in magnetic resonance spectroscopy

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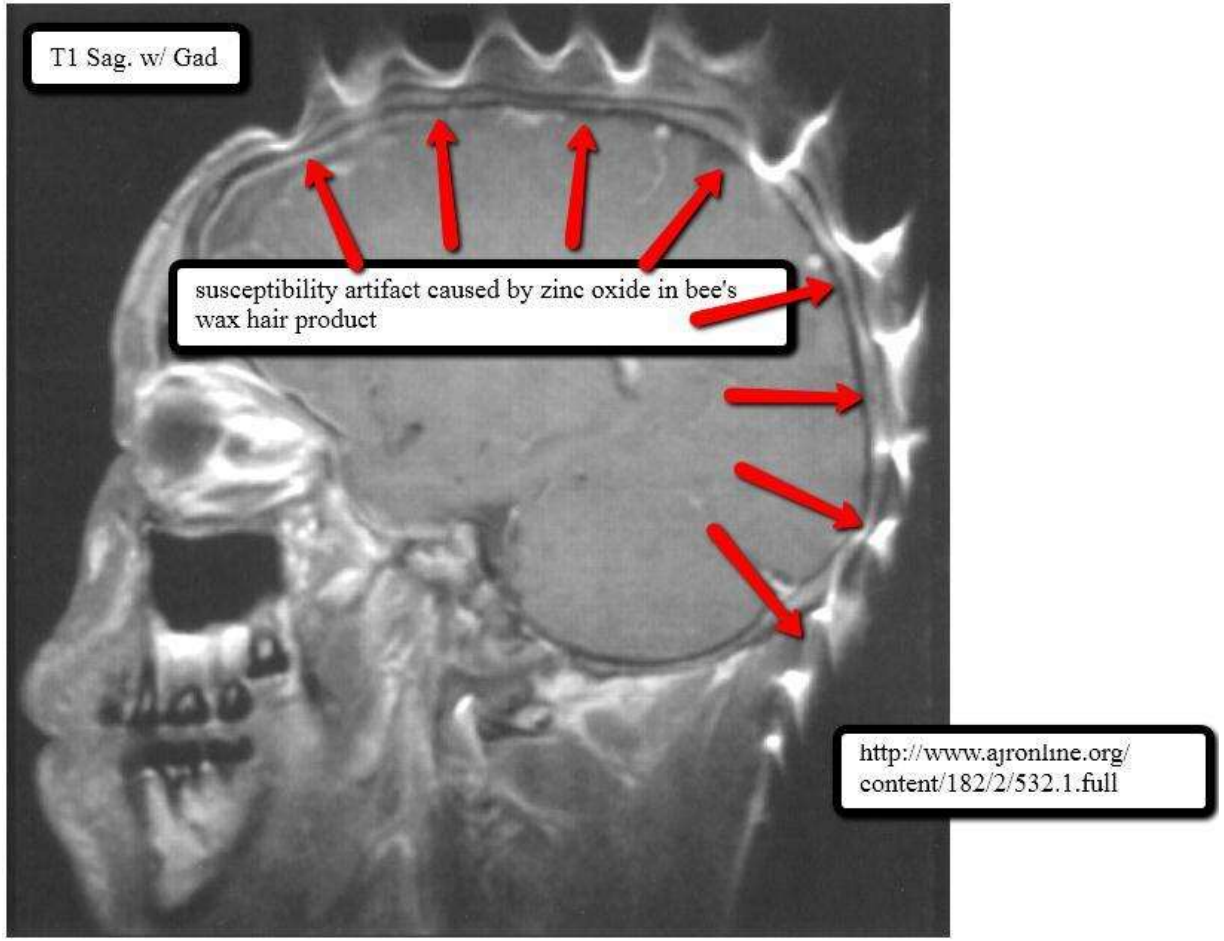
GE HealthCare

Overview

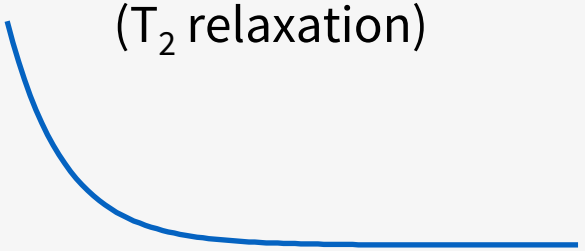
- Lineshape
- Solvent signal
- Baseline
- Phase
- Chemical-shift displacement
- Eddy currents
- Truncation
- DC-Offset
- RF interference
- Frequency drift
- Receiver gain
- Spike noise
- Gradients
- Motion artefacts
- Radiation damping
- RF coils
- SNR
- Discussion and conclusion



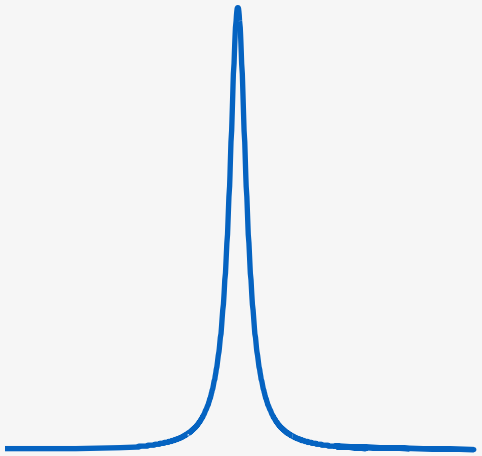
Lineshape

Lorentzian

Exponential decay
(T_2 relaxation)



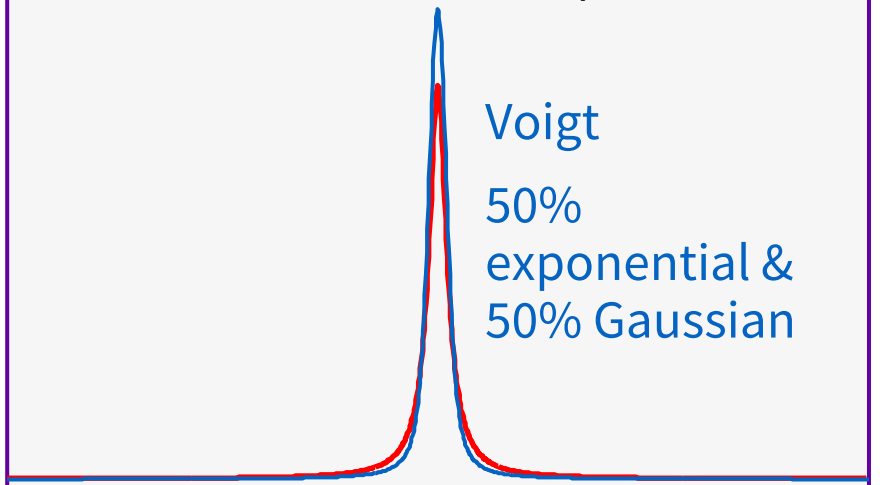
Lorentzian lineshapes



Voigt

(Partly) Gaussian decay (T_2^*)
Multiplication of Exponential with Gaussian decay

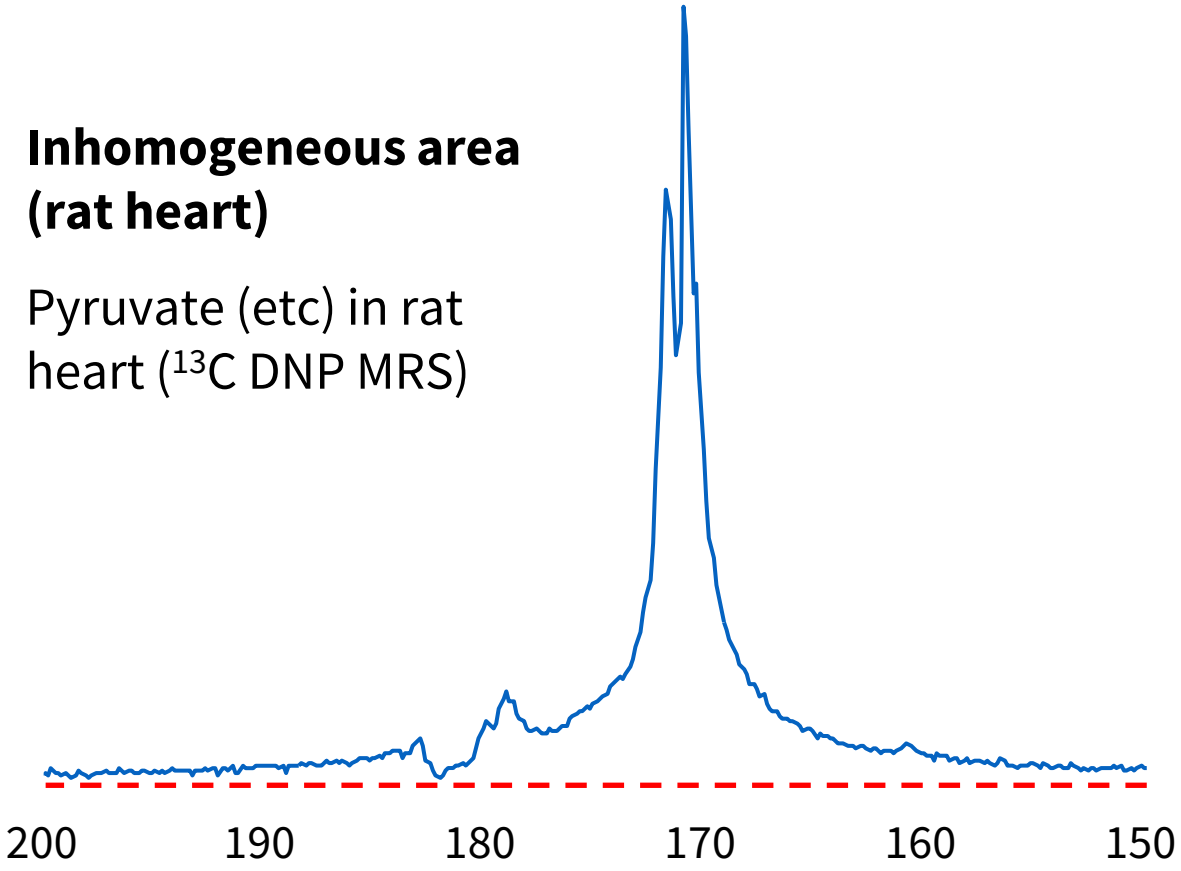
Voigt lineshape:
Convolution of Lorentzian with Gaussian lineshape



