MR hardware considerations for hyperpolarised MRI

Jim Wild

Aarhus October 2024

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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.

80 ml ^{3}He P (~30%) mixed with 920 ml N_2 at 1 bar: $m_0=6.4\times10^{-3}\ JT^{-1}m^{-3}$

- comparable to the m_0 of a 1*l* sample of ^1H_2O at 1.5T ($m_0=4.8\times10^{-3}\ JT^{-1}m^{-3}$)

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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

Noise: $[\Delta f]^{1/2}[4k\,(T_C R_C + T_S R_S)]^{1/2}$ $R_{Coil} \propto \omega^{1/2}$ $R_{Sample} \propto \omega^2$

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

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HP MRI SNR factors: frequency and field strength

SNR dependence with ω_0 :

Coil noise dominated , (low ω_0)

SNR ~ $\omega_0^{3/4}$

Sample noise dominated , (higher ω_0)

SNR ~ **constant**

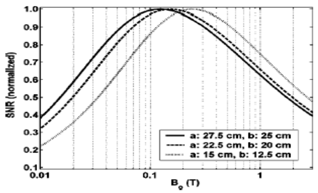

FIG. 3. Field dependence of the SNR for helium lung imaging for various sample/coil sizes (η=0.1).

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)**

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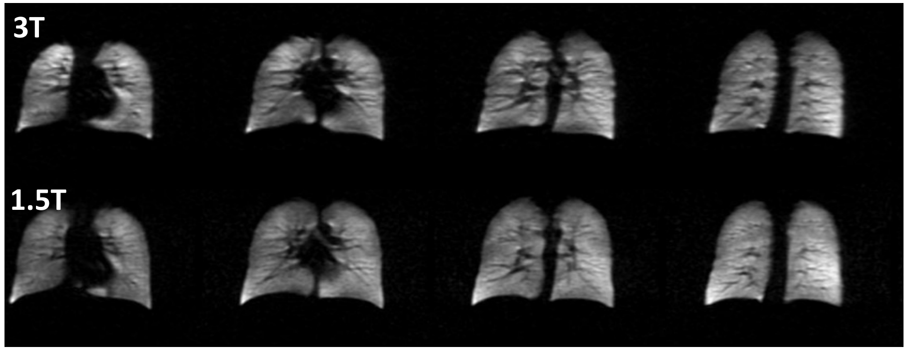
^{129}Xe ventilation MRI effect of B_0



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

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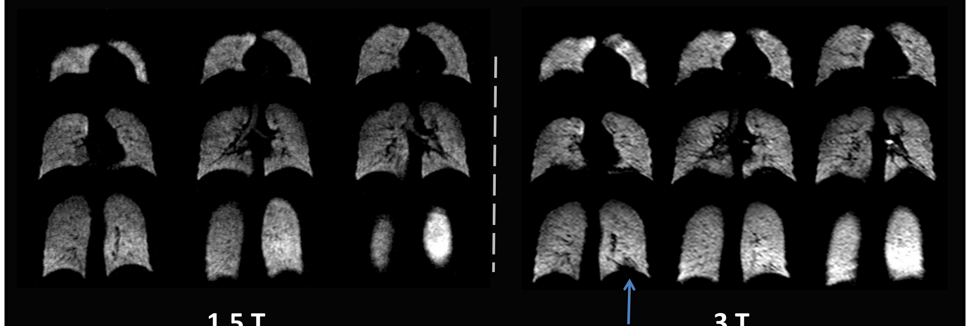
HP ^{129}Xe Gas MRI



1.5 T 3 T

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

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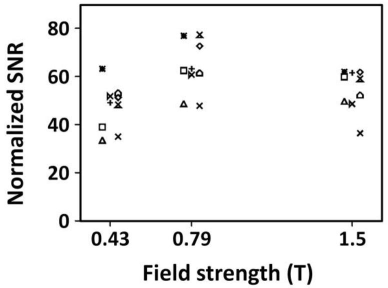
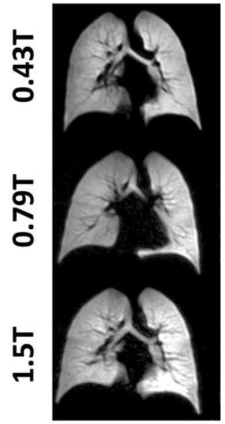
^{3}He ventilation MRI

effect of B_0





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

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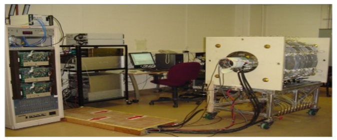
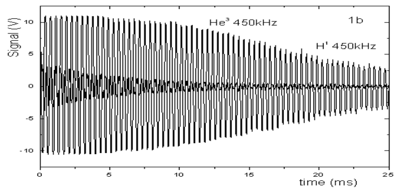
Ultra low field HP MRI

