



University of
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MR hardware considerations for hyperpolarised MRI

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Polarisation and size of signal

Magnetisation density

$$m_0 = \mu PN/2,$$

- μ is the nuclear magnetic moment
- N is the number of atoms per unit volume
- P is the polarisation

e.g. 150 ml ^{129}Xe P (~30%) at 1 bar comparable to a 1L sample of $^1\text{H}_2\text{O}$ at 1.5T

$$(m_0 \sim 5 \times 10^{-3} \text{ JT}^{-1} \text{ m}^{-3})$$

Consider this then gets diluted e.g. 500 ml in 6 L lung volume

Signal and Noise in HP MRI

Received **signal**:

$$S \propto \omega_0 M_0 V_s \eta$$

η coil–sample filling factor, V_s sample volume

M_0 independent of ω_0 (B_0) for HP sample

$$R_{Coil} \propto \omega^{1/2}$$

$$R_{Sample} \propto \omega^2$$

Noise: $[\Delta f]^{1/2} [4k (T_C R_C + T_S R_S)]^{1/2}$

coil loading ratio

$$\rho = 1 - Q_{loaded}/Q_{unloaded} \sim R_S / (R_C + R_S)$$

$$SNR \sim [M_0 \eta V_s] [\Delta f]^{-1/2} \rho^{1/2}$$

“A lossy sample dictates its own SNR” - David Hoult

Edelstein et al. MRM 3(4)-604

HP MRI SNR factors: frequency and field strength

SNR dependence with ω_0 :

Coil noise dominated , (low ω_0)

$$\text{SNR} \sim \omega_0^{3/4}$$

Sample noise dominated , (higher ω_0)

$$\text{SNR} \sim \text{constant}$$

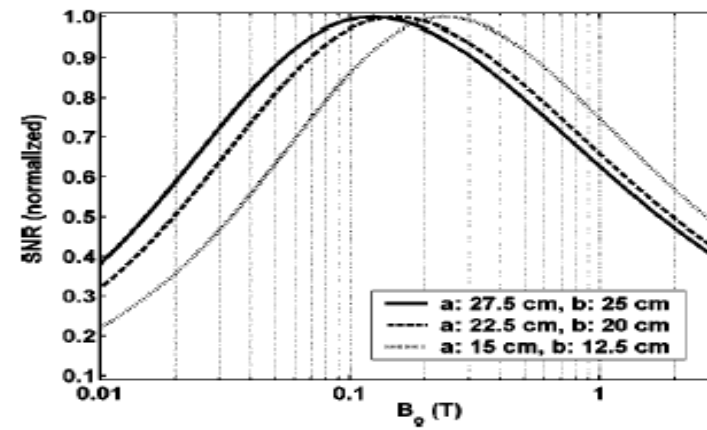


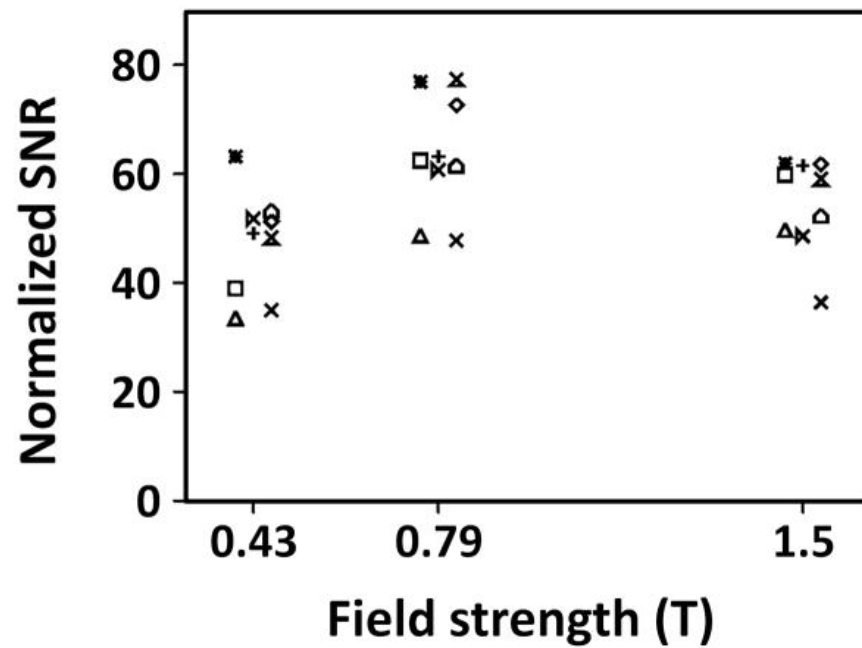
FIG. 3. Field dependence of the SNR for helium lung imaging for various sample/coil sizes ($\eta=0.1$).

Parra-Robles, Med Phys;32(1):221-9.

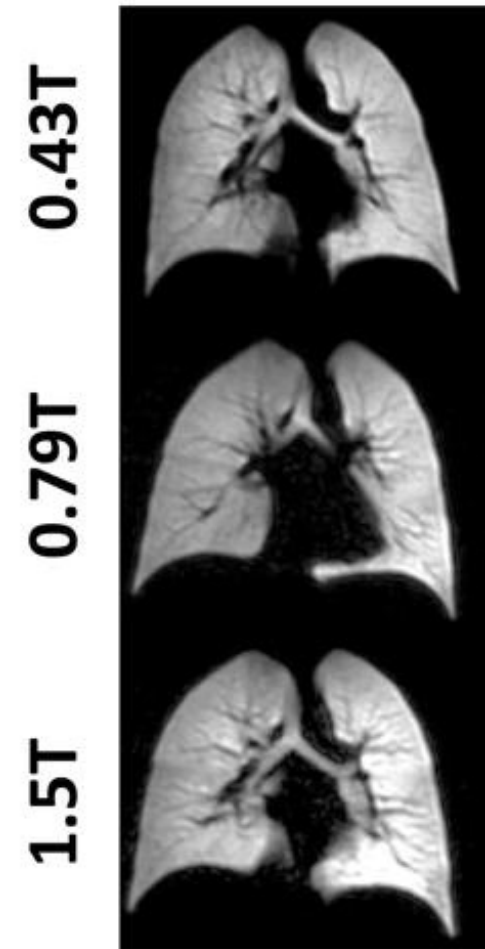
Optimum B_0 **depends on coil size, λ , sample loading, quality of RF engineering, and system electronics (preamp NF)**

Do the experiment with best coil and electronics you can optimised to your frequency regime **best field strength is the one you have (cheapest)**

^3He ventilation MRI



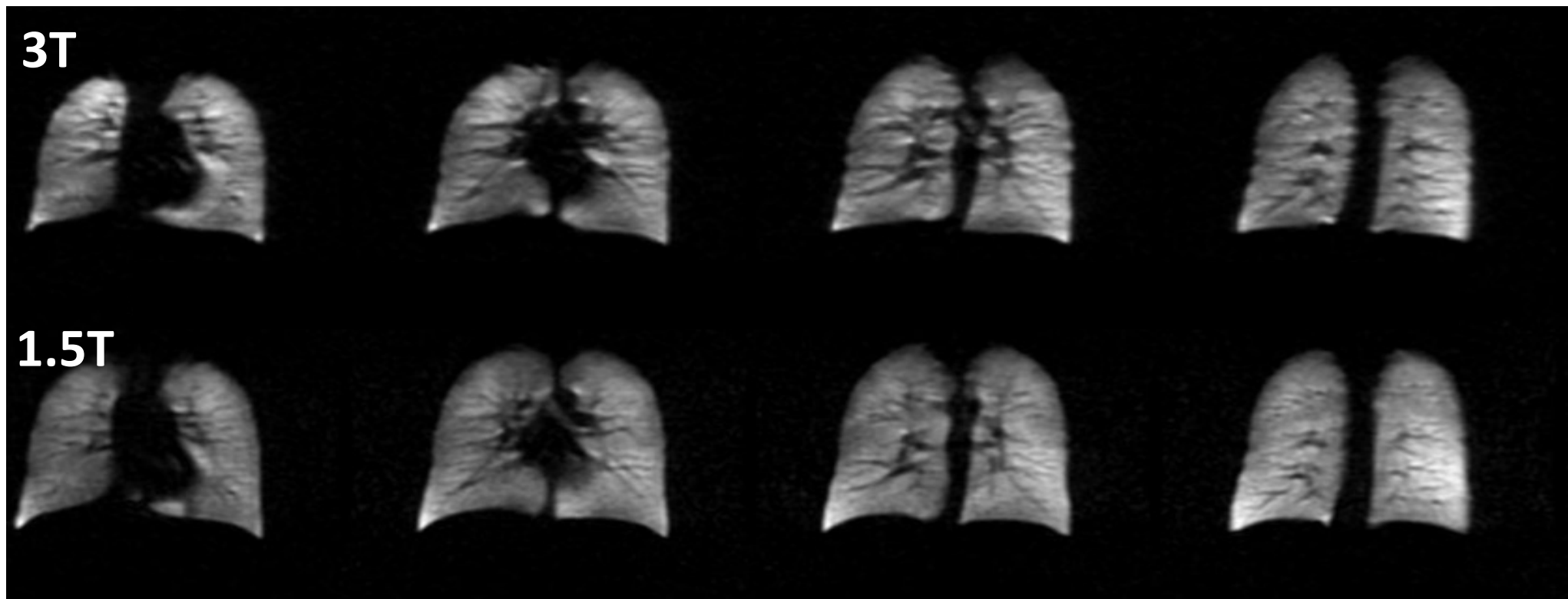
effect of B_0



Komlosi et al Magn Reson Med. 2017 Oct;78(4):1458-1463.

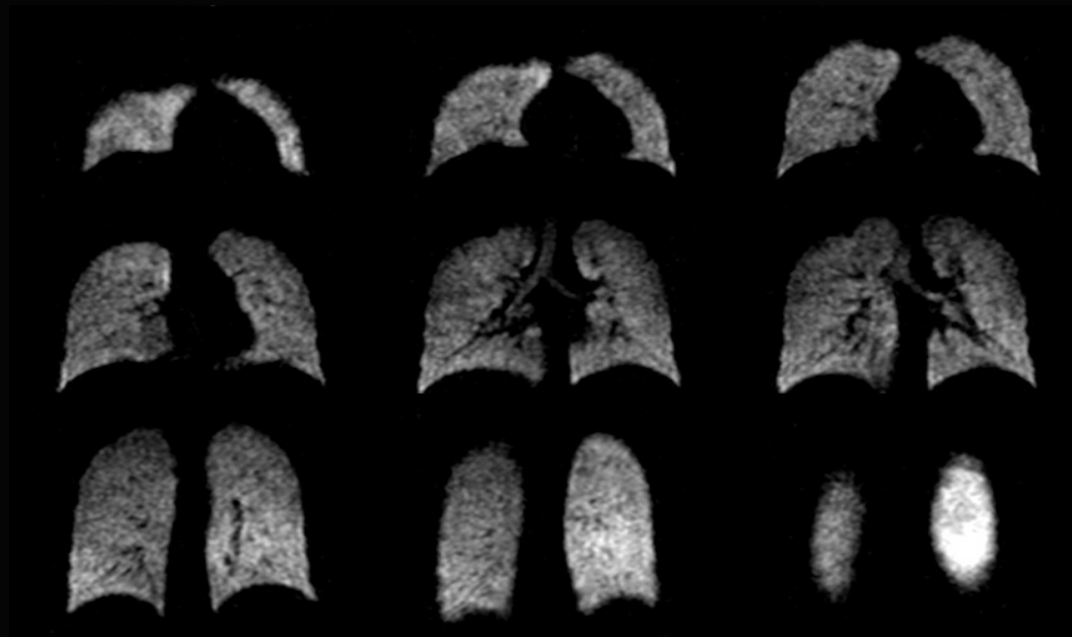
^{129}Xe ventilation MRI

effect of B_0

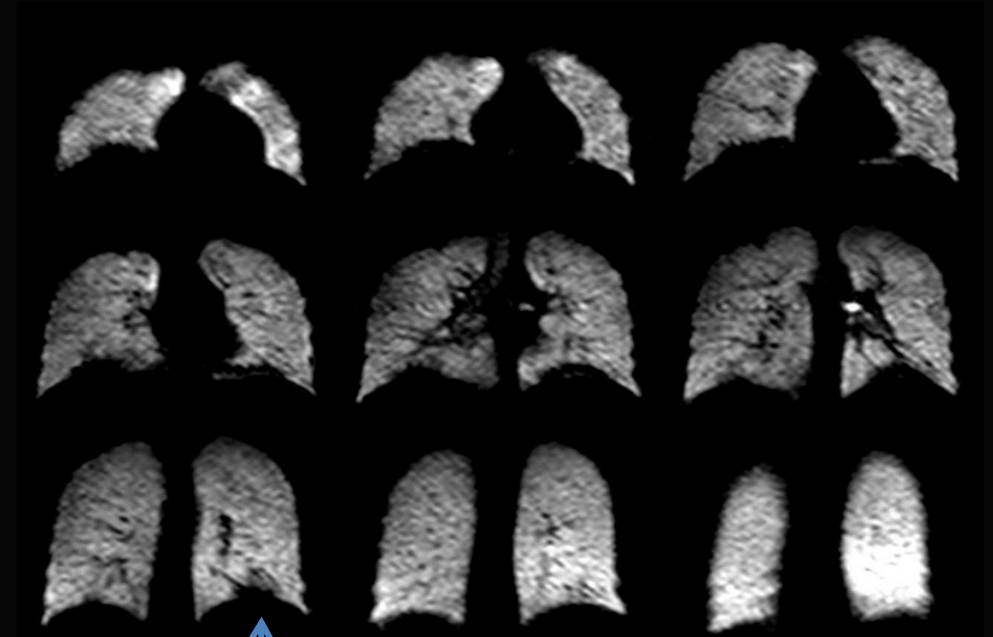


Xu et al Magn Reson Med. 2012 Dec;68(6):1900-4.