Lineshape: Peak Distortions

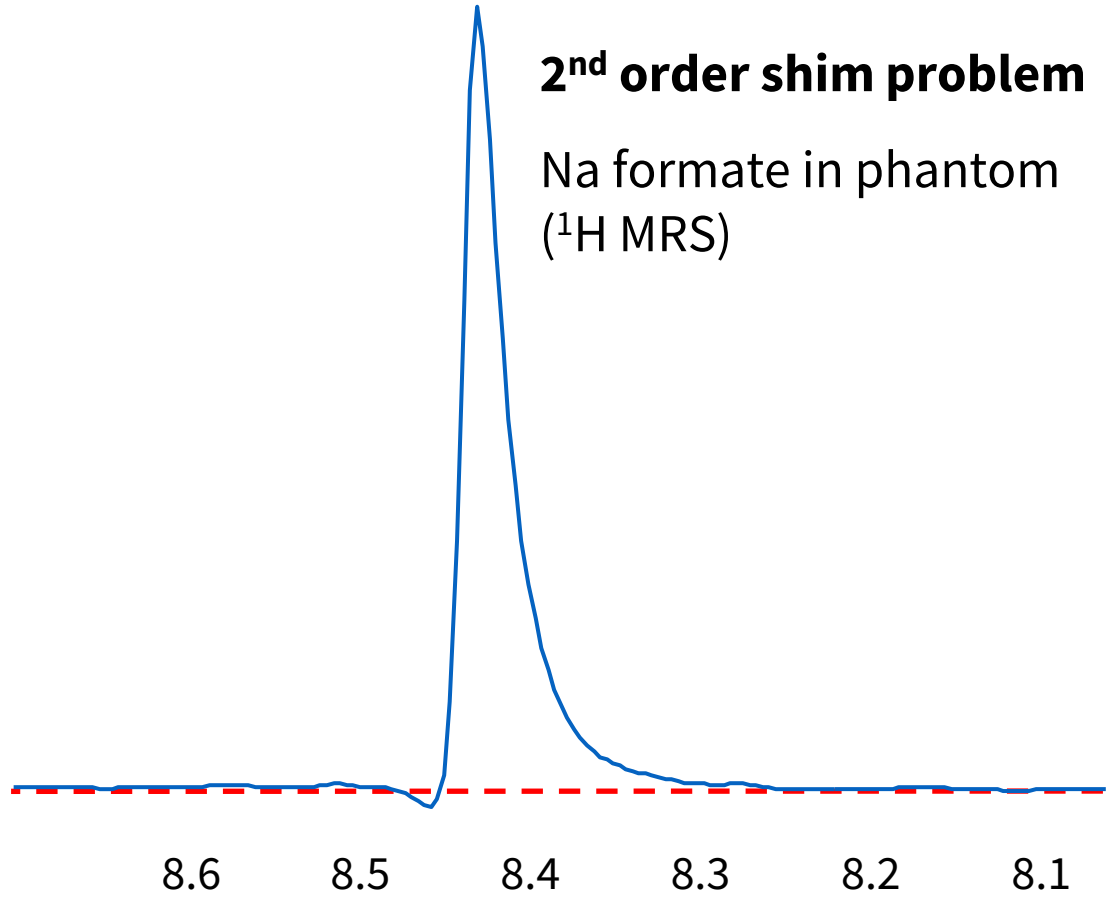
Inhomogeneous area (rat heart)

Pyruvate (etc) in rat heart (^{13}C DNP MRS)



2nd order shim problem

Na formate in phantom (^{1}H MRS)

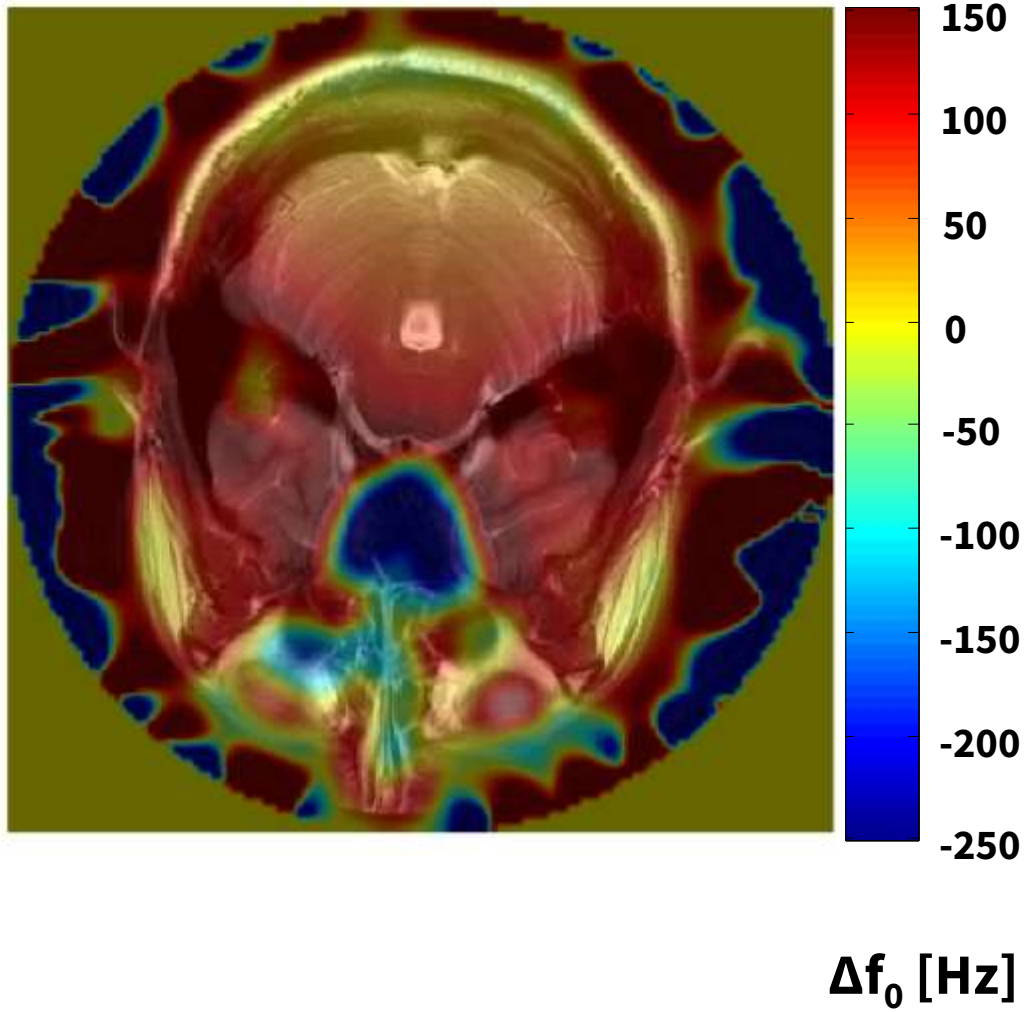


Lineshape: B0 Field Inhomogeneity

- Susceptibility differences in sample (eg: air – tissue) →B_0 inhomogeneity
- Residual scanner inhomogeneity

Remedies

- Shimming
- Choose benign regions
- Reconstruction with B_0 correction
- Lower B_0