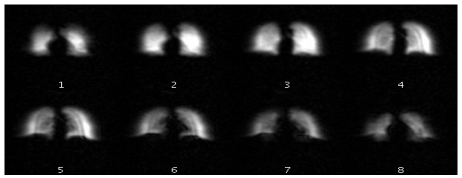


HP MR possible at very low fields:

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 ^{1}H signal – limits applications





HP 3He at 65 G

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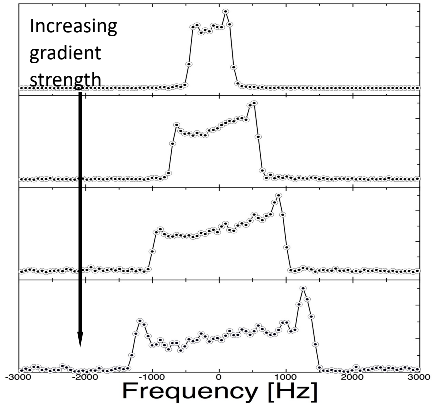
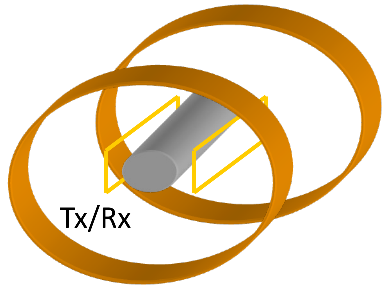
MRI of $^{3}He/^{129}Xe$ in the cell at 10G ~ 30kHz





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

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Preparing a clinical MR scanner for broad band HP nuclei imaging

Jim Wild

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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

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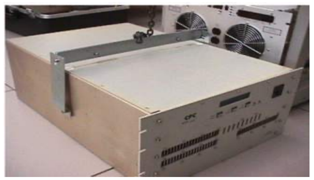
Equipment room – Broadband RF Amplifier

RF Amplifier

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



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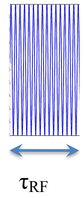
The equipment room - RF amplifier

RF Power requirements at different frequencies



Power

$$\int_{O}^{\tau_{RF}} V\cos(\omega t) I \sin(\omega t).dt$$

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

Flip angle

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

A 'broadband' RF amplifier should deliver at all frequencies

RF amplifier linearity

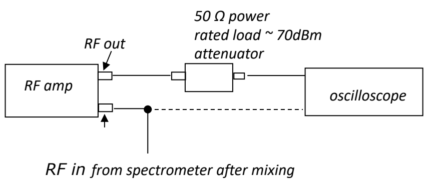
HP acquisitions need to operate with:

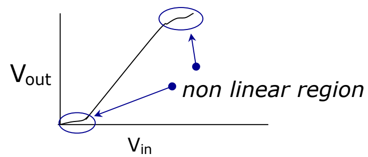
(i) very low F.A:

- e.g. 3D spoiled gradient echo imaging

& (ii) high F.A.:

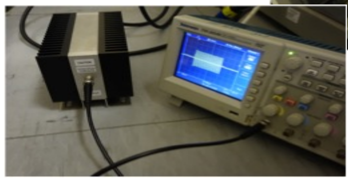
- e.g. ^{129}Xe dissolved phase spectroscopy – lung coil 90° FA