HP ^{129}Xe Gas MRI



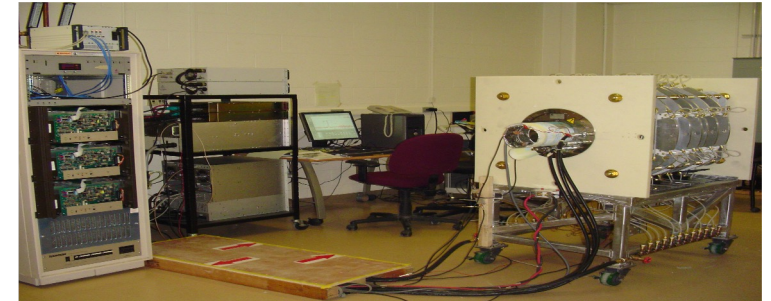
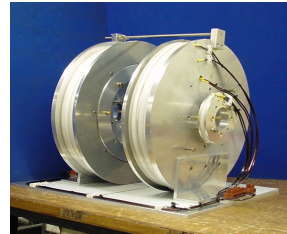
1.5 T



3 T

Stewart et al., Magn Reson Med, 74, 2 (2015).

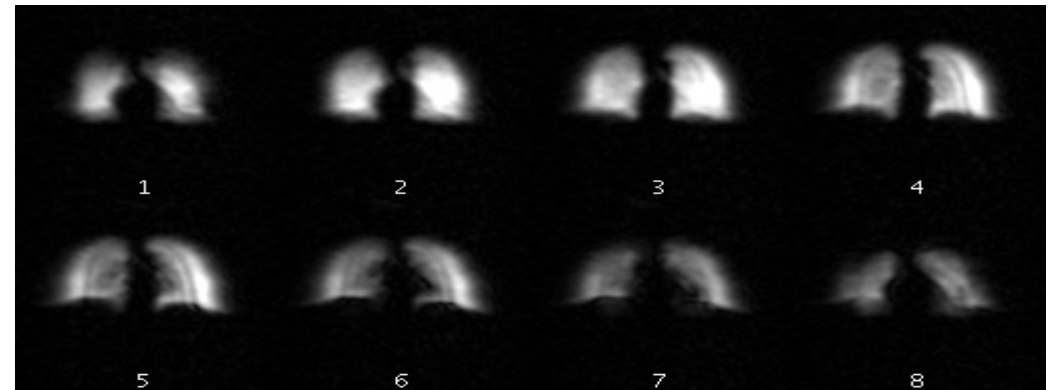
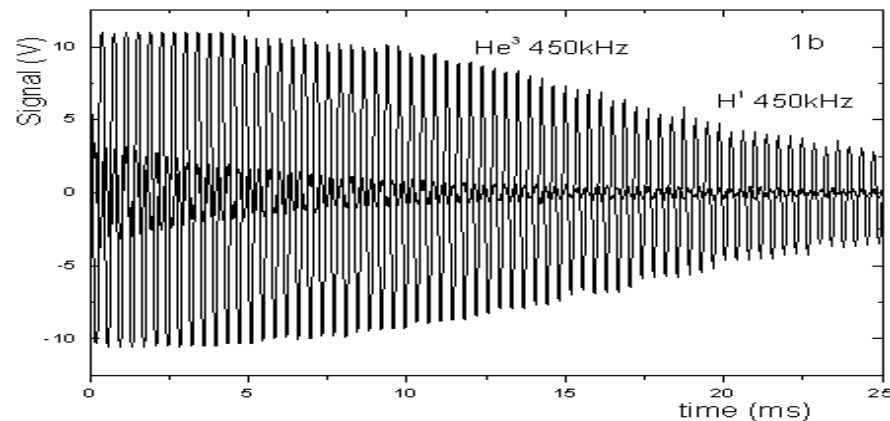
Ultra low field HP MRI



HP MR possible at very low fields:

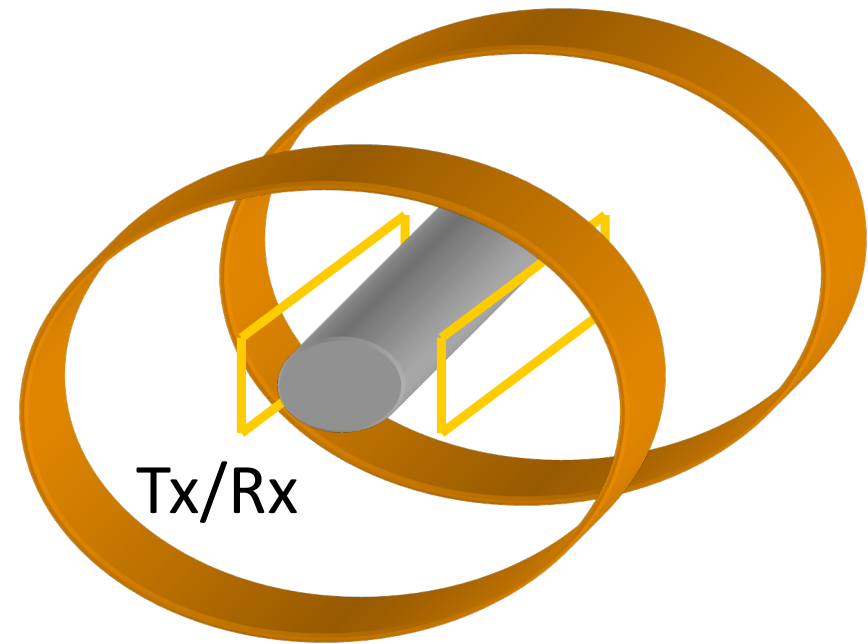
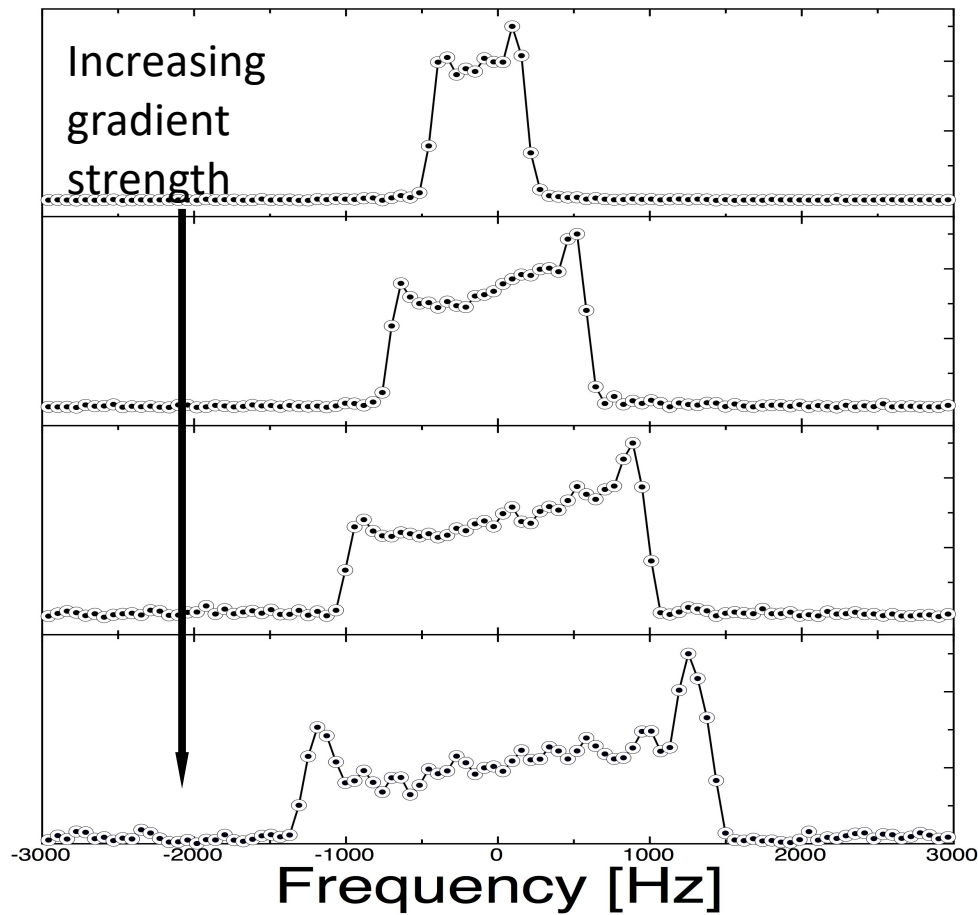
Pros: cheap, lightweight, portable, v. long T2s, learn a lot about MR engineering, same RF coils for different nuclei – tune B_0

Cons: painful to build, weaker ^1H signal – limits applications



HP 3He at 65 G

MRI of $^3\text{He}/^{129}\text{Xe}$ in the cell at 10G ~ 30kHz



- Gradient across cell
- AE amplifier
- Direct digital sampling (NI)

Preparing a clinical MR scanner for broad band HP nuclei imaging

Jim Wild

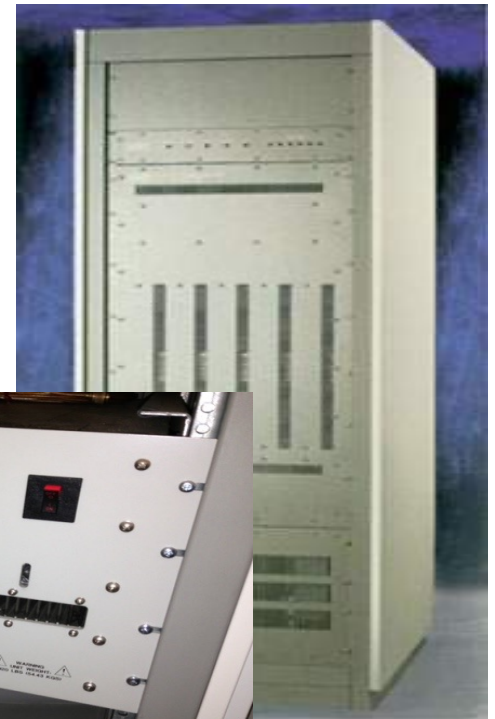
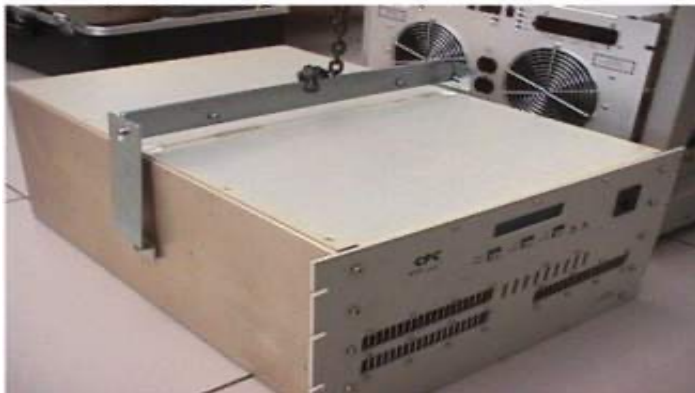
Preparing a MR scanner for broad band HP nuclei imaging

- **The equipment room**
- **The scanner room**
- **RF coil considerations**
- **The spectrometer**
- **System calibration**
- **HP experiments**

Equipment room – Broadband RF Amplifier

RF Amplifier

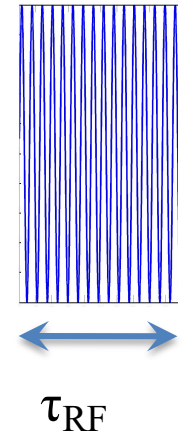
- 1.5T: 2 kW (CPC)
- 3.0T:
 - > 4 kW standard
 - > 8 kW option



The equipment room - RF amplifier

RF Power requirements at different frequencies

Power
$$\int_0^{\tau_{RF}} V \cos(\omega t) / \sin(\omega t) . dt$$



Power requirement to deliver given current in coil linear with ω (γ)