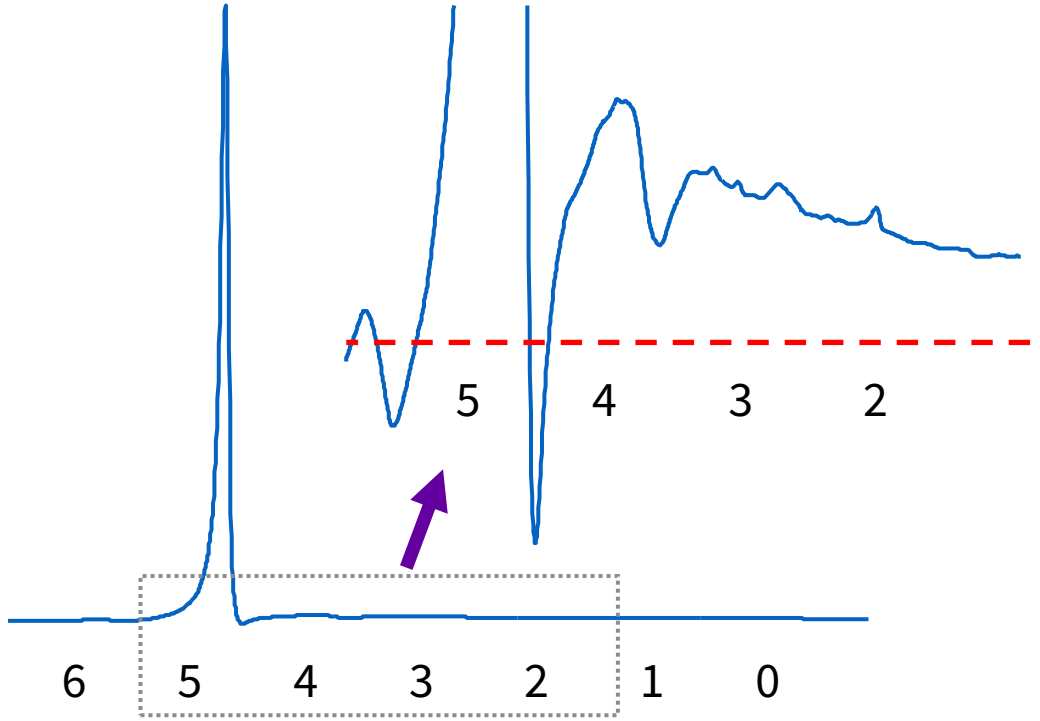
Solvent Signal

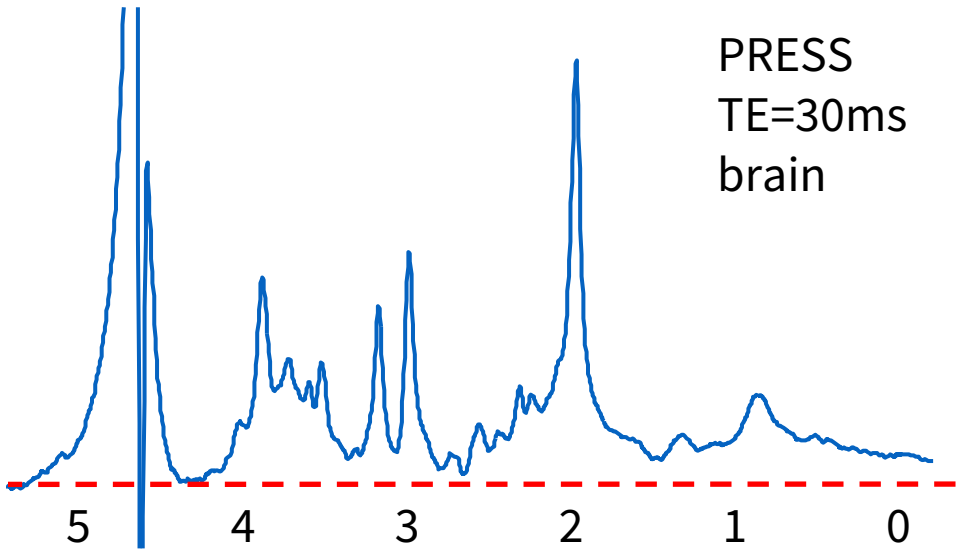
Water (+ fat): $10^5 \times$ stronger than metabolites (in 1H MRS)

→ Problems with baseline + artefacts

Remedies

- Suppression through selective experiments: e.g., CHESS: f-selective excitation of H_2O and gradient spoiling
- Removal during post-processing: e.g., HSDV



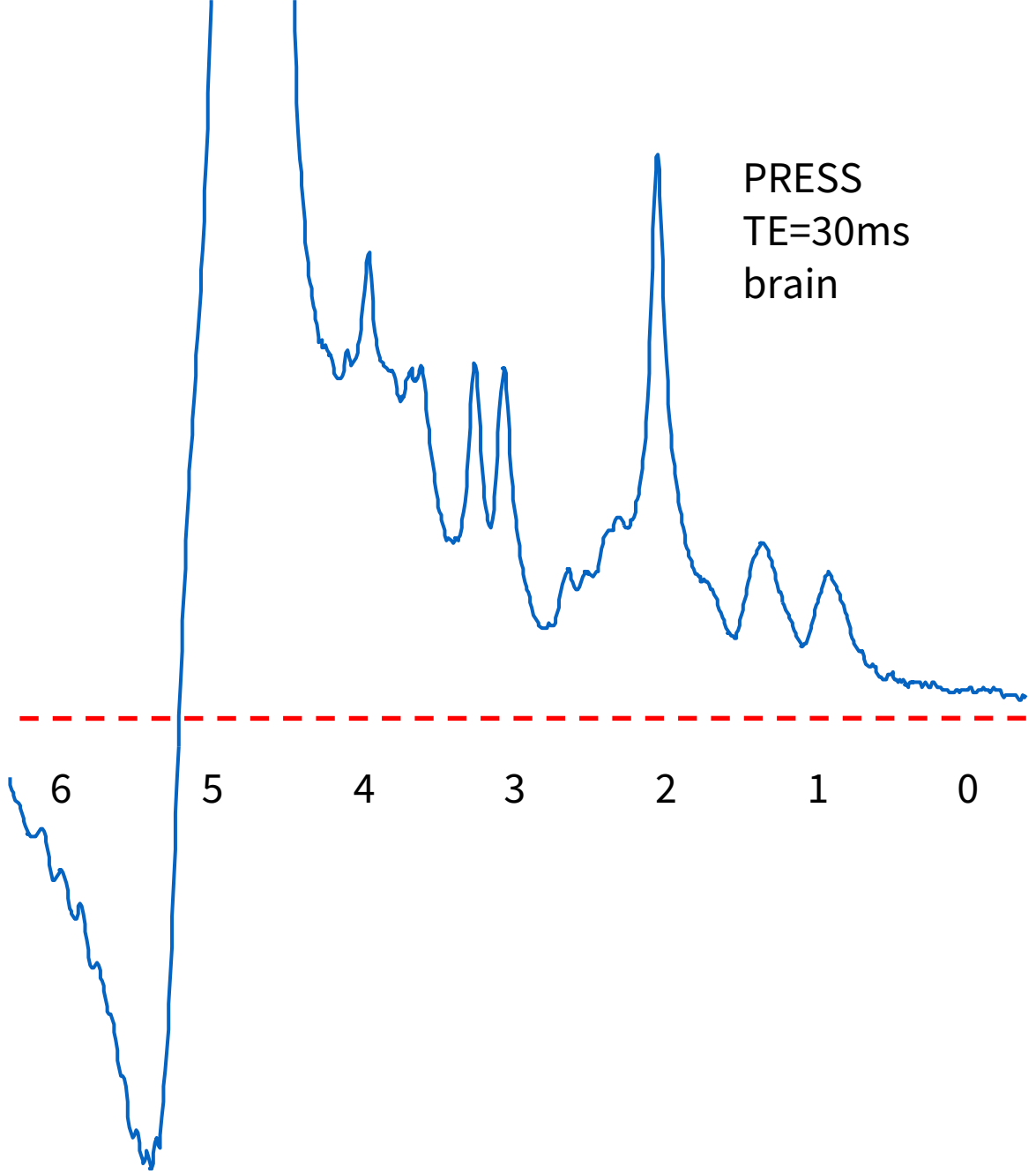


Baseline Distortions

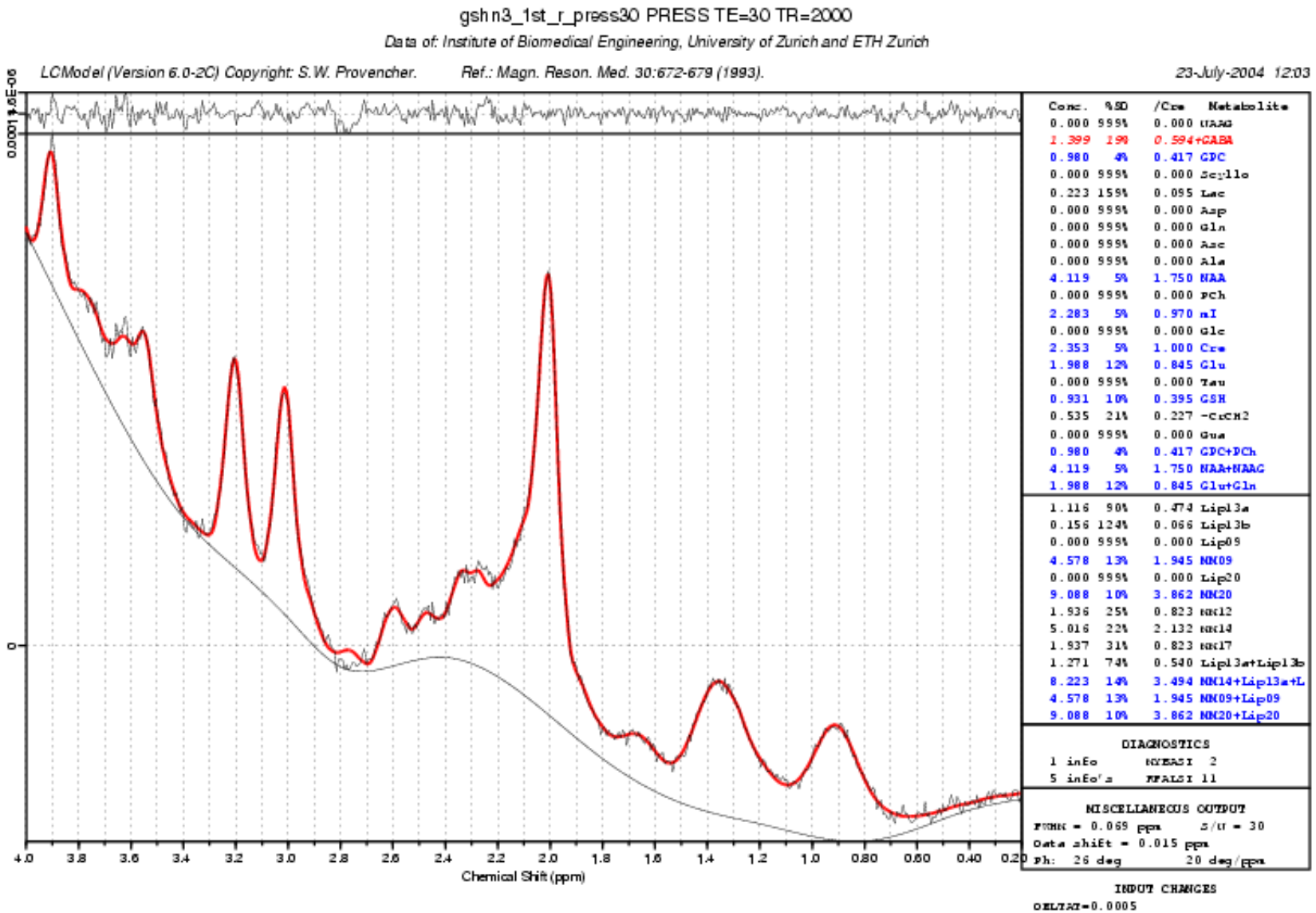
- Mostly from first few points in FID
- Fast relaxing macro-molecules
- Poor water suppression
- Quantification hampered