Checking RF amplifier linearity

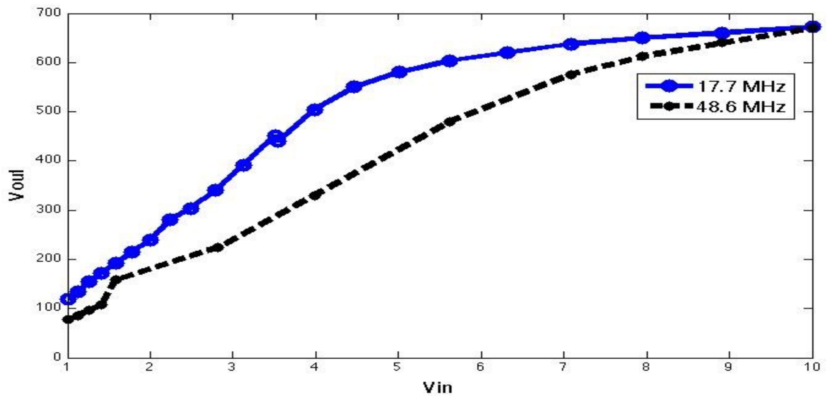
Power rated 50 Ω load
70 dB attenuation



2kW broad band RF amplifier out

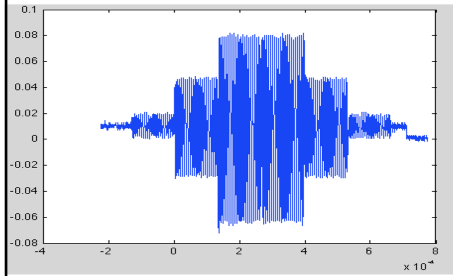
– checking the output

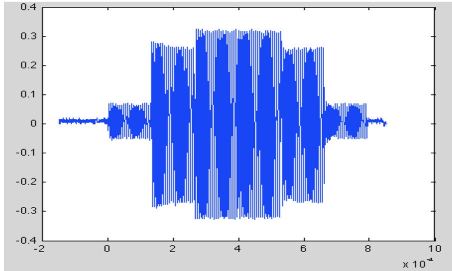
RF amplifier linearity



Gain can behave very differently across frequency range

RF amplifier linearity
– compression of pulse at high transmit gain





TG = 0 **TG = 200**

Composite RF pulse at 17.7 MHz

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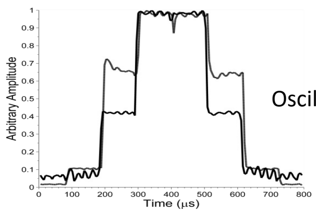
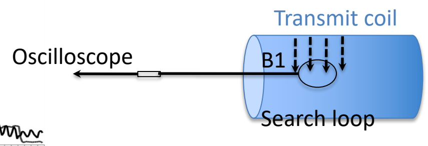
RF amplifier linearity

- Search loop method – measure induced EMF





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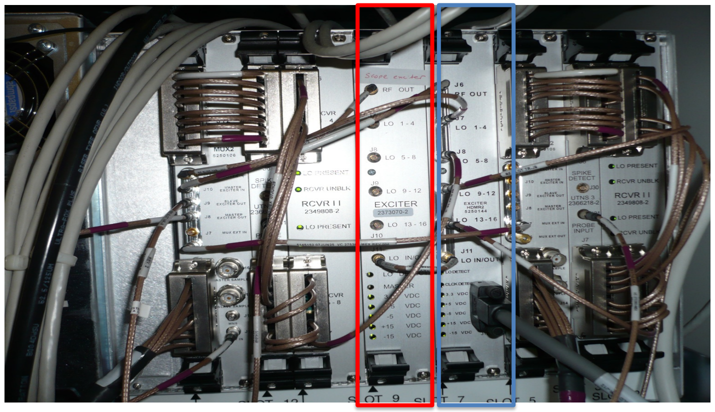
Equipment room – exciters & receiver boards



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

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

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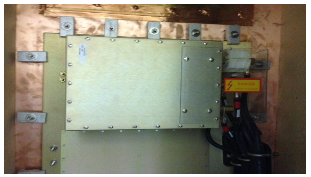
Equipment room – gradients

- 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 cm²/s, in air) on a clinical system (33 mT/m)
- Gradient cable filters

not always tuned for non ^{1}H frequency



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The magnet room

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

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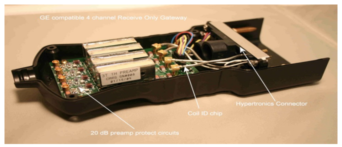
Transmit-Receive (T-R) switch

- 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



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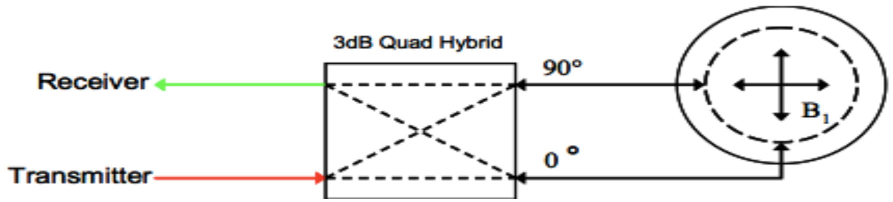
Quadrature hybrid

- Can act as T-R switch

– high isolation between transmit and receive



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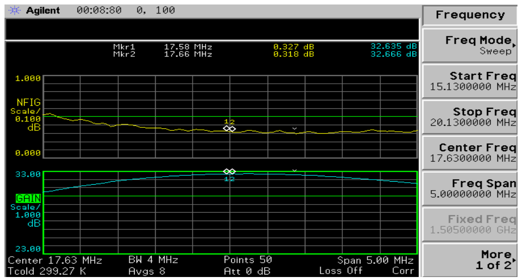
Preamplifiers

