j 2\pi \frac{kl}{N}} \right]$$

k = SLICE (0..N-1)

l = EXCITATION (0..N-1)

N = NUMBER OF SLICES

FOR $N=2$

$$P_2 = \begin{bmatrix} e^{i0} & e^{i0} \\ e^{i0} & e^{i\pi} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

SAME AS H_2!

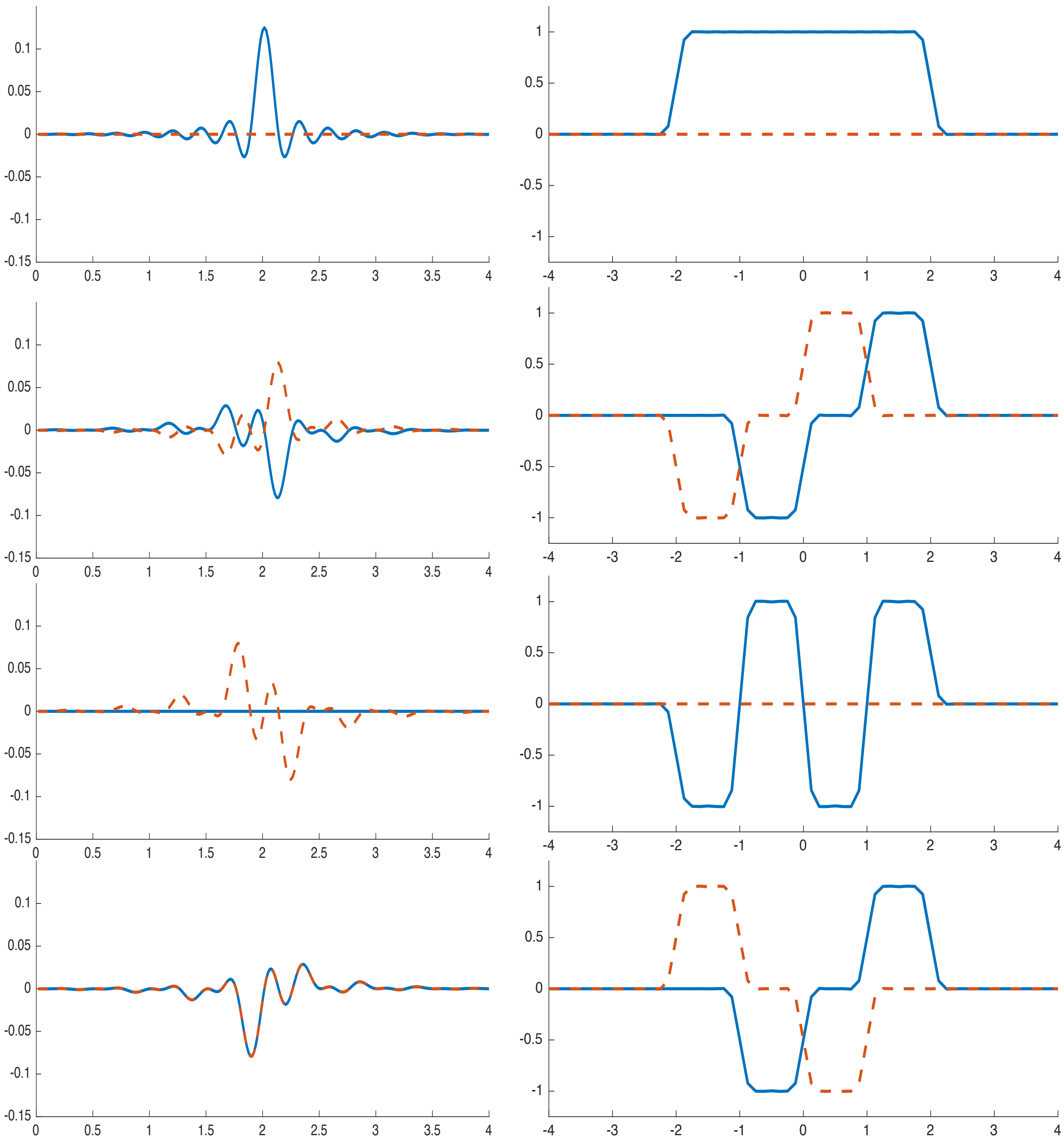
FOR $N=4$

$$P_4 = \begin{pmatrix} e^{i0} & e^{i0} & e^{i0} & e^{i0} \\ e^{i0} & e^{i\pi/2} & e^{i\pi} & e^{i3\pi/2} \\ e^{i0} & e^{i\pi} & e^{i2\pi} & e^{j3\pi} \\ e^{i0} & e^{i3\pi/2} & e^{i3\pi} & e^{i9\pi/2} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & i & -1 & -i \\ 1 & -1 & 1 & -1 \\ 1 & -i & -1 & i \end{pmatrix}$$