Remedies

- Different region
- Improve shim, H_2O/fat suppression
- f-domain: fit polynomial/ spline
- t-domain: take out first points



Baseline Distortions: Spline Fit (LCModel)



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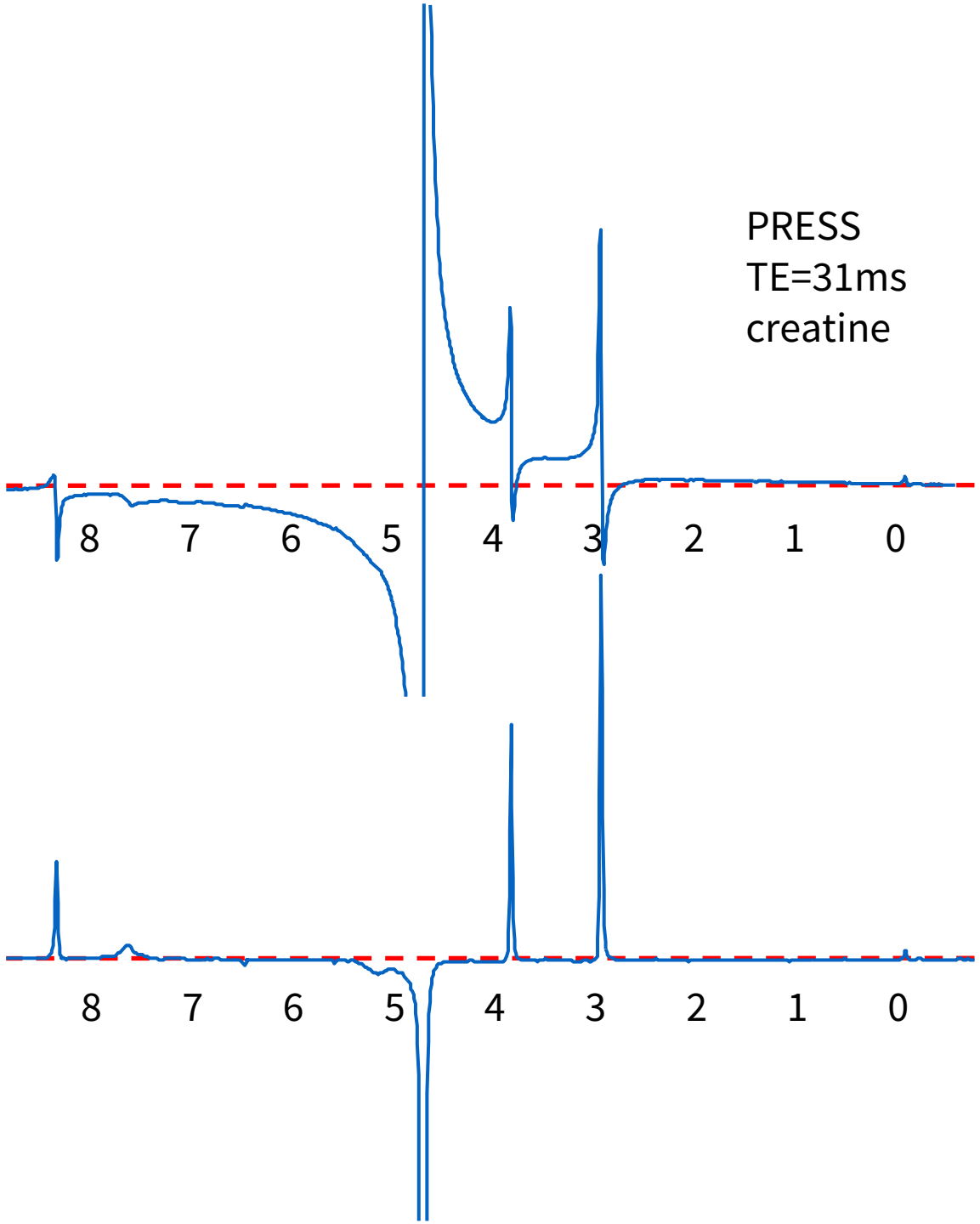
Phase Correction

- Phase of spectra generally unknown
- Zeroth order phase:
  switching of oscillator frequency
- Linear phase:
  delayed sampling start
  (e.g. fidcsi ≈ 2ms)

Remedies

- Phase correction:
  multiply FID with $\exp(i\varphi + i\omega t)$
- Large linear phase
  → correction distorts peaks
- Display magnitude
  Con: broader peaks

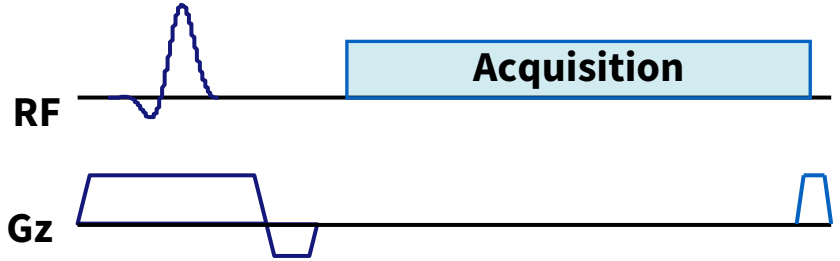


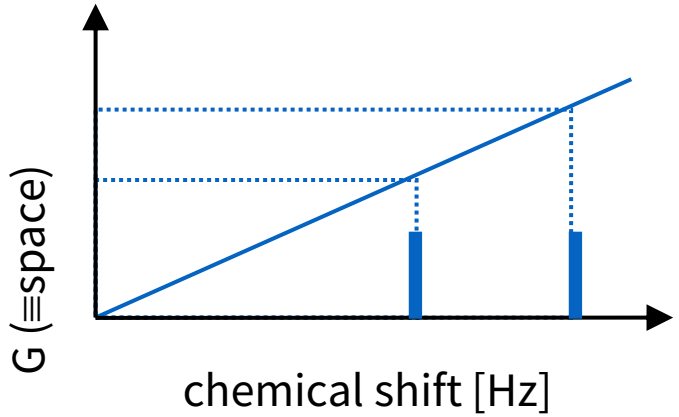
Chemical-Shift Displacement

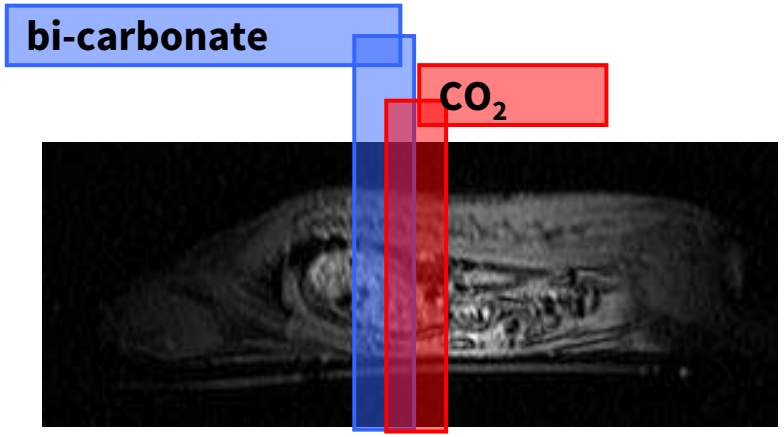
- Bandwidths (BW) of RF pulses limited
- Gradients (gmax) for localisation limited
- Molecules with different chemical shifts are displaced
- 13C Example:
  Bi-carbonate (161 ppm) & $^{13}CO_2$ (125 ppm)
  → Δf = 1200 Hz (B_0=3T)
  BW RF = 2200 Hz → ½ slice displacement
- 1H MRS Example:
  Lactate A_3 (1.3ppm) & X (4.1ppm)
  → Δf=360Hz (B_0=3T)
  BW RF = 800 Hz → ½ voxel displacement

Remedies

- Centre f_0 in between
- Increase gmax/RF BW
- Use spectral-spatial pulses
- Reduce gmax/RF BW and utilise displacement for encoding
- Broadband pulses