- 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 ~ 30 dB Gain

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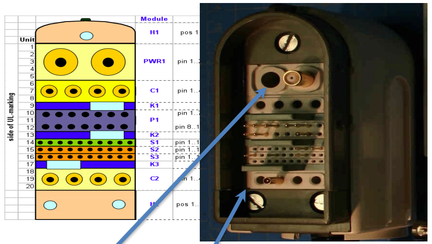
RF interfacing



Tx out 4kW MNS

Single Rx in
(4-6 ch available)

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

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RF coil considerations for HP MRI

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

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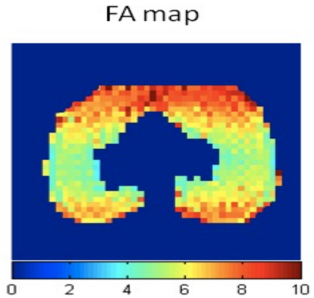
RF coil transmit receive sensitivity vs homogoneity?



- "Coat hanger" RF coil ok for first steps
- Need better B1 homogoneity and volume coverage for good in-vivo HP imaging …

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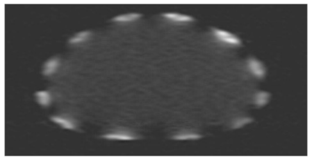
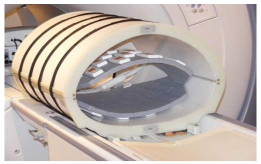
RF transmit homogoneity – birdcage coil

✓B1 homogoneity
✓spacious
✓ space for Rx array
✓ quadrature easy

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





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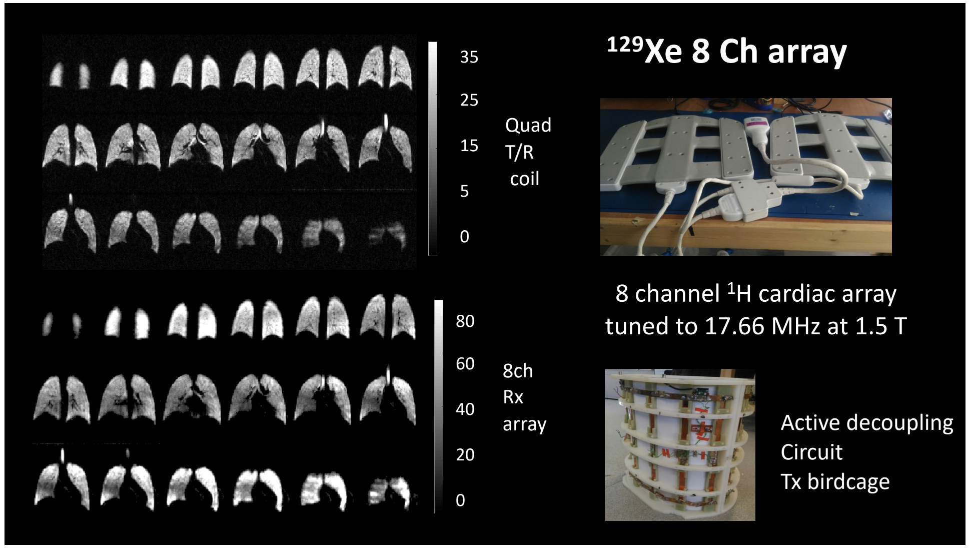

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Flexible T-R coils

✓Closer fitting:

Rx and Tx sensitivity

- good coupling to sample (Ql/Qu)
- power efficient

✓Better filling factor, η

✓Cheap, light, portable

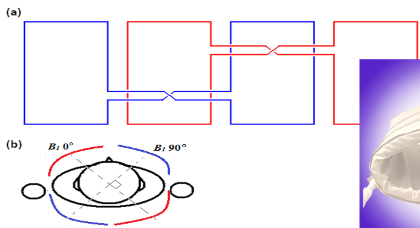
✓Smaller coil – less coupling to ^{1}H body coil and trap