DFT MTX

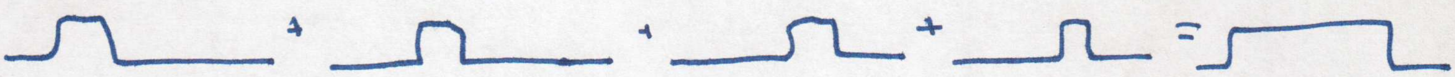
POMP N=4 Pulses and Slice Profiles



MAIN ISSUE RF PEAK AMPLITUDE

ONE OF THE PULSES IS ENCODED AS

+1, +1, +1, ..., +1

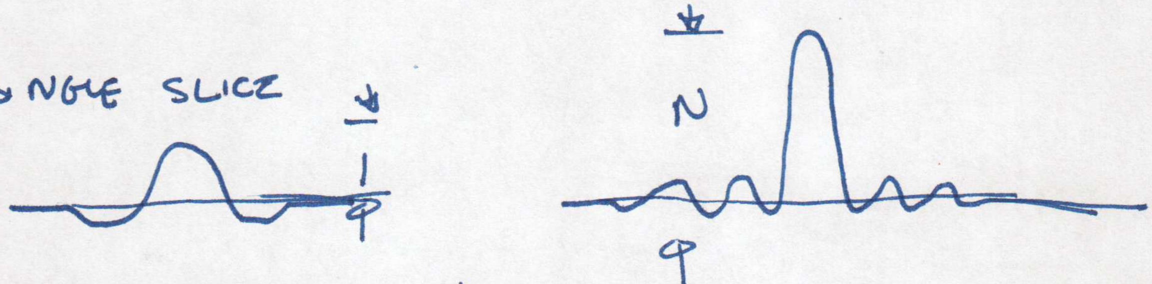


TIME BANDWIDTH INCREASES BY N

RF AMPLITUDE INCREASES BY N

RF PEAK POWER INCREASES BY N^2!

SINGLE SLICE



NOT SUSTAINABLE!

SOLUTION LET EACH SLICE HAVE ITS OWN PHASE OFFSET

WHAT WE WANT IS THAT

$$H_N \begin{pmatrix} e^{i\theta_1} \\ \vdots \\ e^{i\theta_N} \end{pmatrix} \quad \text{OR} \quad P_N \begin{pmatrix} e^{i\theta_1} \\ \vdots \\ e^{i\theta_N} \end{pmatrix}$$

ARE CHOSEN SO THAT THE RESULT MINIMIZES THE MAXIMUM VALUE

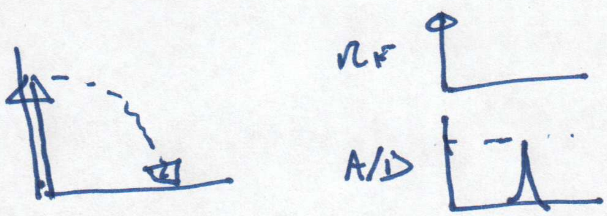
THE HADAMARD AND POMP ENCODINGS ARE THE WORST FOR THIS!

HOW DO WE CHOOSE SOMETHING BETTER?