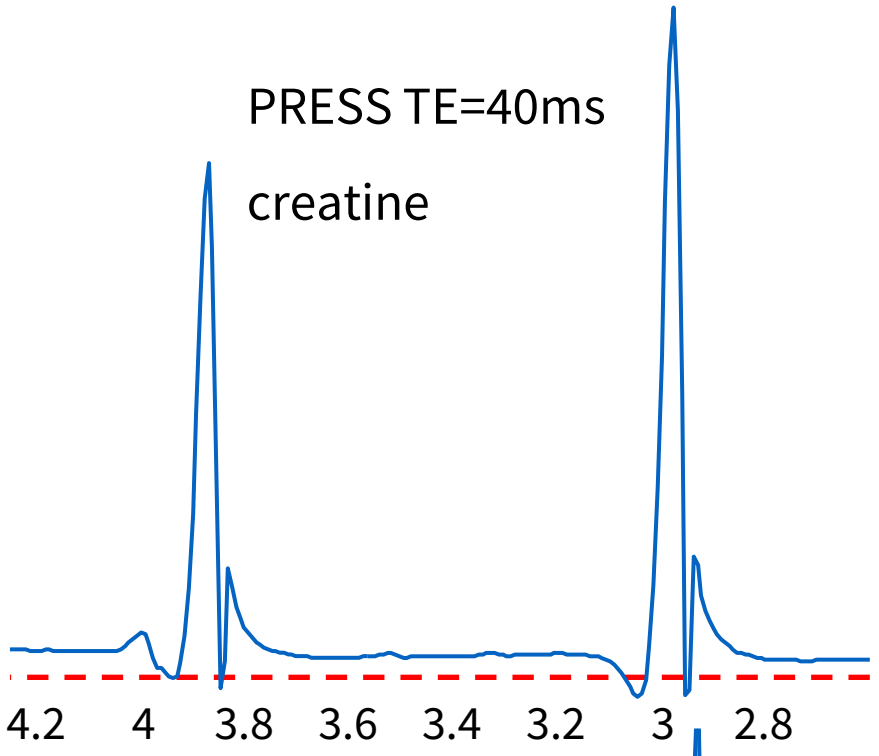
Eddy Currents

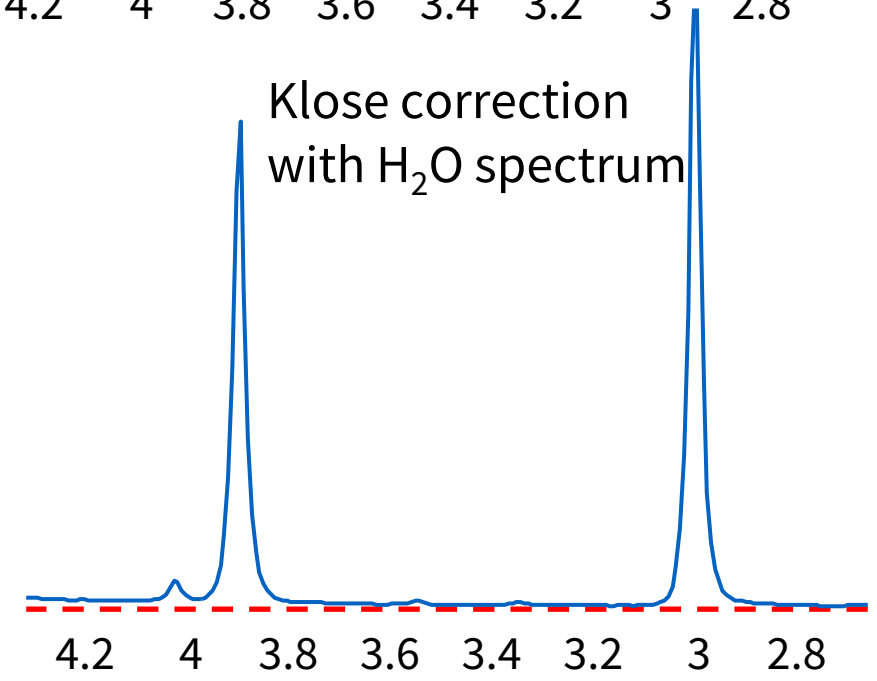
Conductive material in scanner
→ induction of eddy current

- Additional gradients (time + space dependent)
- Distorted lineshapes
- Intricate compensations already existing (optimised hardware + gradient pre-distortion)

Remedies

- Use robust encoding methods *(eg Cartesian trajectories)*
- Derate gradients
- 1H MRS(I): division of phase of FID by reference *(eg Klose correction)*
- Measure distortion and correct for in reconstruction *(eg Dyun method, gradient monitoring with field probes)*





Eddy Currents: f0 Modulation in MNS

Eddy current compensation (“grafidy” on GE) consists of

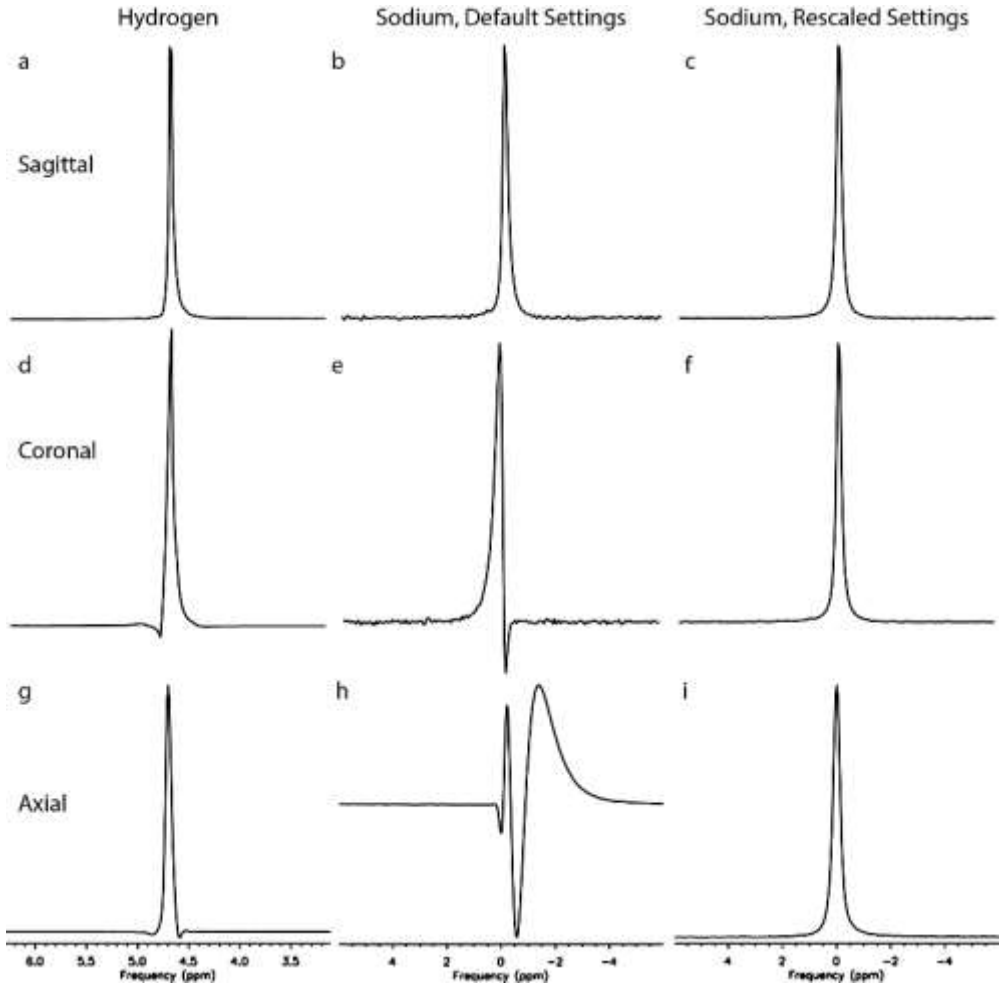
- Pre-emphasis of gradient waveforms fed into gradient amps
- Modulation of centre-frequency f0

Model coefficients determined via measuring response to gradient pulses with gradient probes at different spatial positions

Problem with MNS: f0 modulation relative to 1H freq
→ overcompensation for other nuclei

Remedies

- Modify calibration files for MNS (not recommended)
- Upgrade to MR30 (fixed in product now)