Flip angle

$$\alpha = \gamma \int_0^{\tau_{RF}} B_1 . dt = \gamma B_1 \tau_{RF}$$

A 'broadband' RF amplifier should deliver at all frequencies

RF amplifier linearity

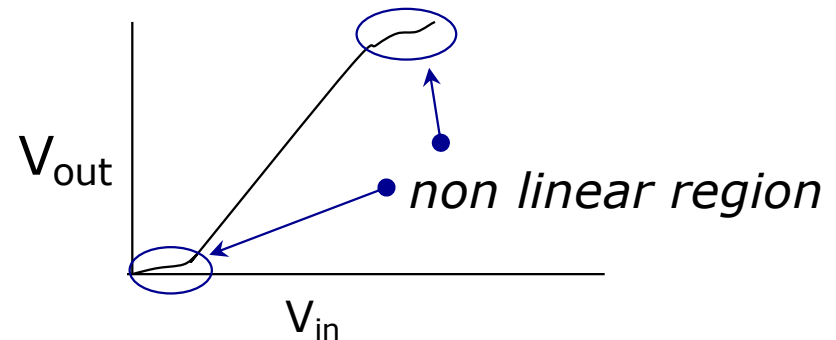
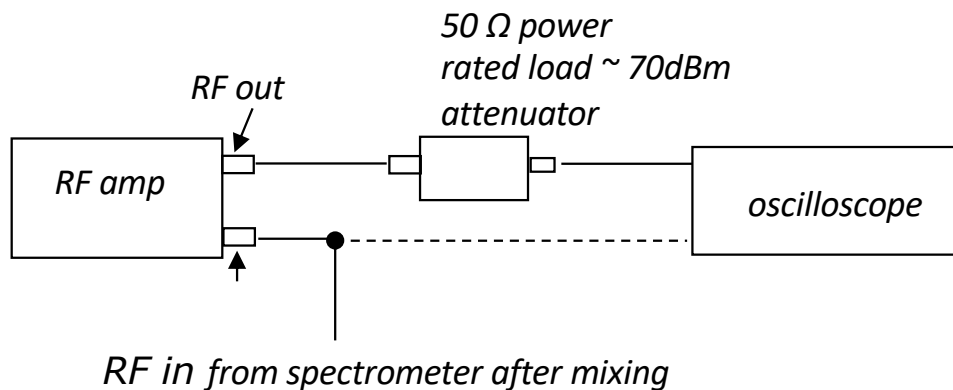
HP acquisitions need to operate with:

(i) very low F.A:

- e.g. 3D spoiled gradient echo imaging

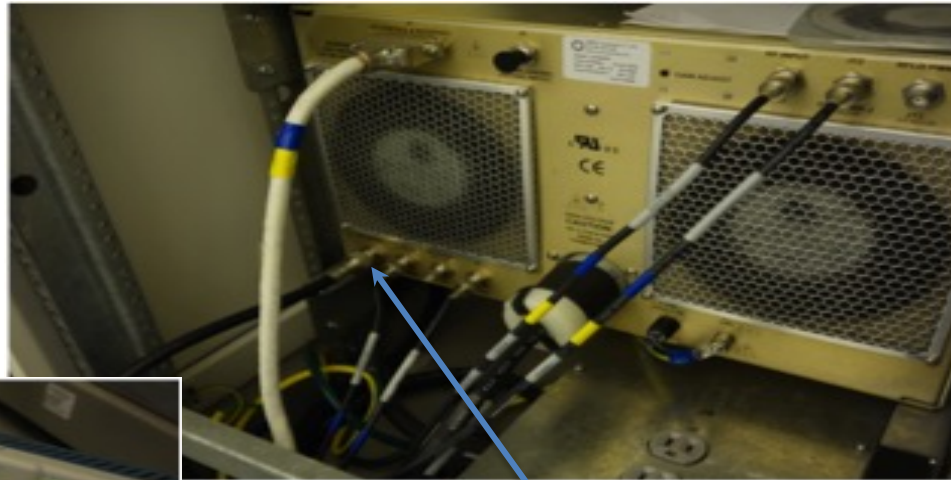
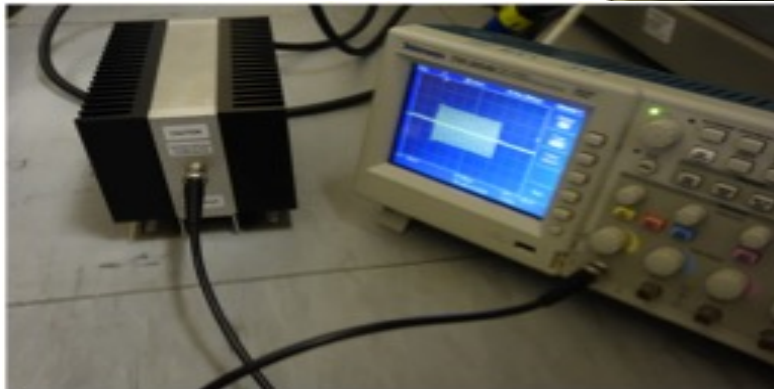
& (ii) high F.A.:

- e.g. ^{129}Xe dissolved phase spectroscopy – lung coil 90° FA



Checking RF amplifier linearity

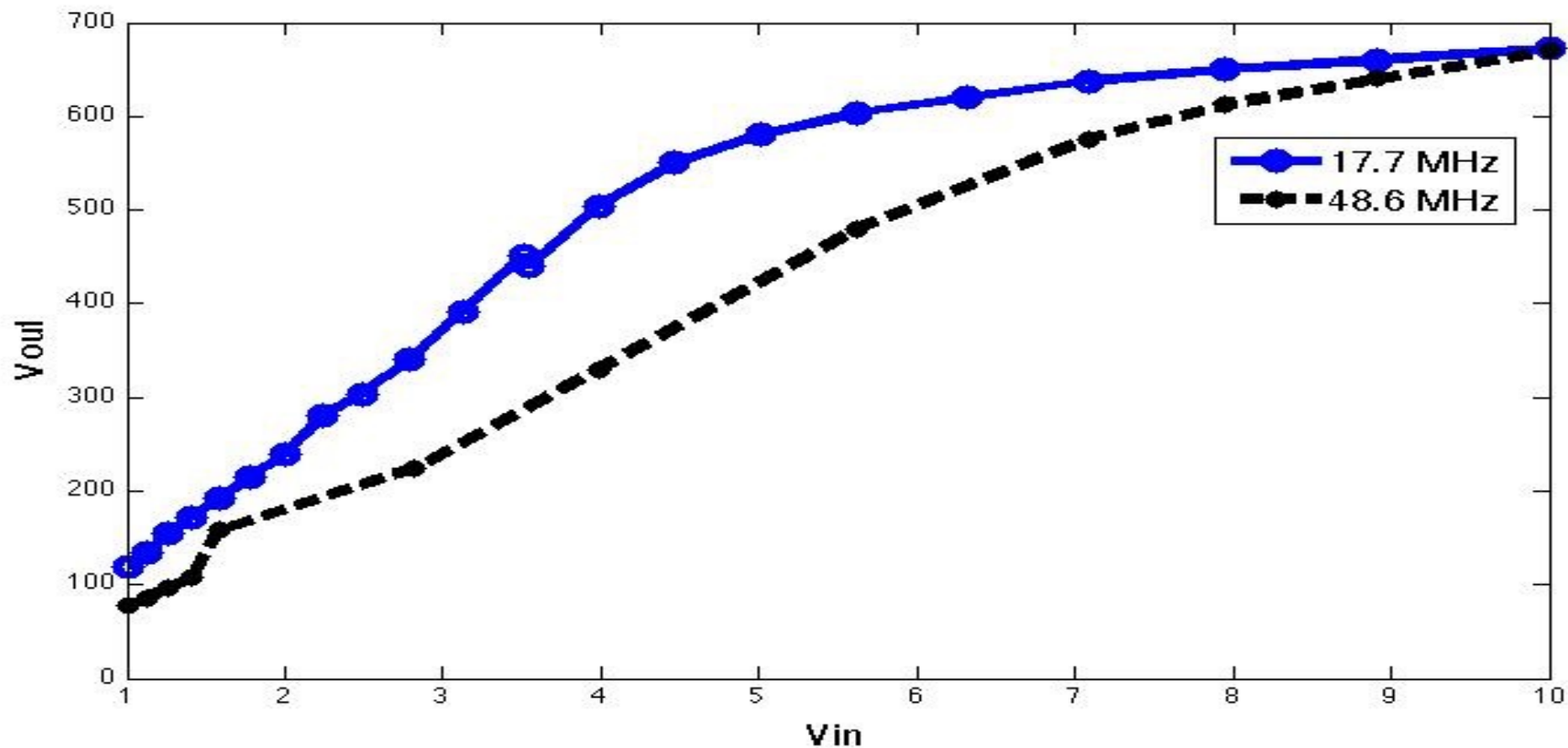
Power rated 50 Ω load
70 dB attenuation



2kW broad band RF amplifier out

– checking the output

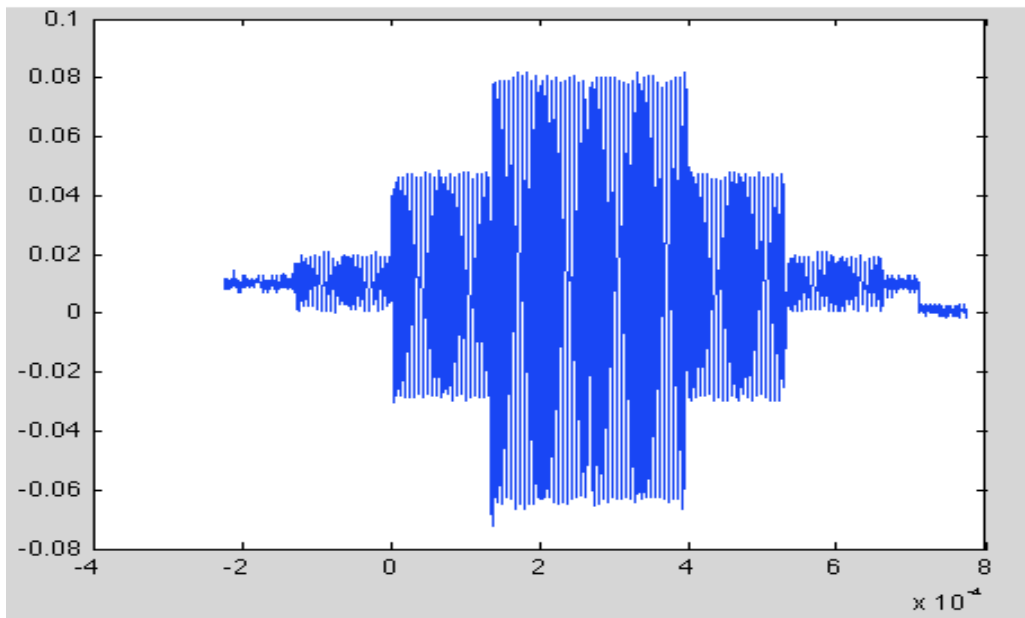
RF amplifier linearity



Gain can behave very differently across frequency range

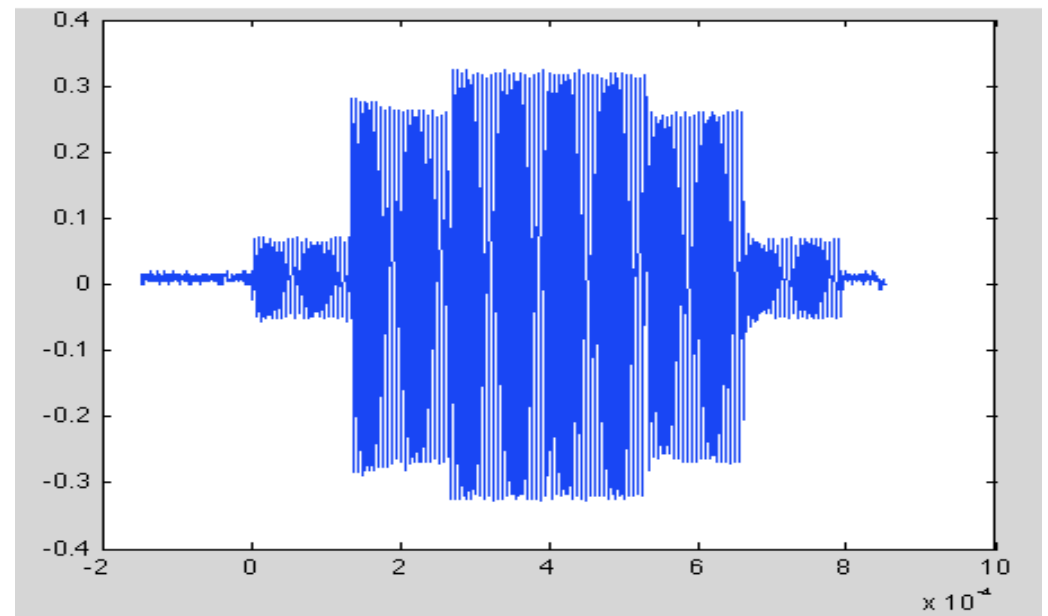
RF amplifier linearity

- compression of pulse at high transmit gain



TG = 0

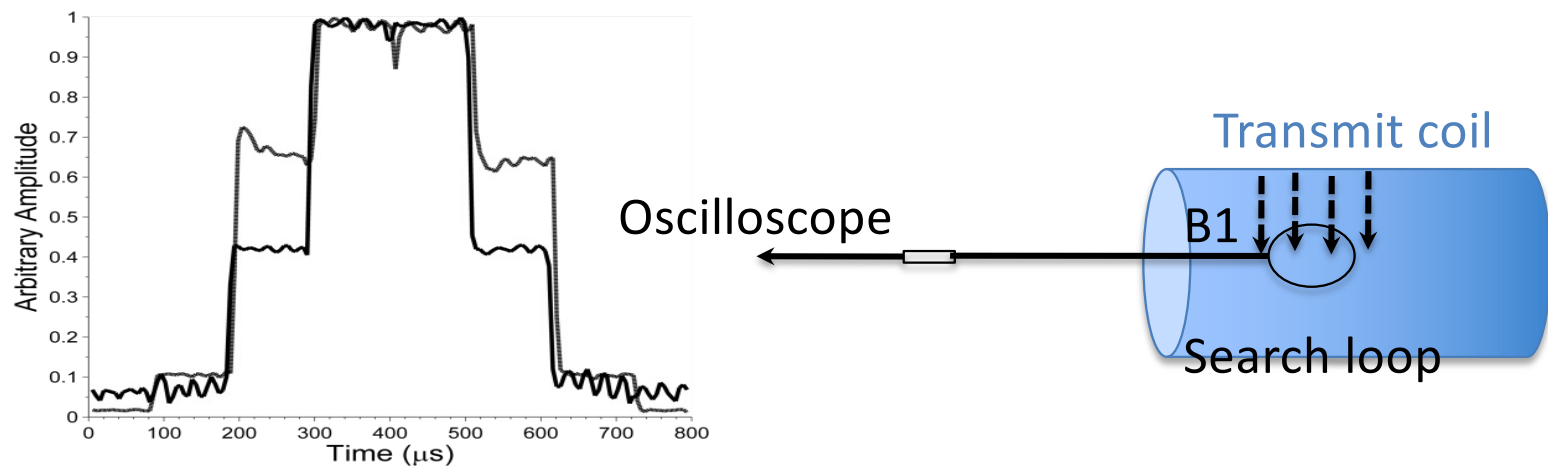
Composite RF pulse at 17.7 MHz



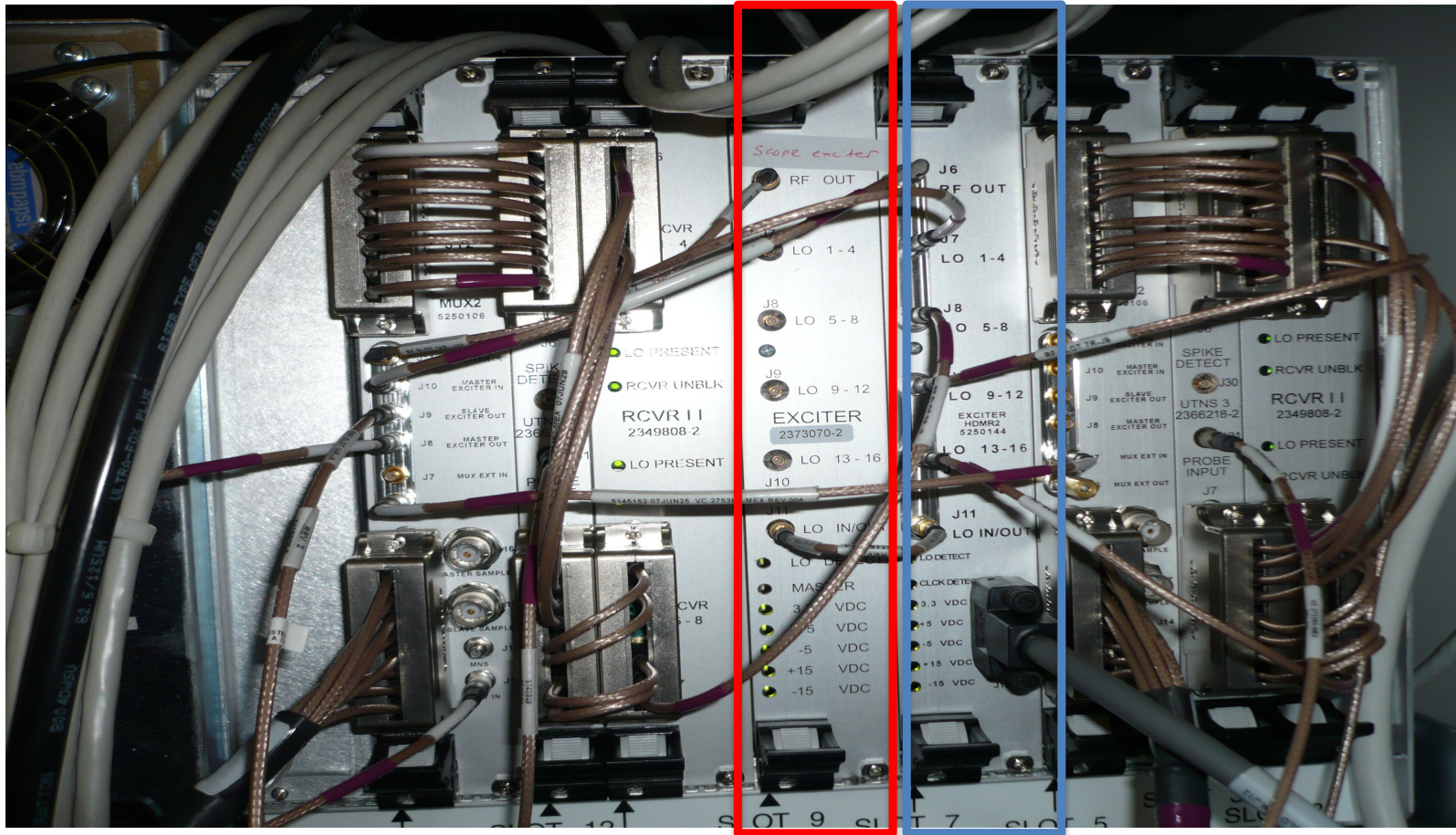
TG = 200

RF amplifier linearity

- Search loop method – measure induced EMF



Equipment room – exciters & receiver boards



Slave exciter: MNS (in EPIC: rho2, omega2, theta2) - broadband

- Master exciter: 1H (in EPIC: rho1, omega1, theta1) – narrow band

Equipment room – gradients

- Required gradient strength scales with $1/\gamma$
- Need strong gradients for small FOV imaging of ^{13}C and ^{129}Xe , small bore magnet gradients usually good enough
- b-values – gradient strengths limit capability for short diffusion time with ^{129}Xe ($D_0 = 0.14 \text{ cm}^2/\text{s}$, in air) on a clinical system (33 mT/m)
- Gradient cable filters
not always tuned for non ^1H frequency



The magnet room

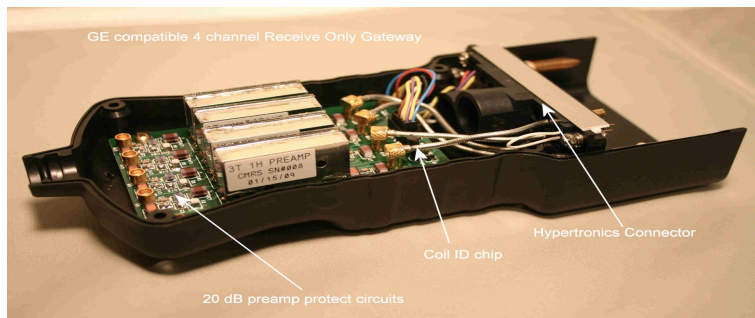
- Transmit-Receive (T-R) switches
- Pre-amplifiers
- Interfacing to the scanner
- **RF hardware**

Unwanted noise sources – RF cage test

Frequency	Field	Test Position	Outside Reference Level (dB)	Inside Reading (dB)	Attenuation Level (dB)	P = Planewave
5.89MHz	P/E	A	-6	-99	93	Door
5.89MHz	P/E	B	-6	-99	93	Window
5.89MHz	P/E	C	-6	-102	96	Pen Panel
21.29MHz	P/E	A	-0.64	-91.75	91.11	Door
21.29MHz	P/E	B	-0.64	-89.98	89.34	Window
21.29MHz	P/E	C	-0.64	-99.43	98.79	Pen Panel
64MHz	P/E	A	15	-88	103	Door
64MHz	P/E	B	15	-82	97	Window
64MHz	P/E	C	15	-71	86	Pen Panel

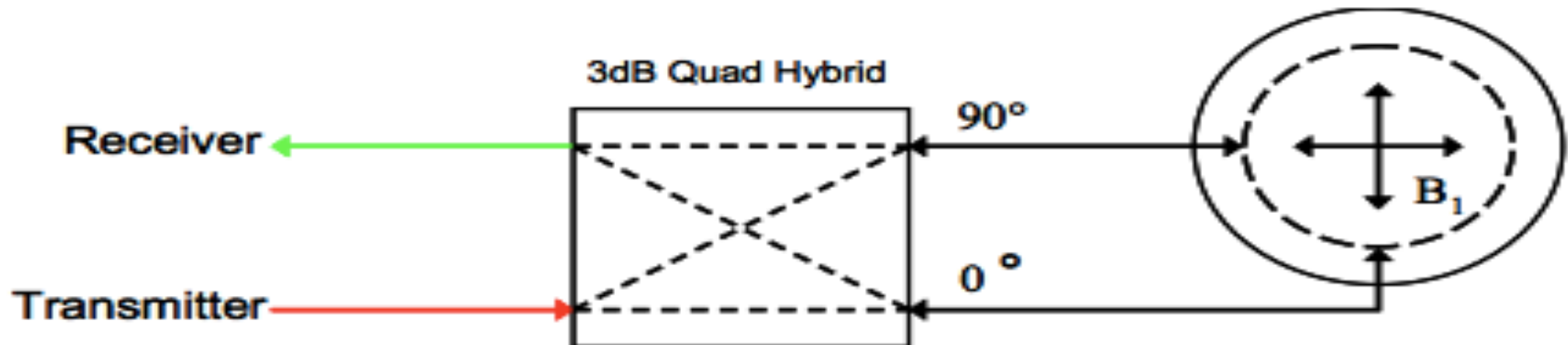
Transmit-Receive (T-R) switch

- T-R switch – is a tuned circuit :
 - high isolation between transmit and receive lines
- broadband T-R switches are not optimum
- Needs to be power rated for Tx power 8kW reflection
- May need short ring down for UTE
- On board **tuned** preamplifier

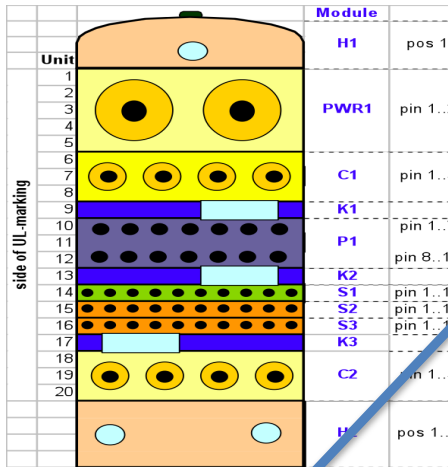


Quadrature hybrid

- Can act as T-R switch
 - high isolation between transmit and receive



RF interfacing



Tx out 4kW MNS

Single Rx in
(4-6 ch available)

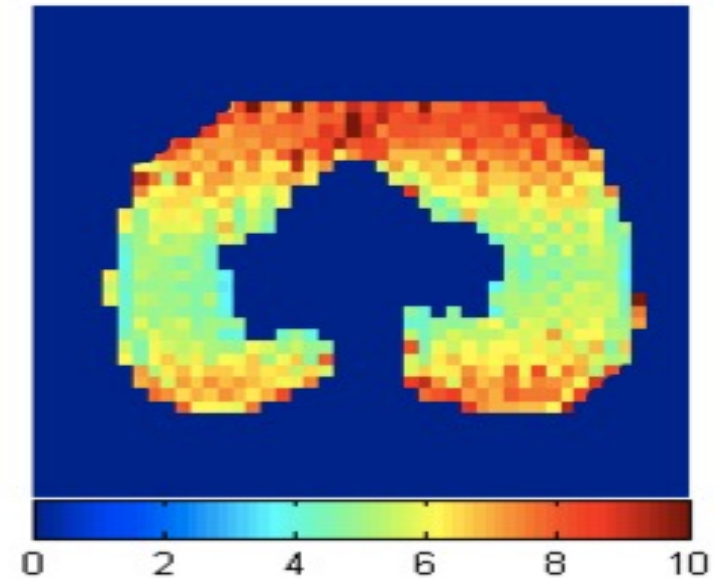
**e.g. Philips 3T Achieva MNS
– ODU interface**

RF coil considerations for HP MRI

- space and size constraints of the bore
- Transmit and receive sensitivity
- B1 homogeneity,
- Loading – higher frequency, sample loading more
- Decoupling - traps, passive and active decoupling, isolation from ^1H body coil
- Need for ^1H signal T-R
- Scope for multiple receivers – parallel imaging
- Cost!

RF coil transmit receive sensitivity vs homogeneity?