✗ B1 homogeneity

✗ Flex geometry more prone to changes in

✗ High SAR near conductors

✗ Limited space for Rx array



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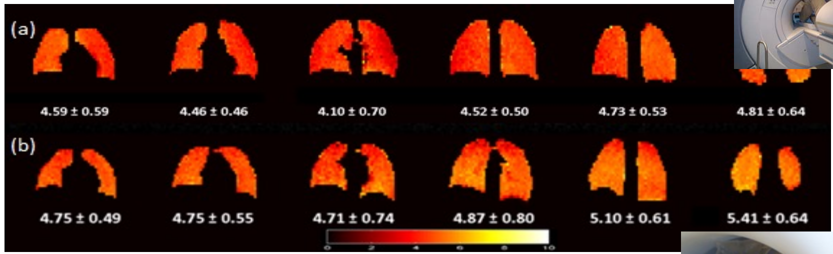
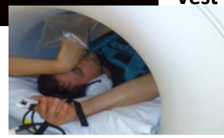
RF transmit homogoneity - ^{129}Xe



Birdcage

Vest



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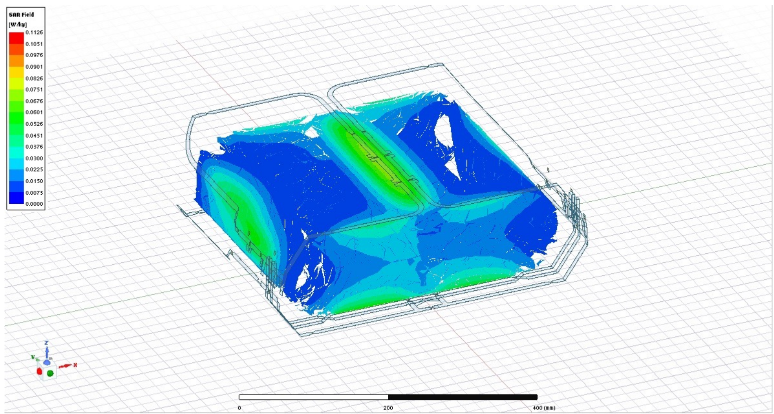
SAR considerations for all coils



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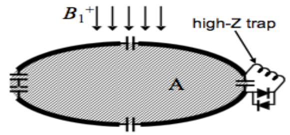
RF coupling and detuning interactions with ^{1}H body coil– birdcage coil



HP nucleus transmit-receive coil

Needs S21 isolation from 1H body coil

- Vital for good ^{1}H 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)

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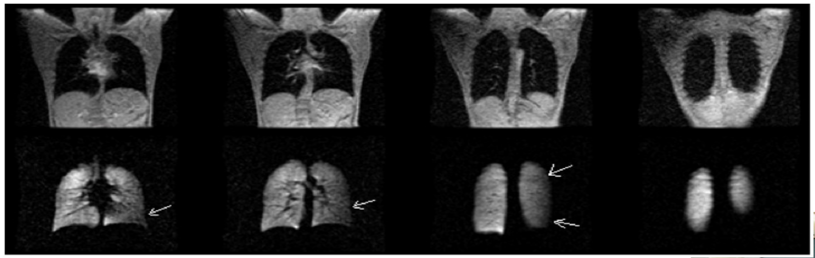
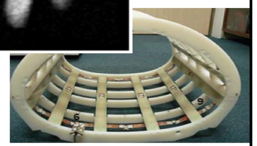
RF coupling and detuning interactions with ^{1}H body coil– ^{129}Xe birdcage coil





Interaction with 1H body coil causing B1 inhomogoneity

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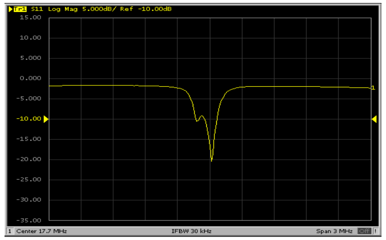
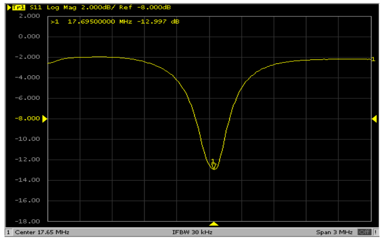
RF coupling between ^{1}H body coil X nucleus coil





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

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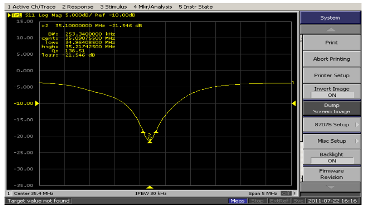
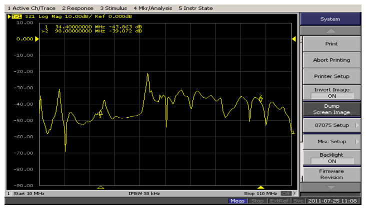
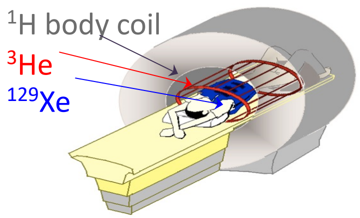
Simultaneous multi nuclear MRI