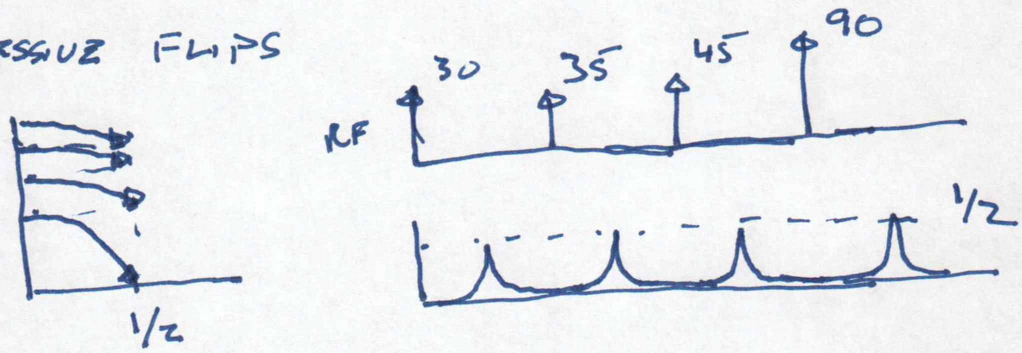
ASIDE: HOW MUCH MAGNETIZATION CAN WE STORE IN M_{xy}?

PROGRESSIVE FLIP ANGLES

SINGLE PULSE



PROGRESSIVE FLIPS

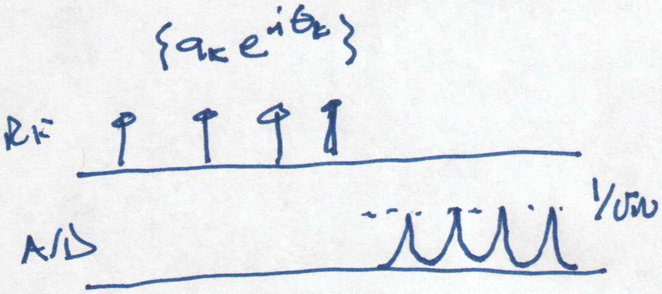


N ECHOES, EACH OF AMPLITUDE $1/\sqrt{N}$

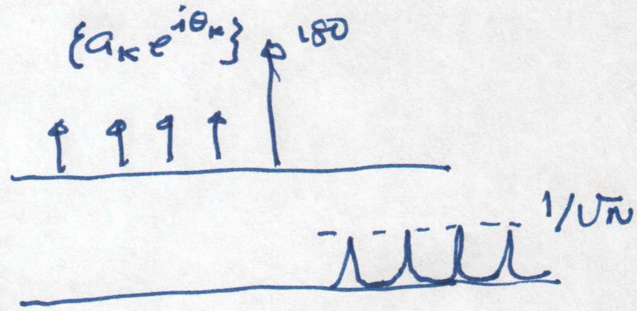
$$\theta_n = \sin^{-1}\left(\frac{1}{\sqrt{N-n}}\right) \qquad n = (0..N-1)$$

REMARKABLY, WE CAN KEEP ALL OF THESE COHERENCES IN M_{xy} AT THE SAME TIME!

BURST EXCITATION (HENNIG)



FORWARD ECHOES



REVERSE ECHOES

SOLUTIONS

WE WANT TO FIND

$$\underline{b} = \{a_k e^{i\theta_k}\} = \begin{pmatrix} a_0 e^{i\theta_0} \\ \vdots \\ a_{N-1} e^{i\theta_{N-1}} \end{pmatrix}$$