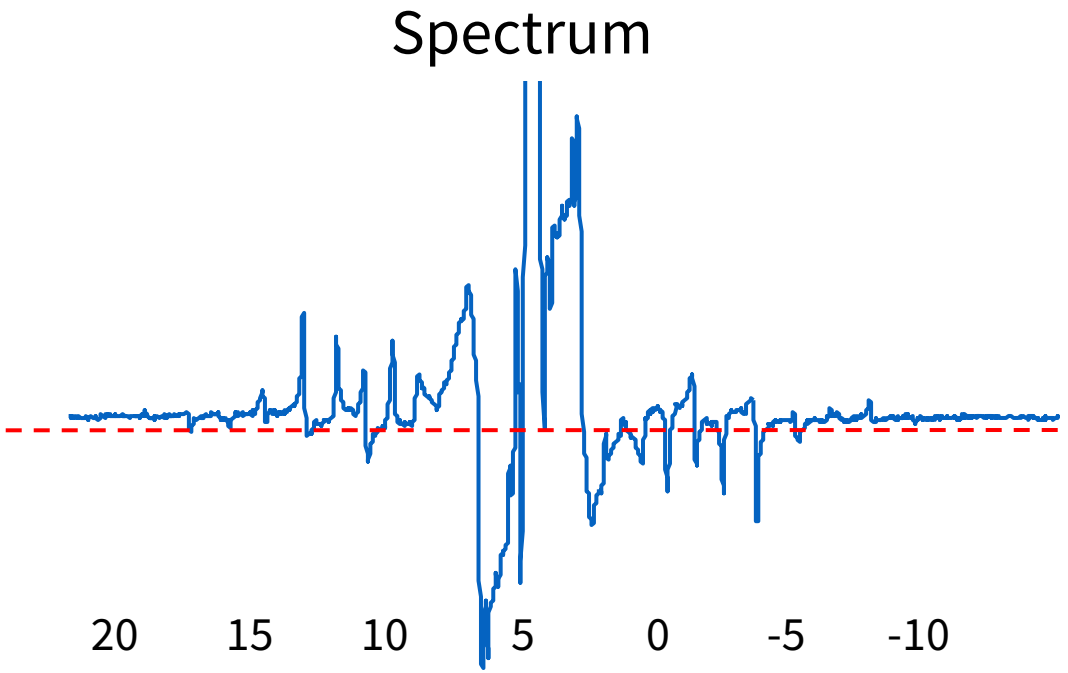
Courtesy to Mary McLean, Cambridge

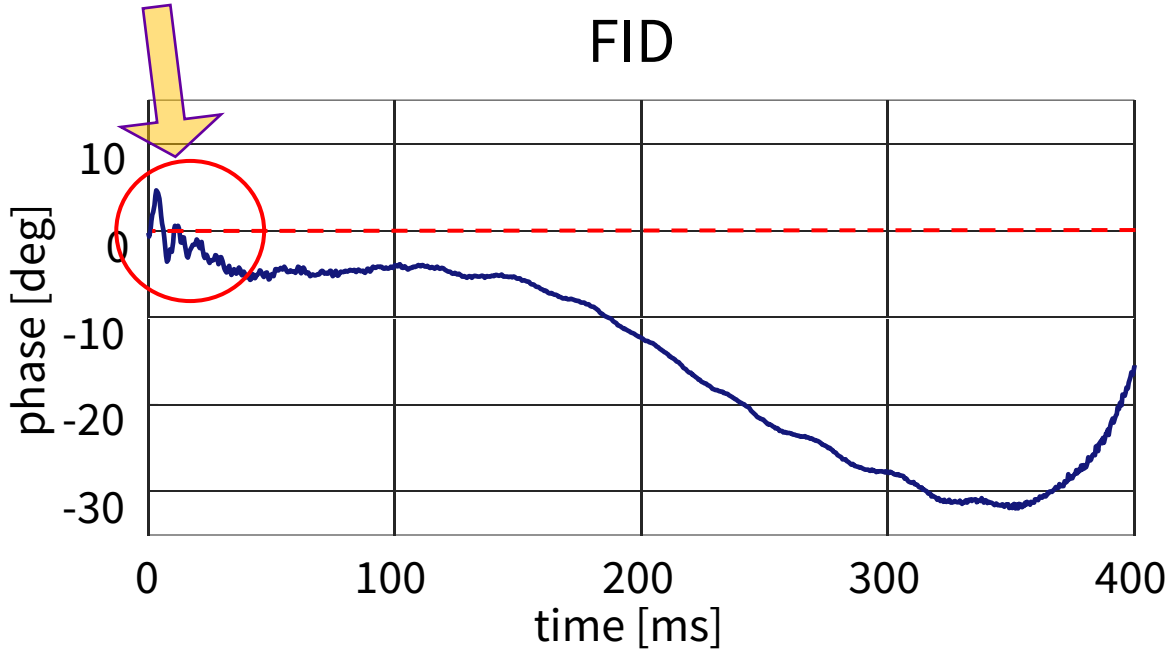
Sidebands

- Gradient vibrations
- Cyclic eddy currents
- Strong solvent signal

Remedies

- Better water suppression
- Hardware modifications:
  mount gradients centric + better
- Post-processing:
  correct with reference signal, model-based removal





R Hurd, MRM40, 343-347 (1998).