S11 ^{129}Xe coil





S21 ^{129}Xe – ^{3}He coils   S21 < -35 dB

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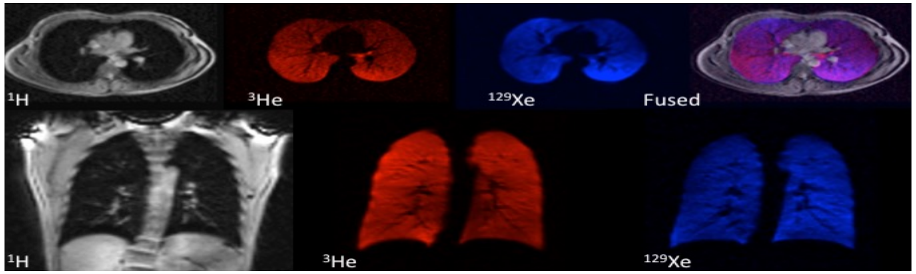
$^{3}He^{129}Xe^{1}H$ lung MRI - same breath



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

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

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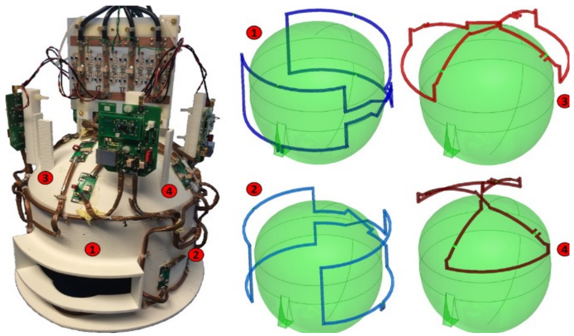
Array coils – N elements versus wavelength



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The spectrometer

- Pulse sequence conversion and programming for MNS/imaging (vendor specific)
- Disable any ^{1}H functionality that might destroy magnetisation

- prescans, gain calibration, auto shimming, dummy scans

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First experiments

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

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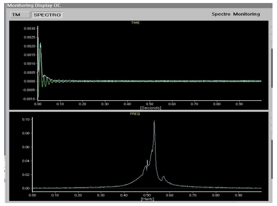
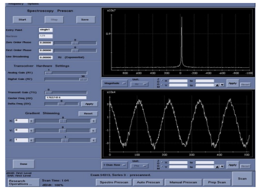
First experimental steps- finding the NMR signal

Thermal phantom



^{3}He / ^{129}Xe gas cell 2bar with 1 bar O_2
– shorten T1 to seconds from hours
(T1 proportional to 1/[O2]) T1 129Xe in air ~ 20s
^{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

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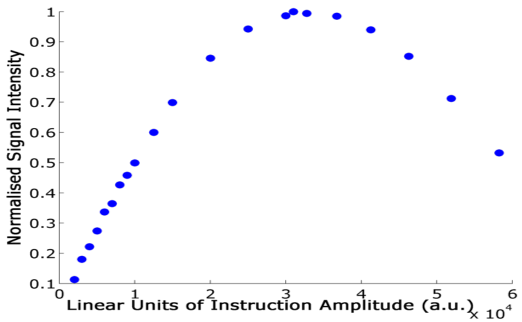
calibrating transmit gain

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

Fit signal to sin(α)



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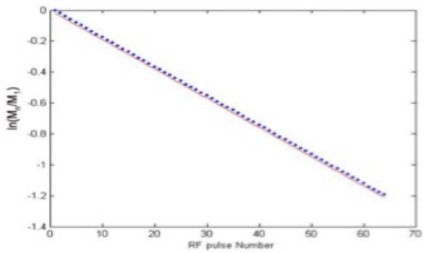
calibrating transmit gain: HP sample

- Perform series of gradient spoiled pulse-acquires

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



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

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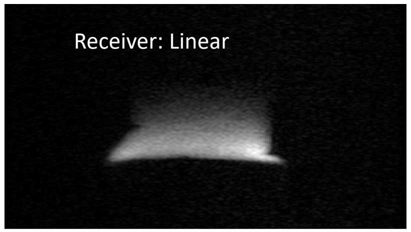
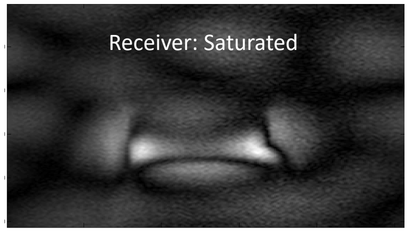
Receive gain setting