FA map

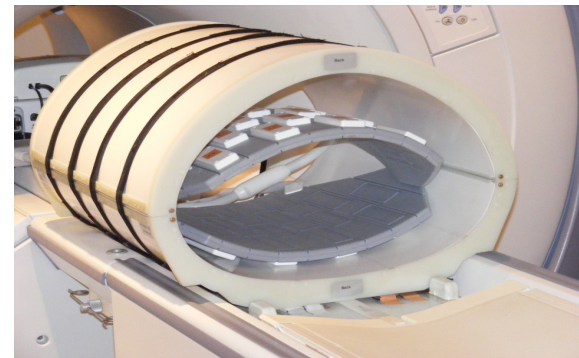
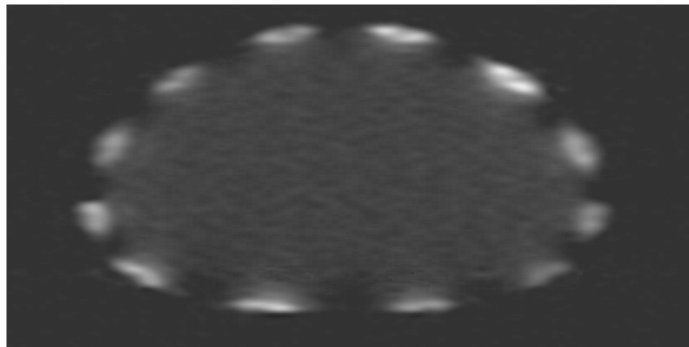


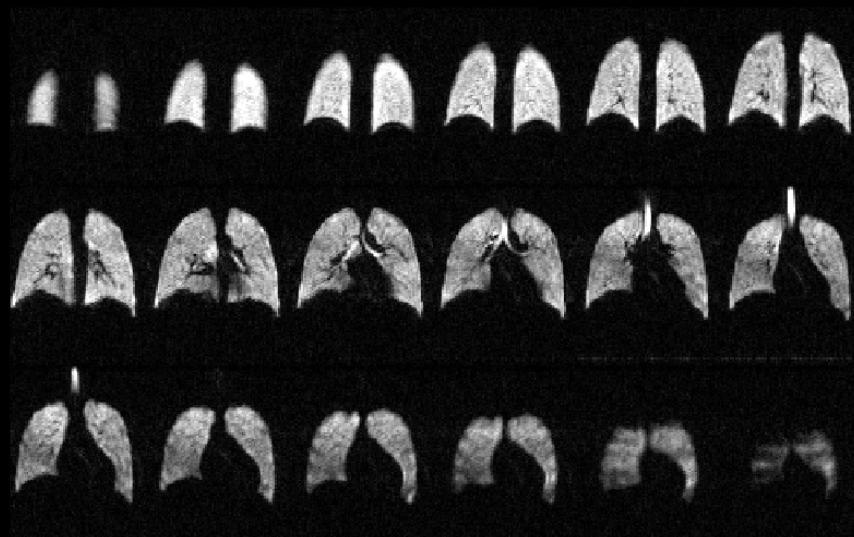
- “Coat hanger” RF coil ok for first steps
- Need better B1 homogeneity and volume coverage for good in-vivo HP imaging ...

RF transmit homogeneity – birdcage coil

- ✓ B1 homogeneity
- ✓ spacious
- ✓ space for Rx array
- ✓ quadrature easy

- ✗ Expensive
- ✗ Less power efficient – much of magnetic energy around rungs
- ✗ Less portable
- ✗ Bigger coils – inductive coupling to ^1H body coil





35

25

15

5

0

Quad
T/R
coil



80

60

40

20

0

8ch
Rx
array

^{129}Xe 8 Ch array



8 channel ^1H cardiac array
tuned to 17.66 MHz at 1.5 T



Active decoupling
Circuit
Tx birdcage

Flexible T-R coils

✓ Closer fitting:

Rx and Tx sensitivity

- good coupling to sample (Q_l/Q_u)

- power efficient

✓ Better filling factor, η

✓ Cheap, light, portable

✓ Smaller coil – less coupling to

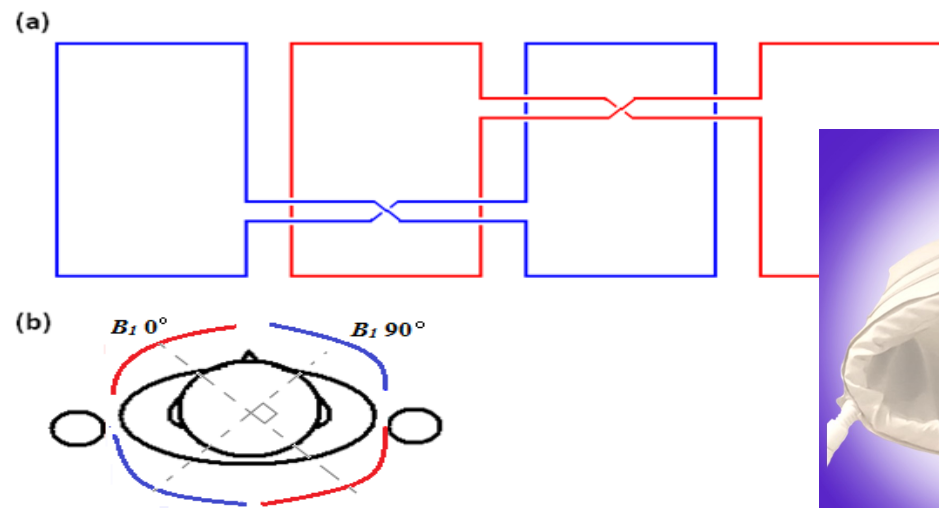
^1H body coil and trap

✗ B_1 homogeneity

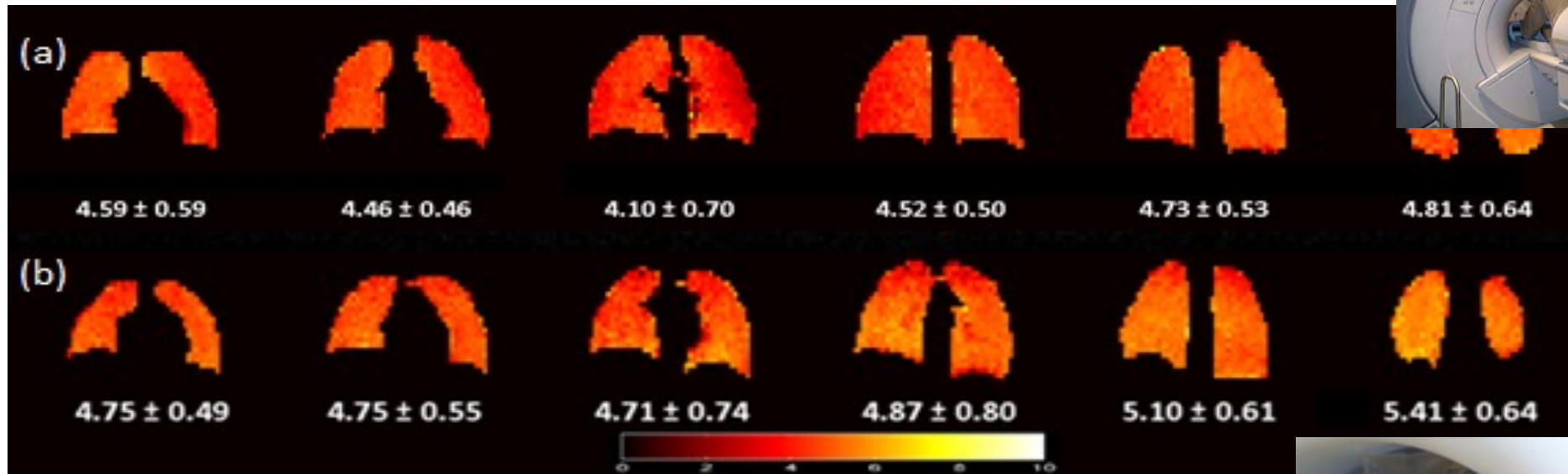
✗ Flex geometry more prone to changes in