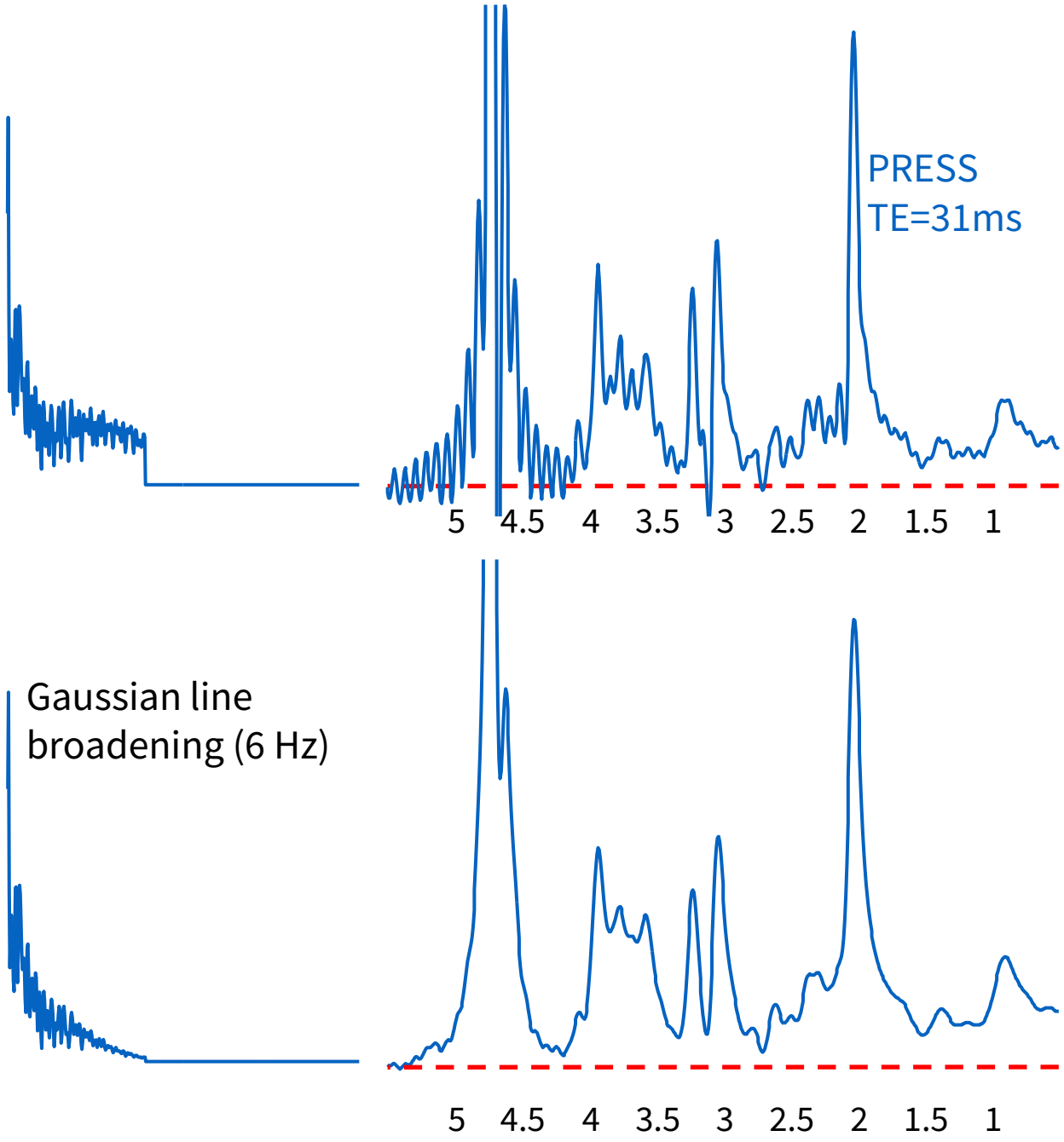
Truncation Artefact

Too short sampling

- Step function
  → sinc wiggles

Remedies

- Longer sampling
- Filtering
- Linear prediction/ maximum entropy

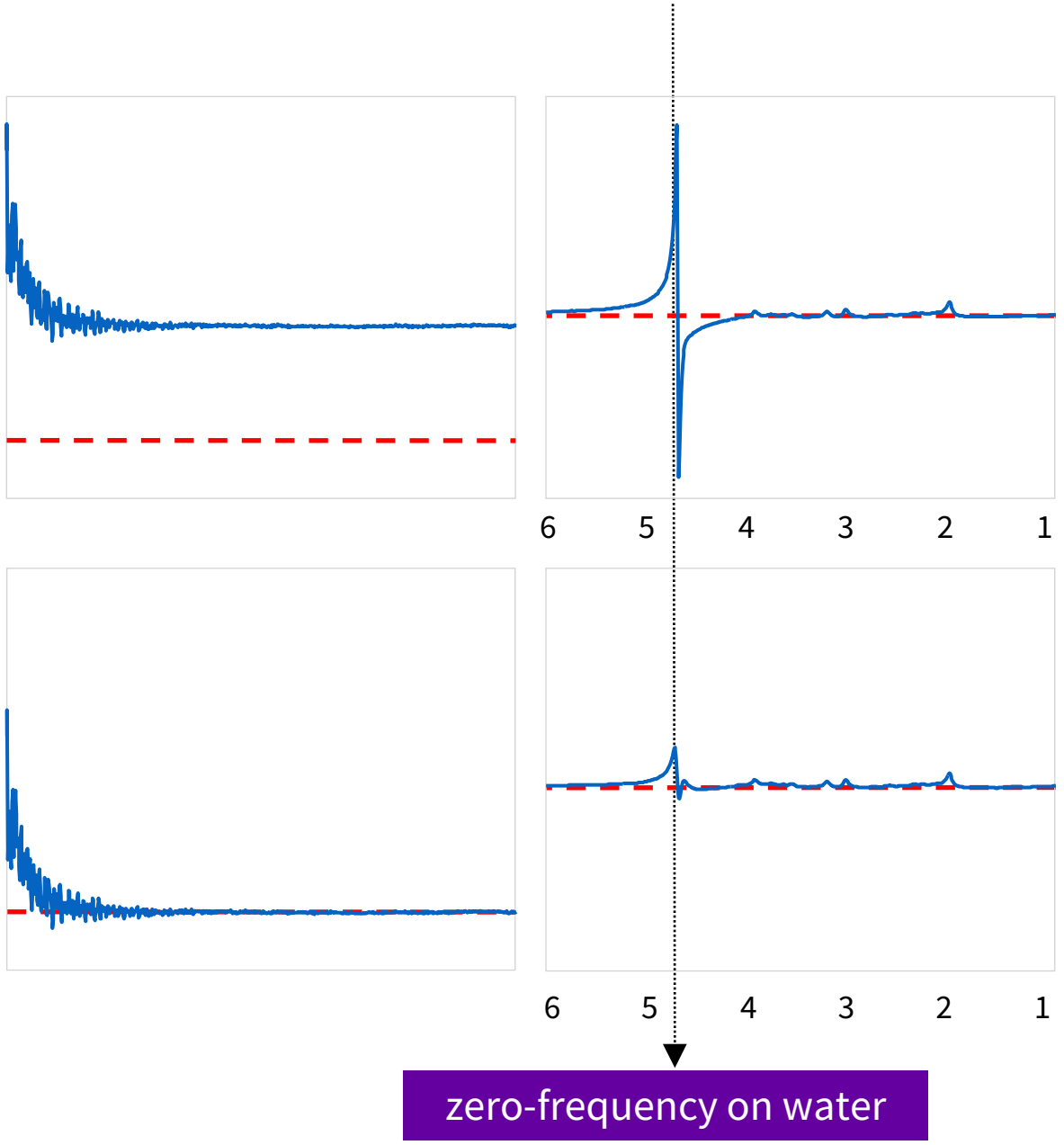


DC Offset

- Decay to constant
- Delta peak at zero-frequency

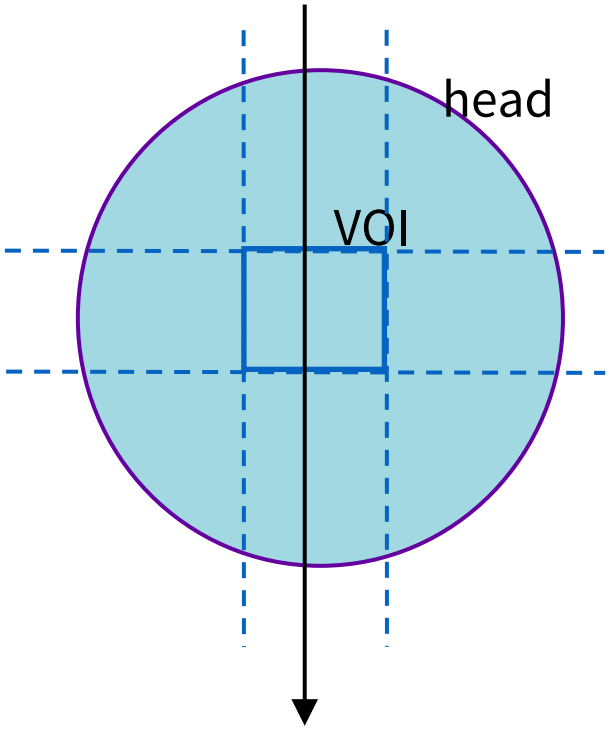
Remedies

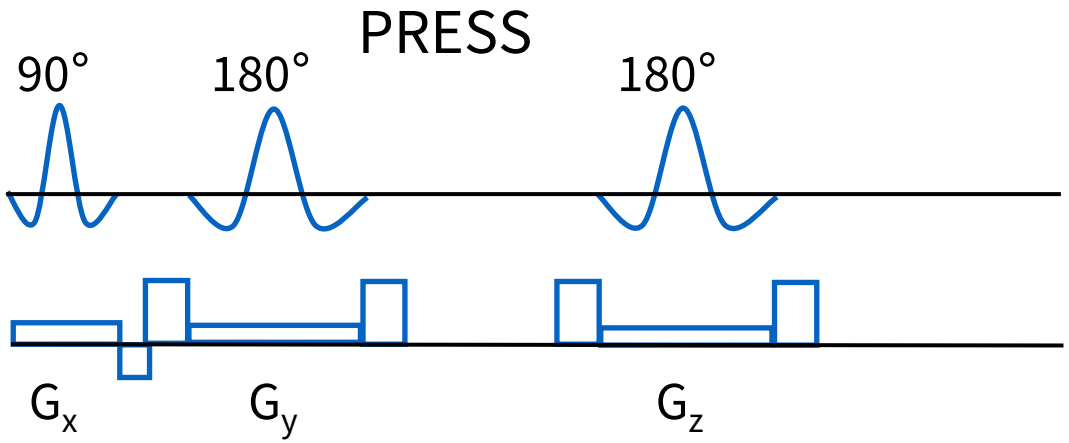
- Phase cycling
- Subtract last 10% of FID

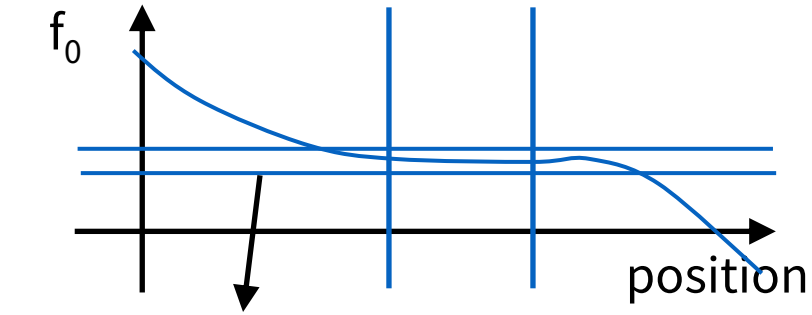


Ghosts

- Insufficient water suppression outside VOI
  → huge water signal
- Small imperfections of 180° pulses + insufficient spoiling
  → generation of echo outside VOI
- Especially with 2nd order shimming





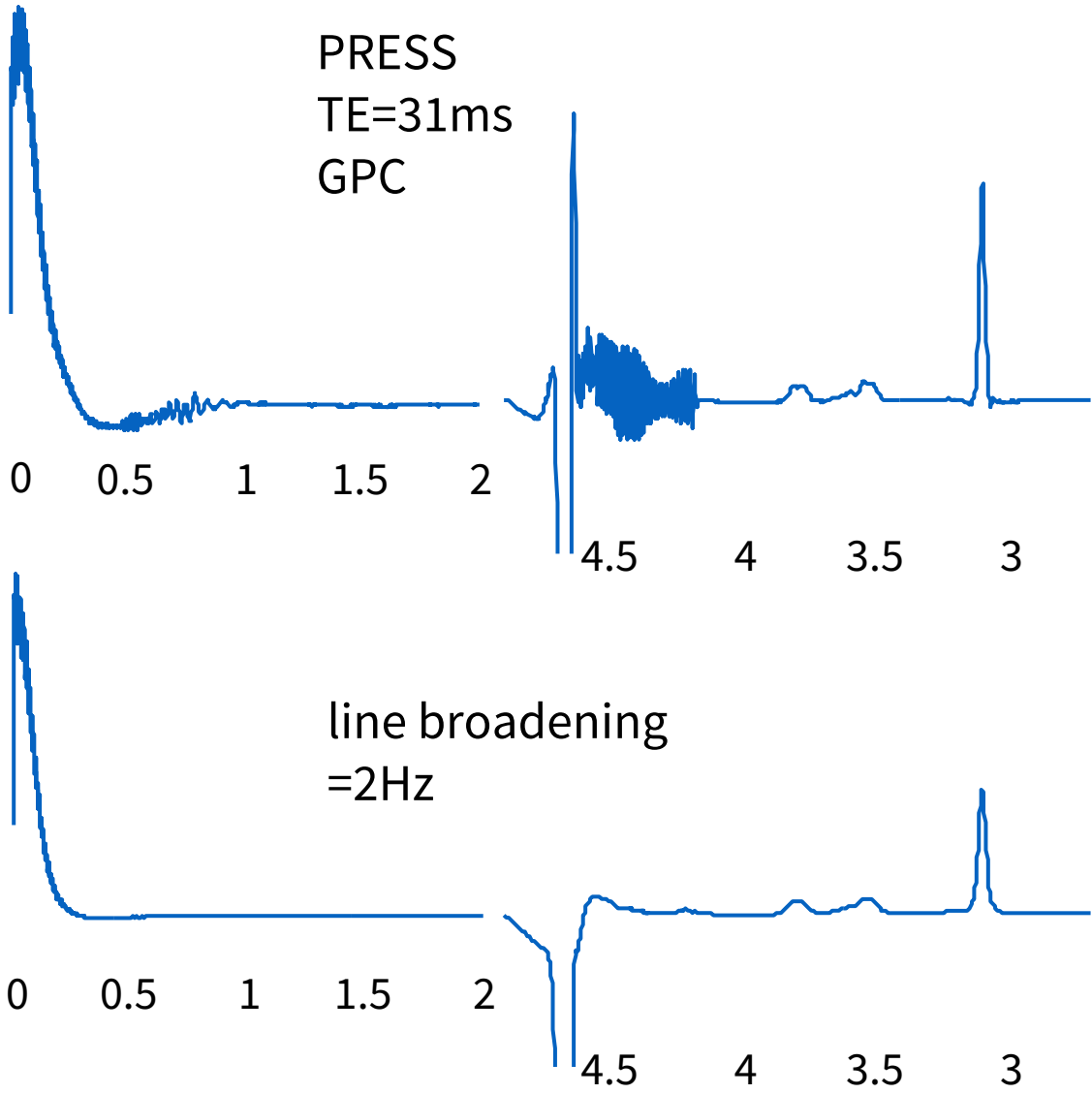


f-selectivity of H_2O suppression pulse

Ghosts

Remedies

- More crusher gradients
- Phase cycling
- Wider f-selectivity
- Less 2nd order shimming
- Filtering
- Different angulations