SUCH THAT

$$\underline{s} = P_N \underline{b}$$

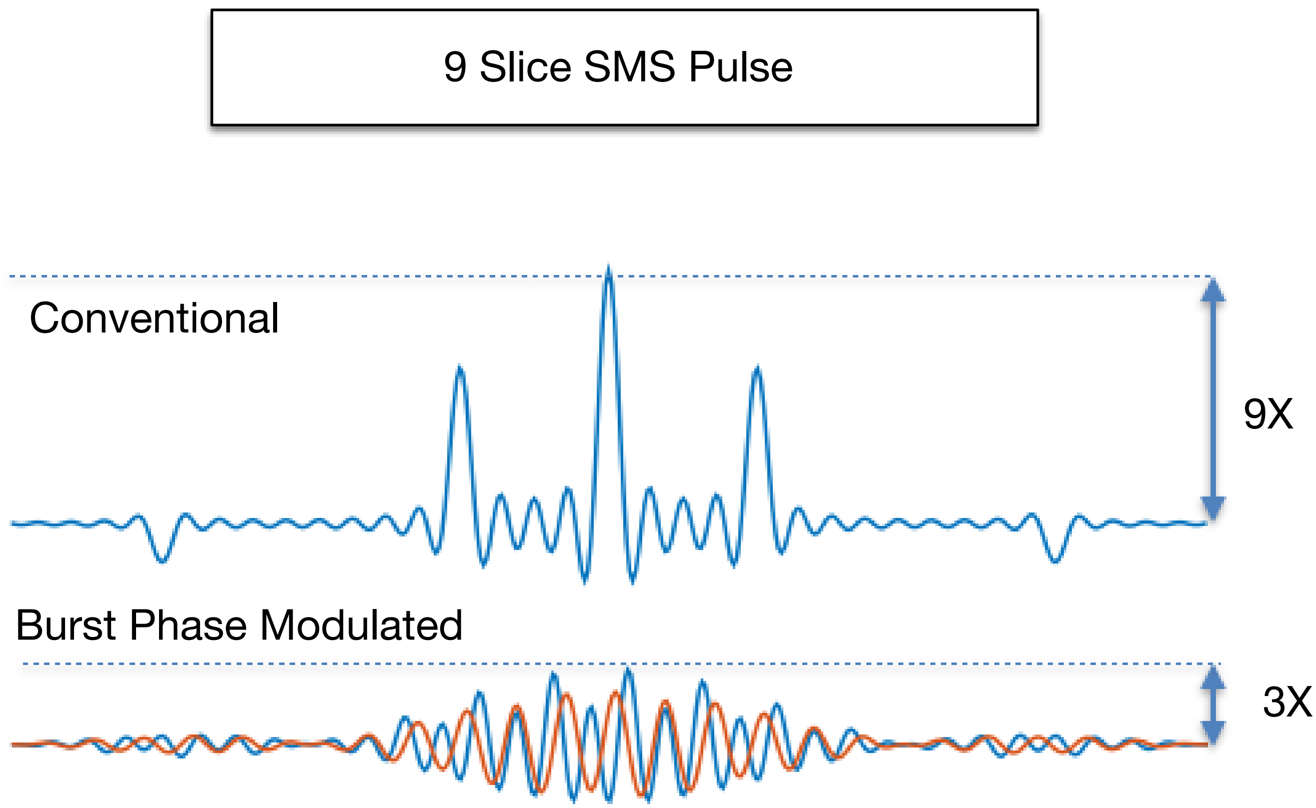
IS < 1, AND HAS A MAXIMUM MINIMUM VALUE

APPROXIMATE SOLUTION (VAN GELDERN)

$$a_k e^{i\theta_k} = \frac{1}{\sqrt{N}} e^{-i \frac{2\pi}{N} \frac{1}{2} k(k-p)}$$