✗ High SAR near conductors

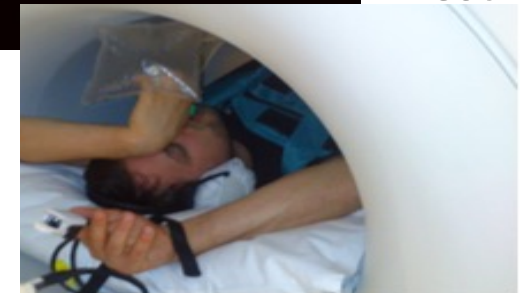
✗ Limited space for Rx array



RF transmit homogeneity - ^{129}Xe

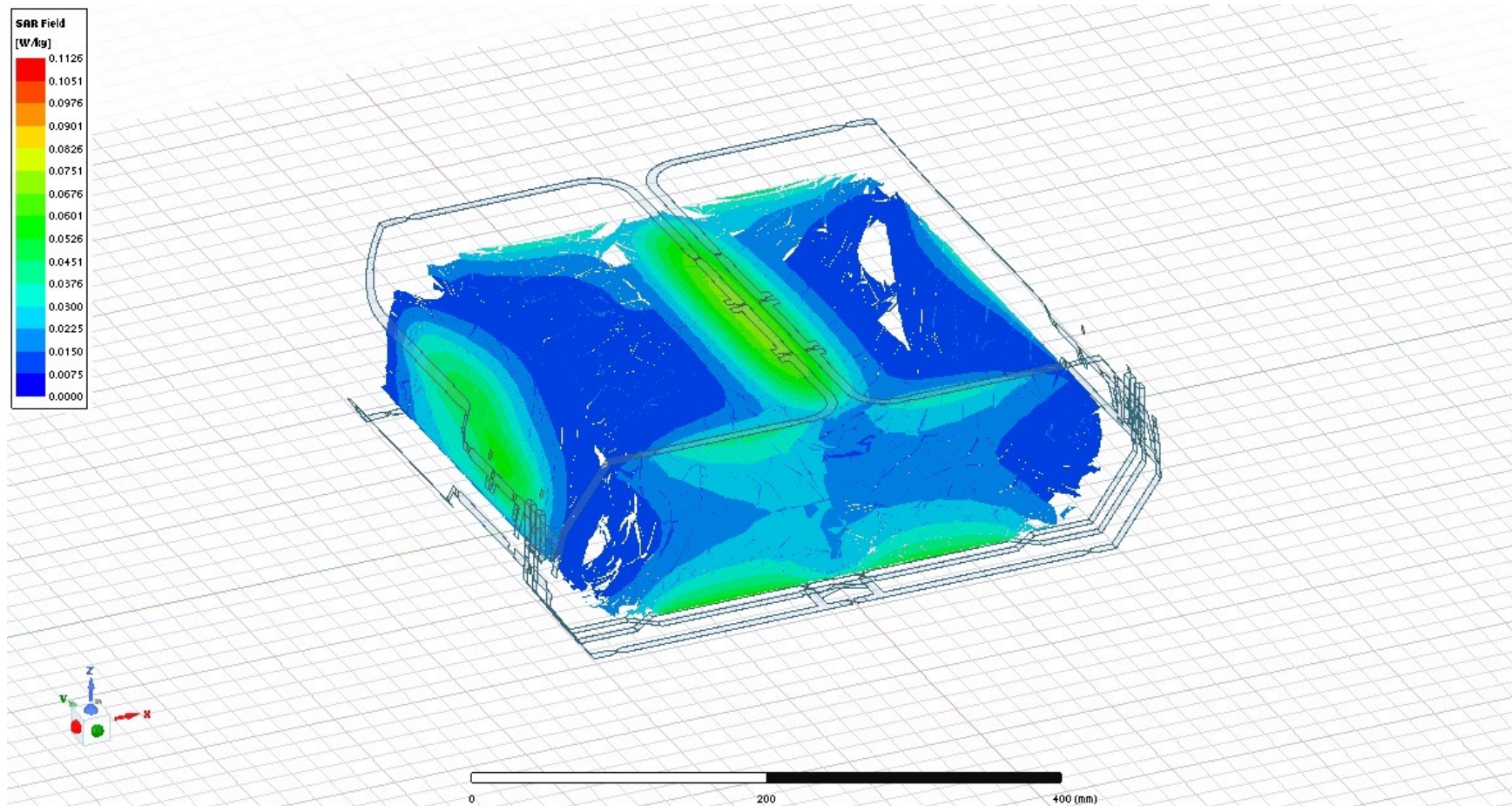


Birdcage

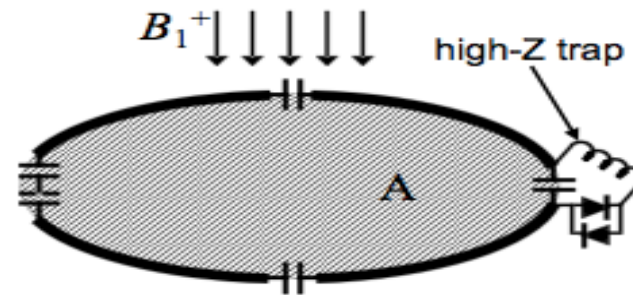


Vest

SAR considerations for all coils



RF coupling and detuning interactions with ^1H body coil– birdcage coil

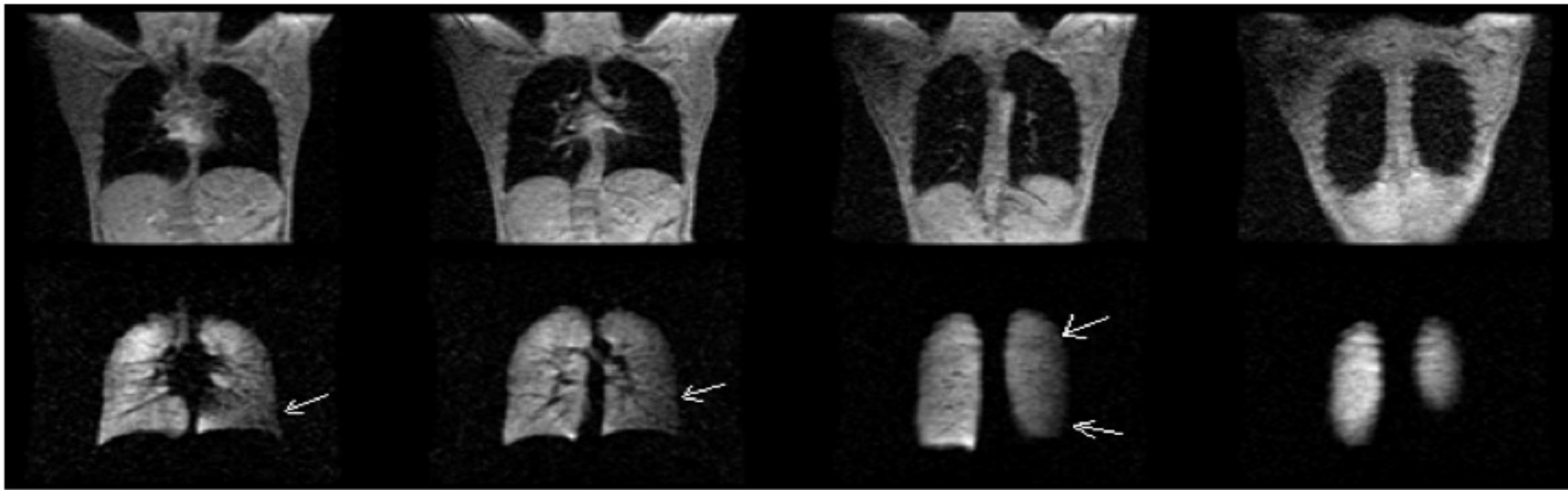


HP nucleus transmit-receive coil

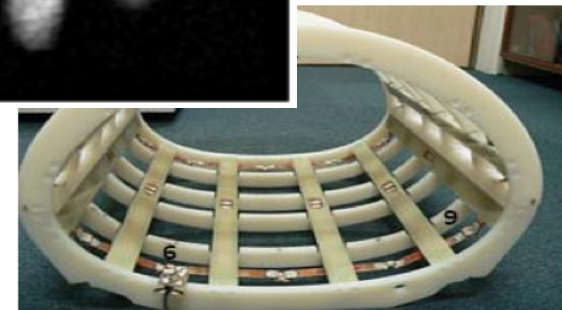
Needs S21 isolation from ^1H body coil

- Vital for good ^1H imaging
- Vital for subject safety – induced currents
- Achieve with passive traps (coil and cable) and active detuning (PIN diodes/MEMS)
- N.B. traps can add noise to the coil (lossy components)

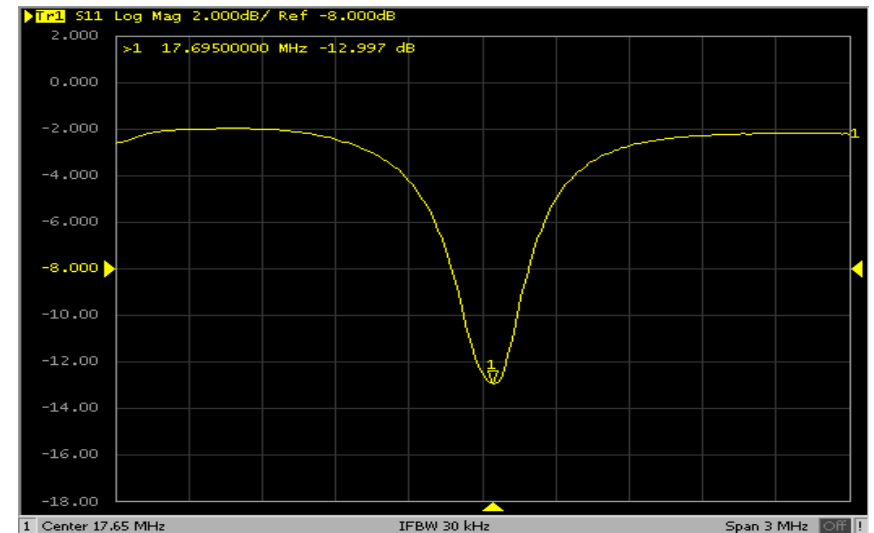
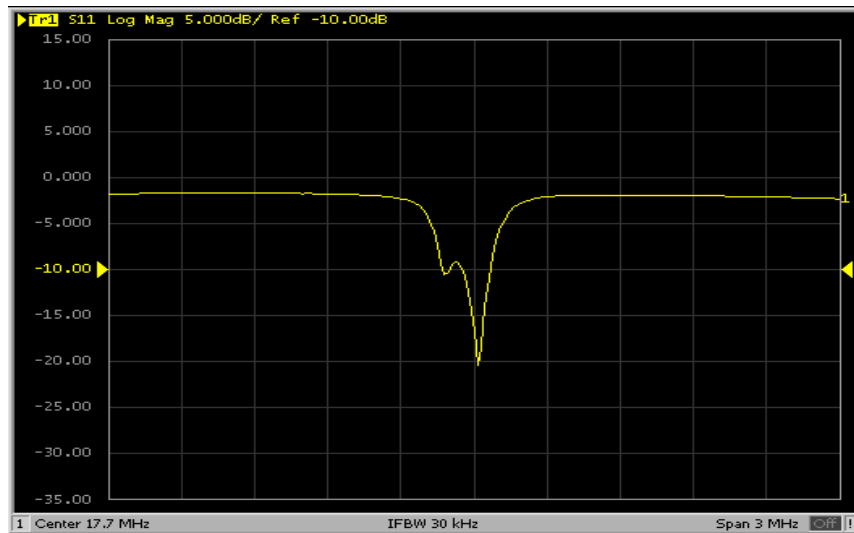
RF coupling and detuning interactions with ^1H body coil– ^{129}Xe birdcage coil



Interaction with ^1H body coil causing B1 inhomogeneity

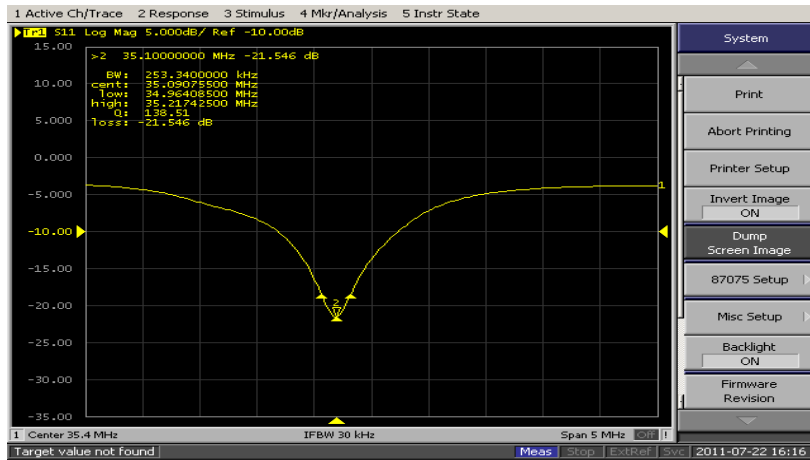


RF coupling between ^1H body coil X nucleus coil

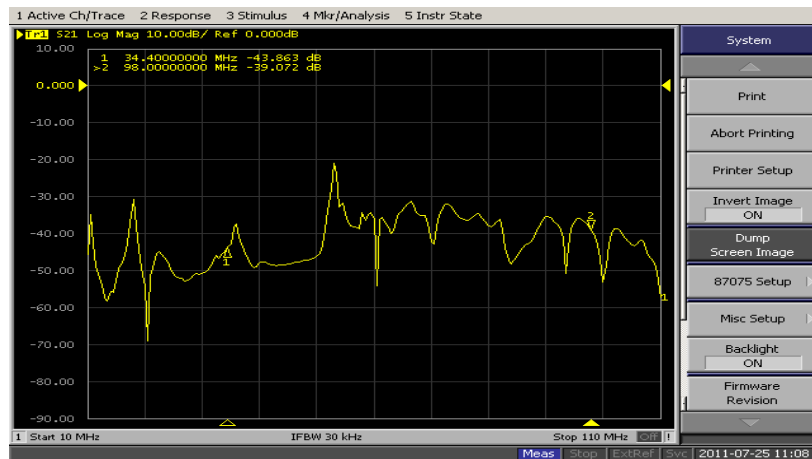


- S11 measurements : after retuning splitting resolved
- Degradation in ^1H image quality – check ^1H body coil tuning with HP coil in place as well as isolation

Simultaneous multi nuclear MRI

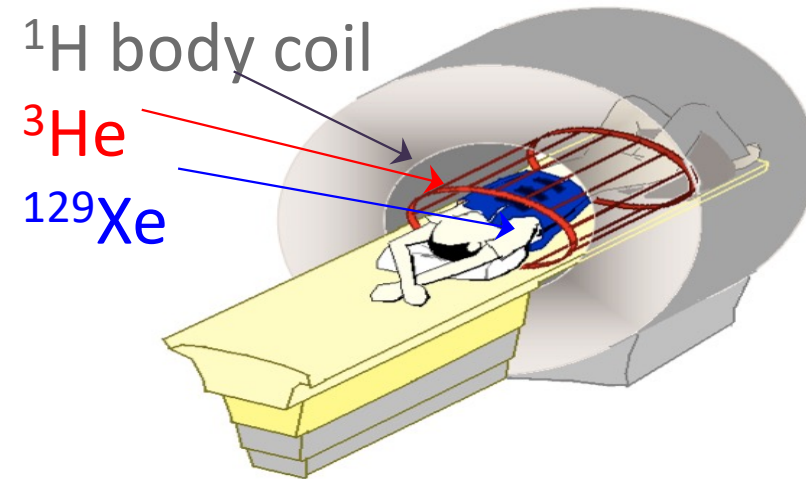


S11 ^{129}Xe coil



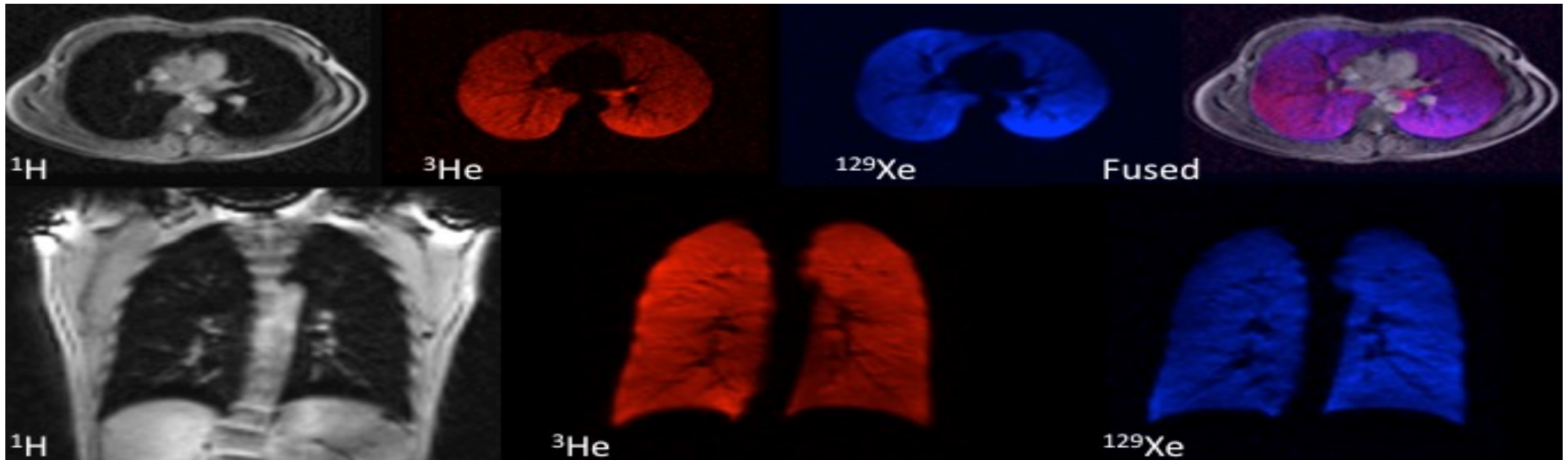
S21 $^{129}\text{Xe} - ^3\text{He}$ coils