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





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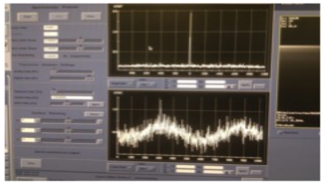
Unwanted noise sources



Unfiltered noise at non ^{1}H frequencies:

Coherent **constant frequency** noise

Gradient power supply, and rapid pulsing of gradient coil generates high frequency noise

- filters in penetration panel tuned to block harmonics @ ^{1}H f_0

Add ferrite chokes to gradient power cables

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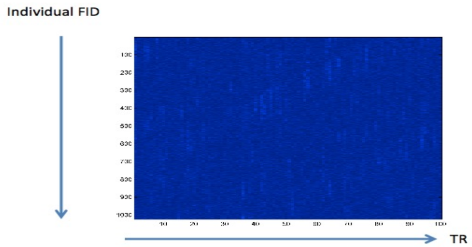
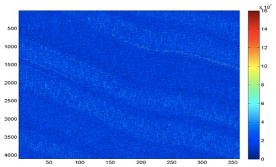
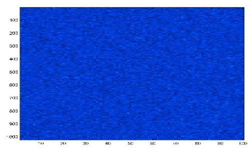
Spike/'splat' gradient noise



Cfxfull=cfyull=cfzfull=0



Power off Gradient Amplifiers



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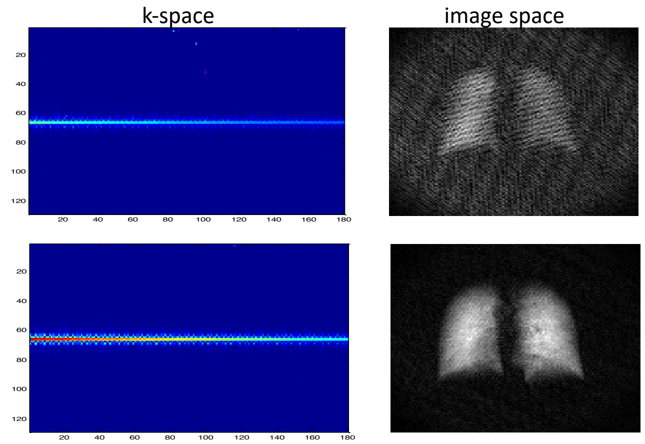
RF coil breakdown - noise spikes



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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

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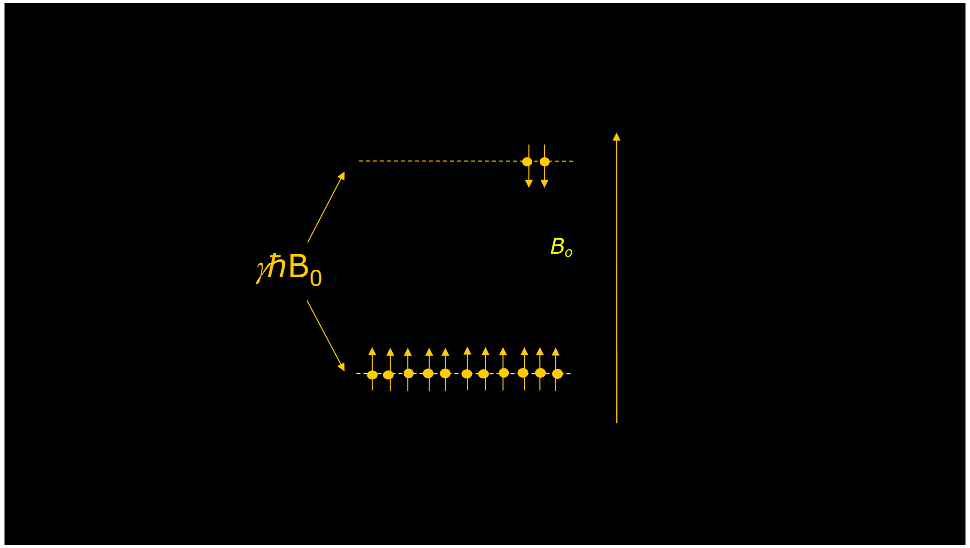