QUADRATIC PHASE, UNIFORM ECHOES

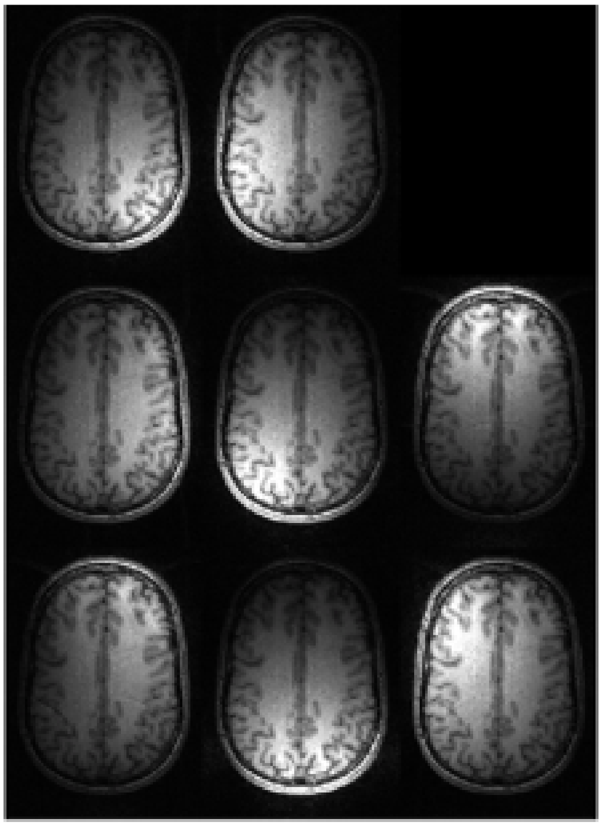
BETTER SOLUTIONS IN HEID PAPER

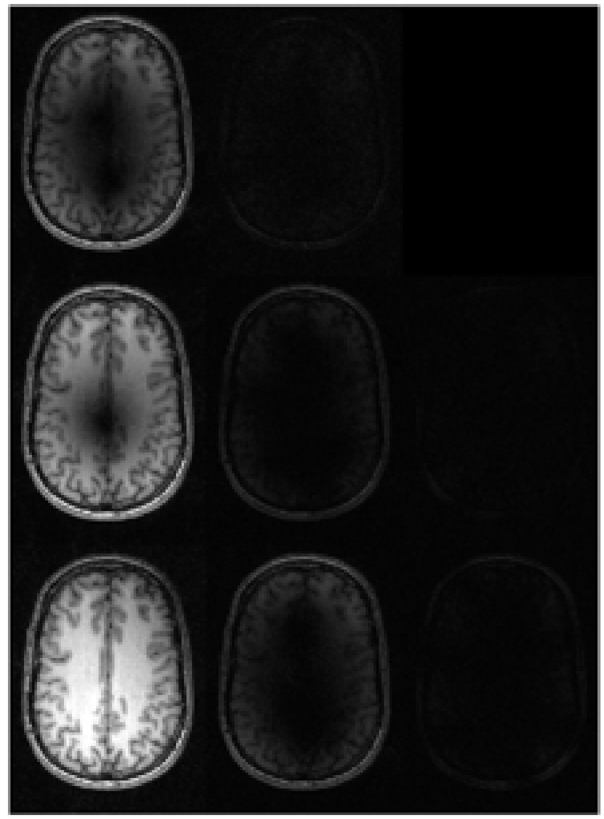


Peak amplitude reduce by a factor of 3
Peak power reduced by factor of 9
Same total power

Simultaneous Multislice

In 2D, SENSE hits a wall at R=4





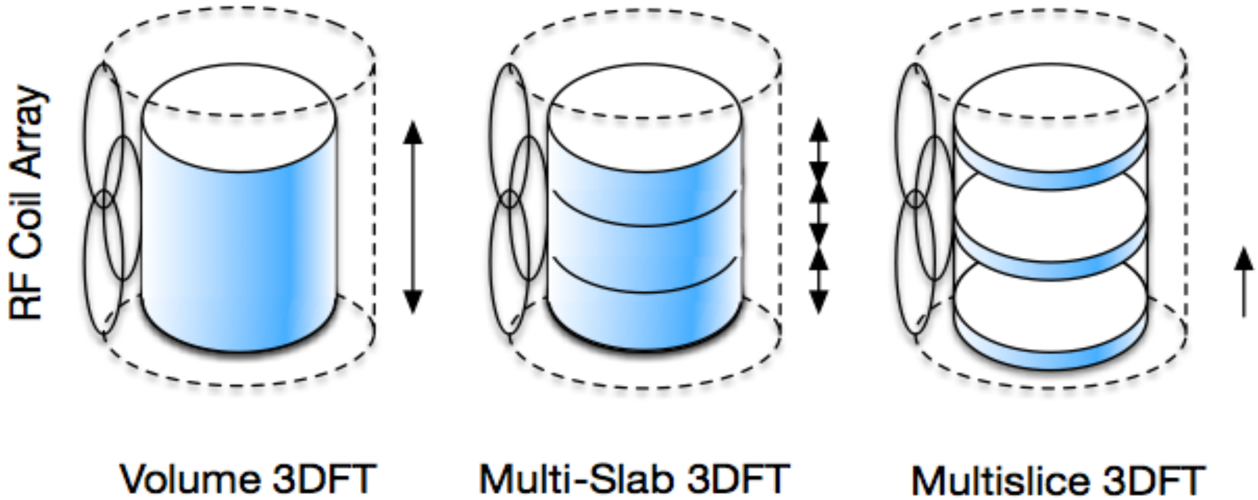
8-channel head coil sensitivities

SVD eigen coils

Higher order modes closer and closer to the edge of the volume

Simultaneous Multislice

Increasing acceleration using z



3DFT doesn’t help: transform in readout, lots of 2D problems

Multislab 3DFT also doesn’t help for same reason

Multislice 3DFT does help!

- Slices widely spaced, very different sensitivities
- Treat the entire recon as 3D parallel imaging