S21 < -35 dB



$^3\text{He}^{129}\text{Xe}^1\text{H}$ lung MRI

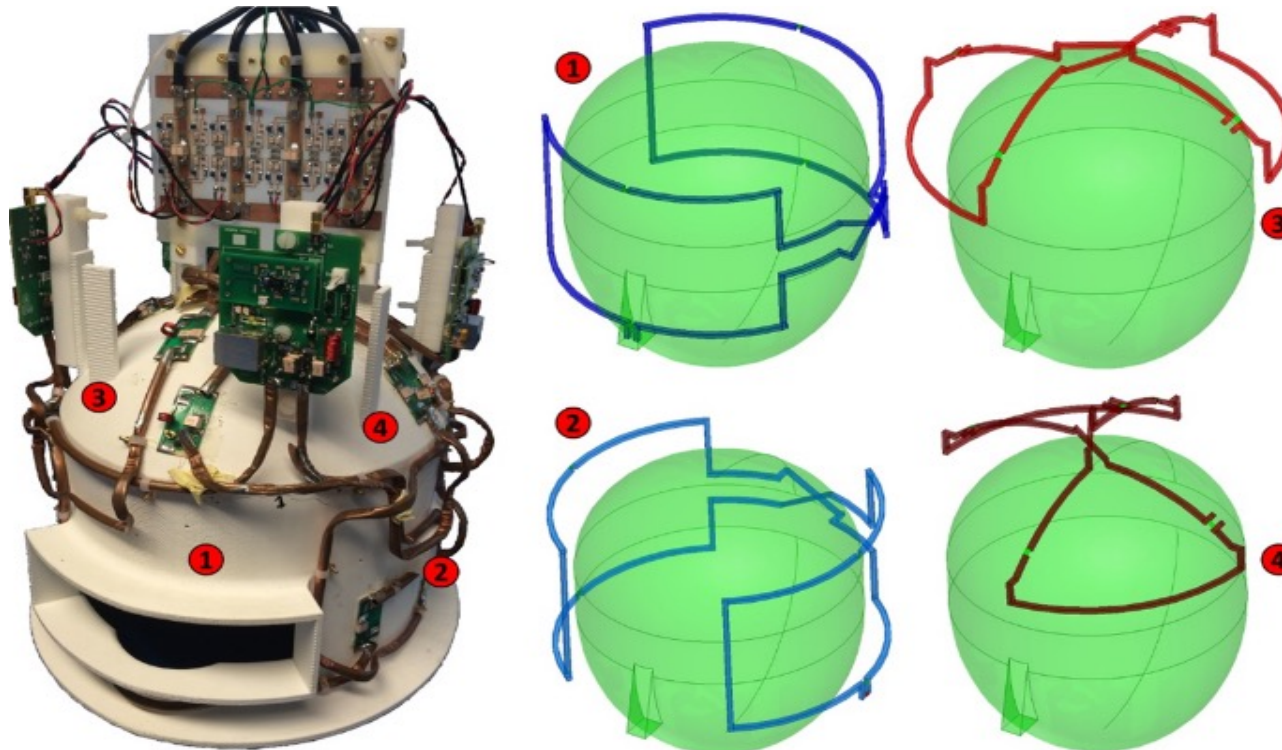
- same breath



Inhaled mixture of 300 ml HP ^{129}Xe at 15% and 300 ml ^3He at 25%

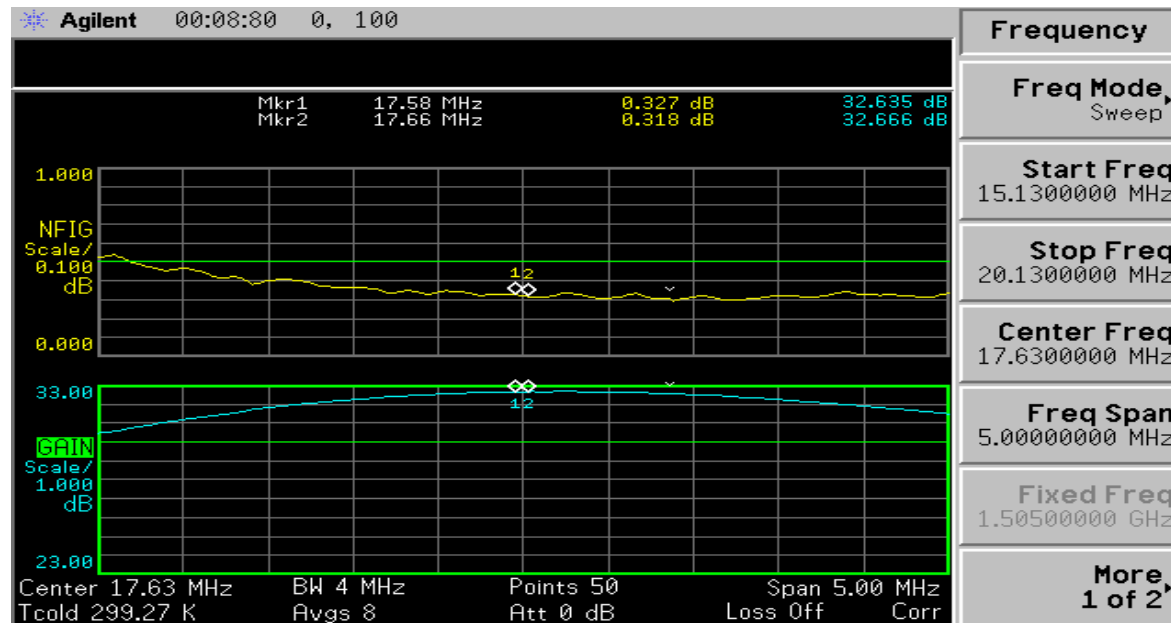
Radiology. 2013; 267(1):251-5

Array coils – N elements versus wavelength

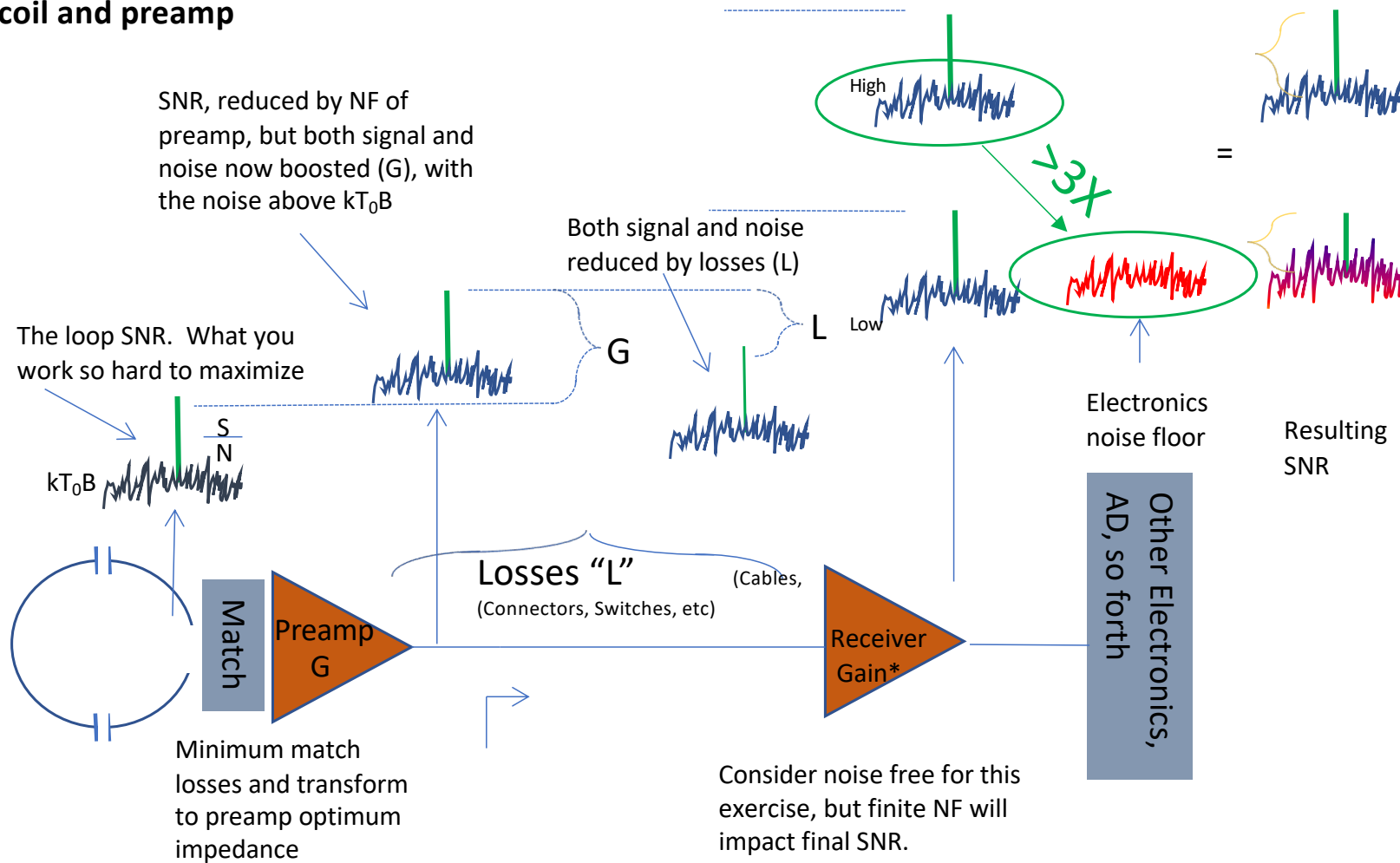


Preamplifiers

- Magnetisation can be weaker, high NF beneficial
- Tuned circuit – low noise high input impedance
- system broad band preamplifiers ARE not optimum

 ^{129}Xe 17.6 MHz $\sim$ 30 dB Gain

SNR of coil and preamp



Simple view: Enough gain to overcome the **red** electronics noise

The spectrometer

- Pulse sequence conversion and programming for MNS/imaging (vendor specific)
- Disable any ^1H functionality that might destroy magnetisation
- prescans, gain calibration, auto shimming, dummy scans, stabilisation pulses

First experiments

- Finding the signal
- Calibrating transmit gain and flip angle
- Calibrating receive gain

First experimental steps- finding the NMR signal

Thermal phantom

^3He / ^{129}Xe gas cell 2bar with 1 bar O_2

– shorten T1 to seconds from hours

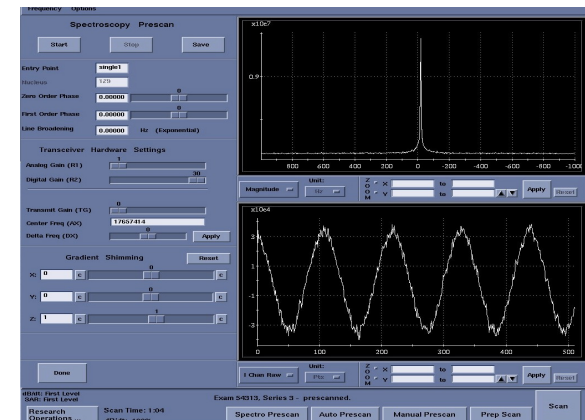
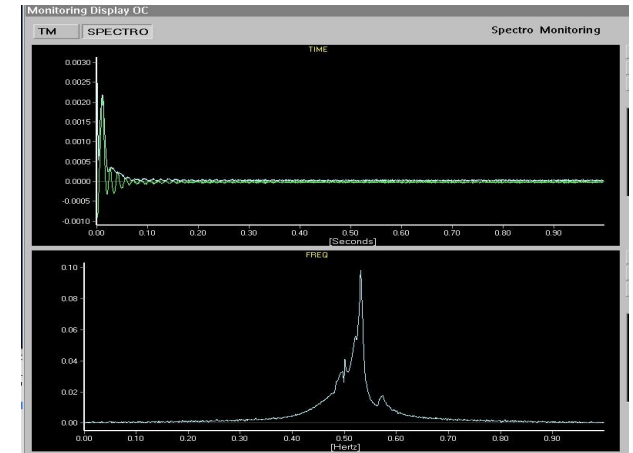
(T1 proportional to $1/[\text{O}_2]$) T1 ^{129}Xe in air $\sim 20\text{s}$