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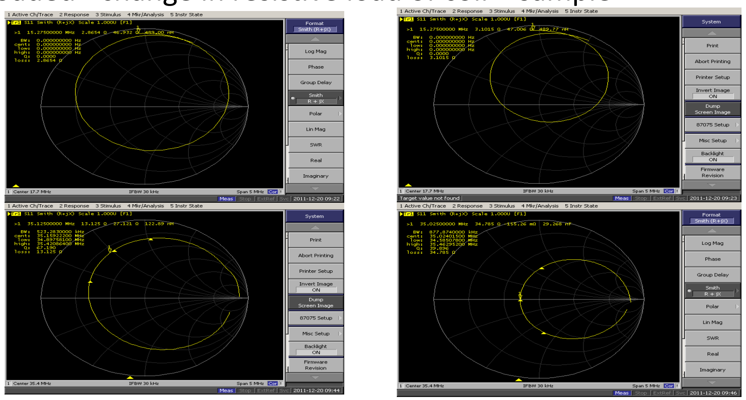
RF coil loading

Matching of coil should improve – measure S_{11} unloaded and loaded - change in resistive load of coil + sample



1.5T
17 MHz

3T
35 MHz

unloaded | loaded

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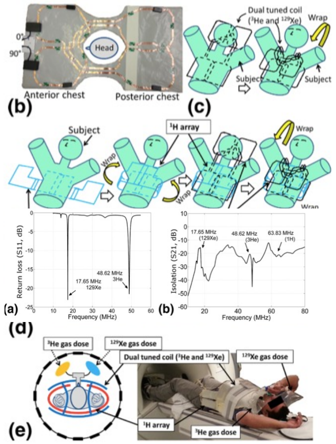
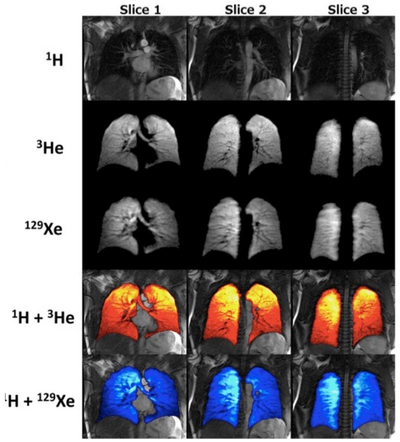
Same-breath imaging of ^{1}H / ^{129}Xe / ^{3}He





Magn Reson Med (2015).

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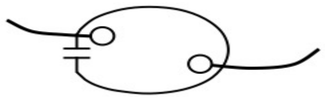
RF coil loading

Resonator Q : ratio of stored – dissipated energy

$$Q = \omega L / R$$

Q_{unload} / Q_{load} gives indication of effective coupling – better coupling to the sample and to **Mxy**

Measure Q with S21 – two port method



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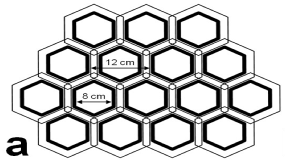
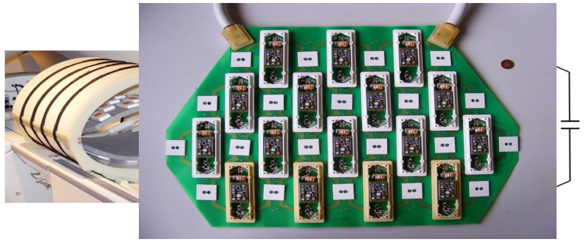
Multiple receiver arrays - 32 ch ^{3}He Array coil





- 2 × 16 channel array of hexagonal elements and shields on flexible PCB
- Decoupling between elements by concentric shields [1] and preamp decoupling [2]
- Active detuning during transmission

collaboration with Rapid Biomedical

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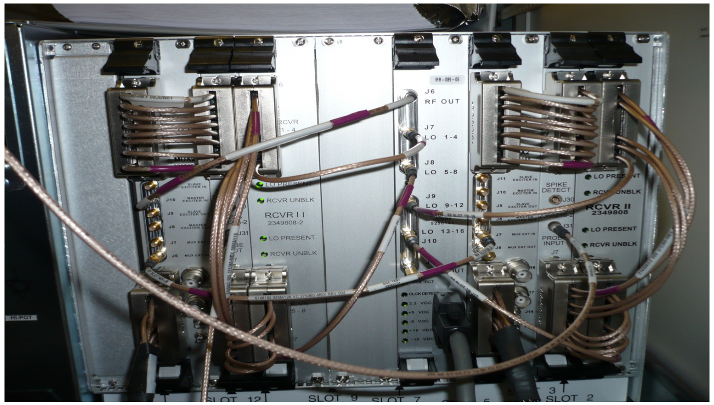
Additional exciters – 32 ch MNS



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