^{13}C e.g. lactic acid with Gd-DTPA

– shorten T1

^{23}Na saline

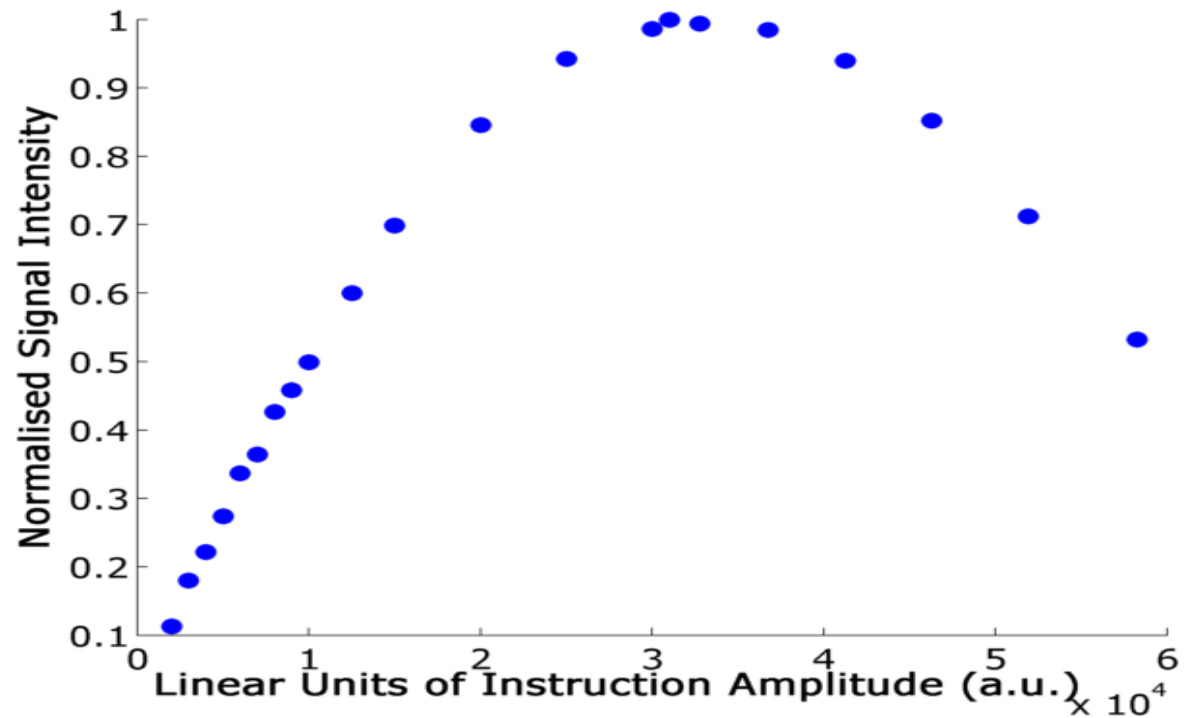
- f_0 sweep – find the FID and spectrum
- signal source and search coil can help tune in



calibrating transmit gain

thermal phantom: sweep transmit gain settings with fixed 'nominal flip angle'

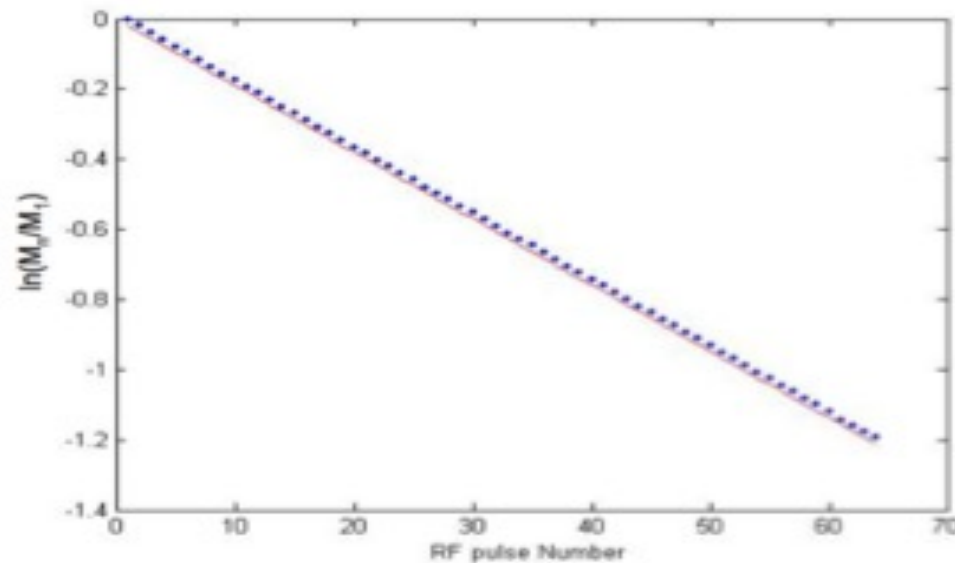
Fit signal to $\sin(\alpha)$



calibrating transmit gain: HP sample

- Perform series of gradient spoiled pulse-acquires

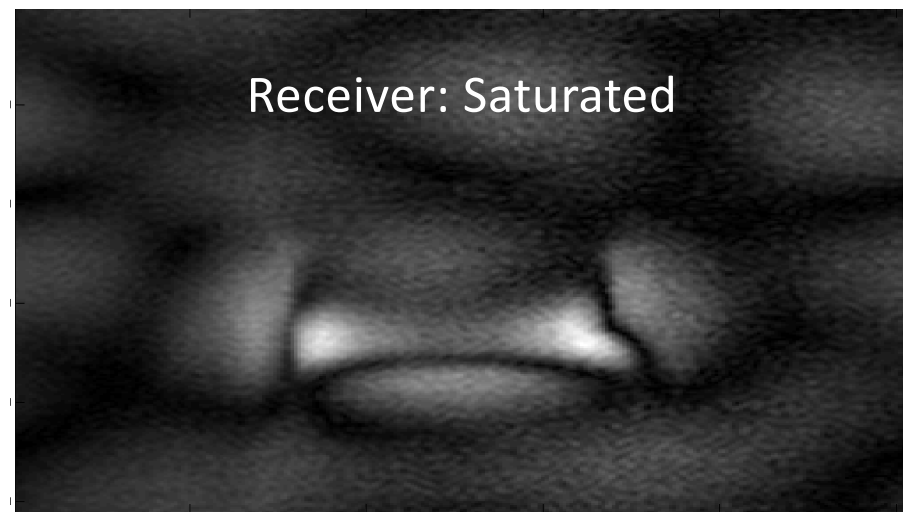
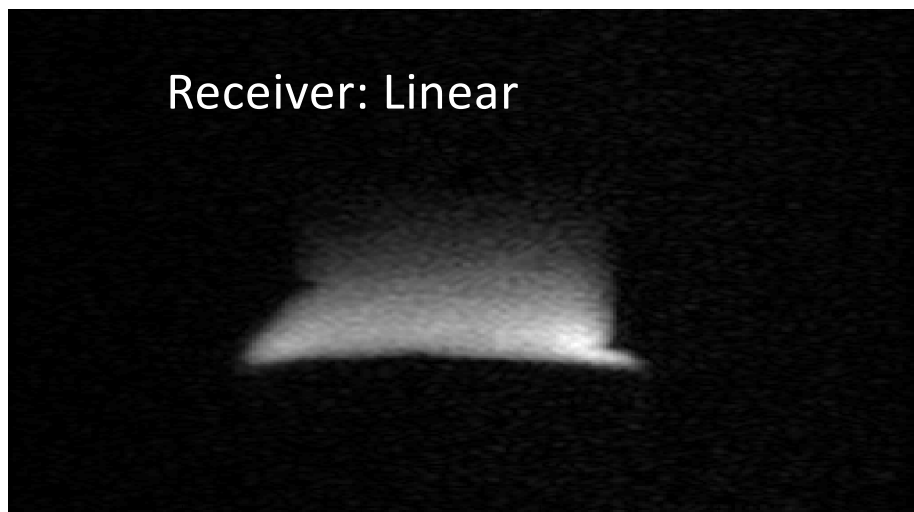
$$M(n) = M_0 \exp(-t/T_1) \cdot \cos(\alpha)^{n-1} \sin \alpha$$



$$\ln[M(n)/M(1)] = (n - 1) \cdot \cos(\alpha) - t/T_1$$

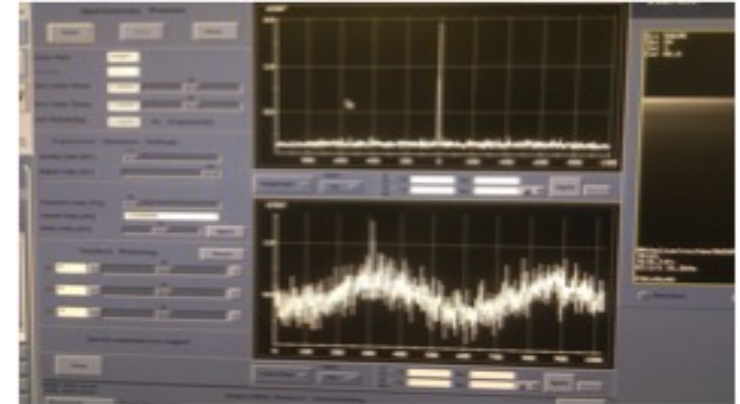
Receive gain setting

- Set analog and digital gain to avoid preamp saturation and signal clipping
- Magnetisation density and equivalent ^1H settings are a good rule of thumb



Unwanted noise sources

Unfiltered noise at non ^1H frequencies:
Coherent **constant frequency** noise



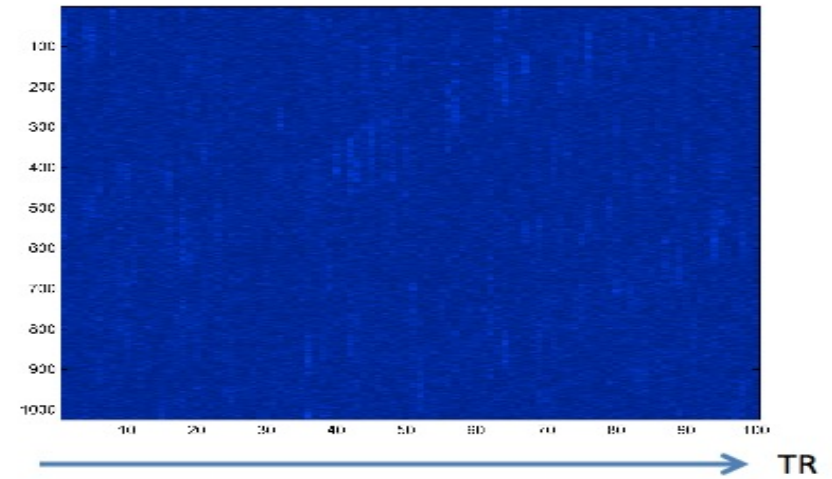
Gradients, power supplies, switching frequencies all generate noise
- filters in penetration panel tuned to block harmonics
@ $^1\text{H } f_0$

Add ferrite chokes to gradient power cables to suppress lower frequencies

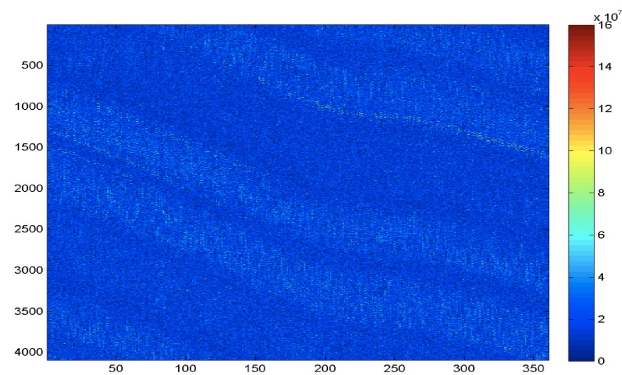


Spike/'splat' gradient noise

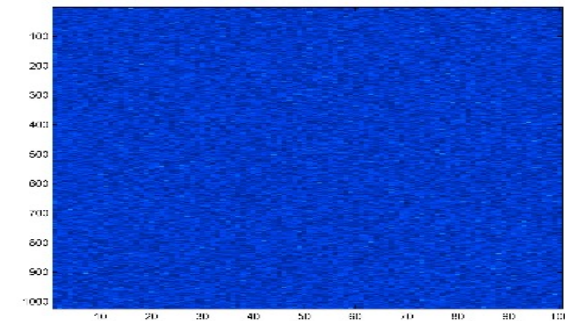
Individual FID



$C_{fxfull}=C_{fyull}=C_{fzfull}=0$



Power off Gradient Amplifiers



RF coil breakdown - noise spikes

k-space

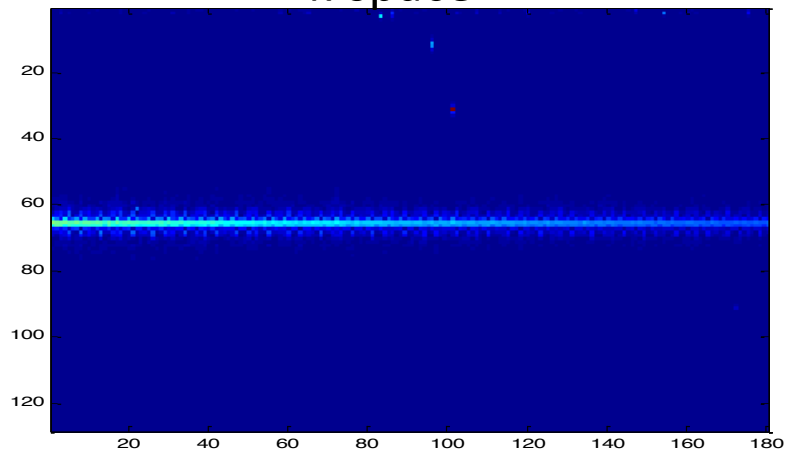


image space