RF Interference (Frequency Domain)

Additional RF signal

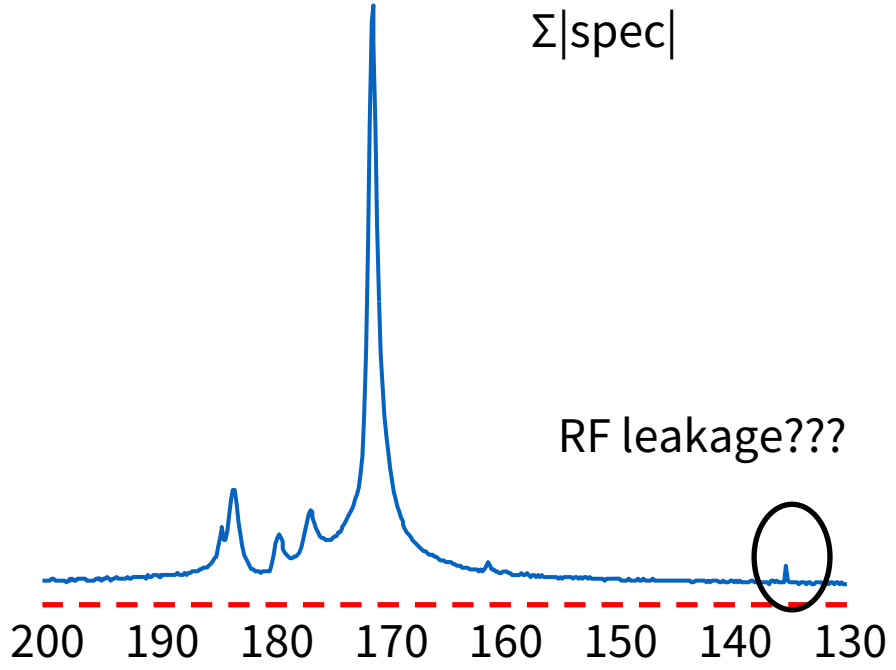
- Reception in RF coils
  → interference with measurements
- Leakage through RF cabin
  → Shielding of room interrupted
- Bad equipment inside room: injection pump,…
- System components emitting noise: gradient amplifier, RF amplifier, power supplies, receive electronics, local oscillators, displays, …

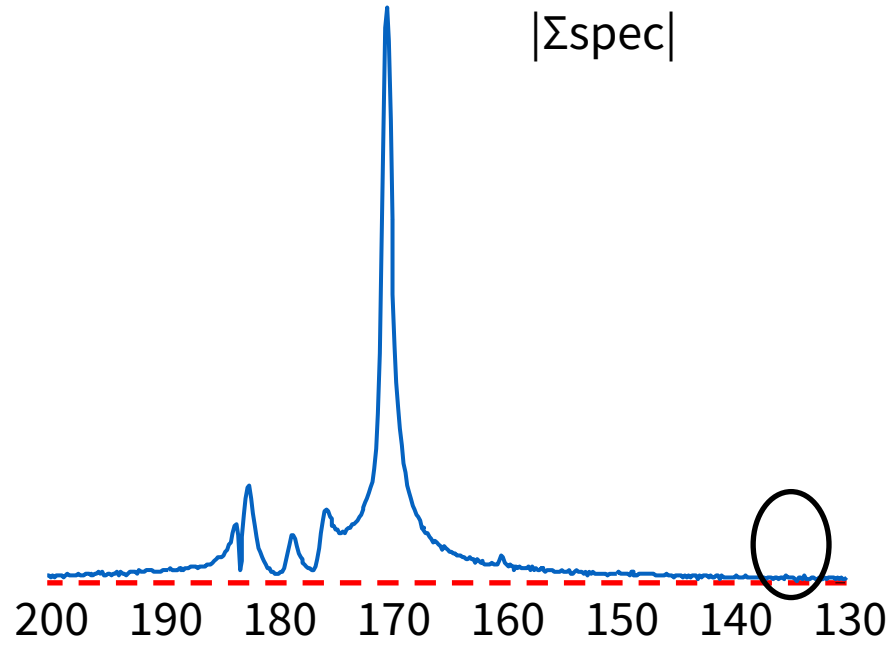
MRI scanners developed and optimised on 1H frequencies

MNS: many frequency bands, lower frequencies challenging

Remedies

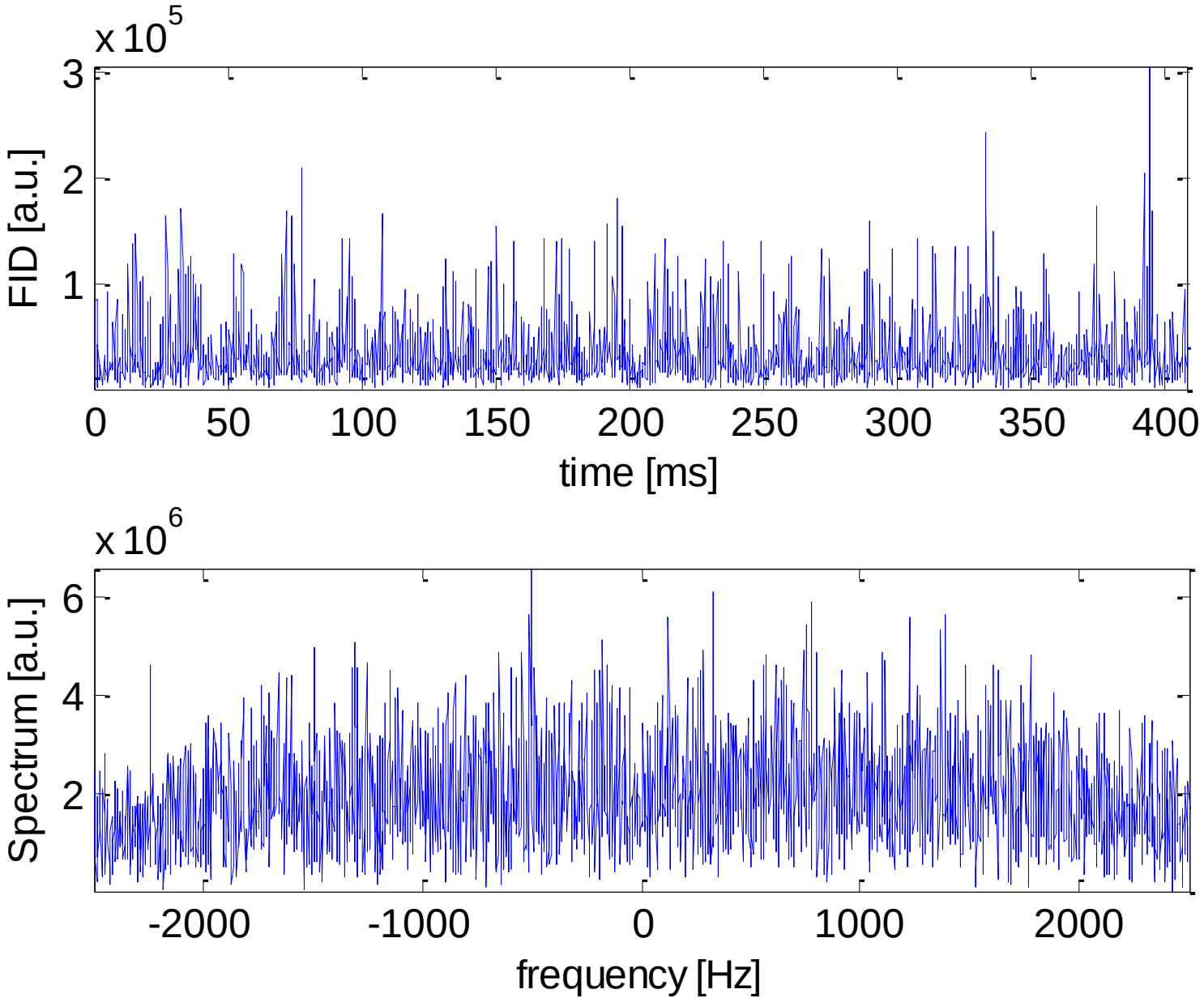
- Track down + eliminate source
- Systematically power off external devices (injector pumps, power supplies) and system components (1H amp, grad amp, power supplies, displays); relocate Rx cables
- Ground (BNC) cables entering MRI room
- Phase cycling
- Use lower receive bandwidth





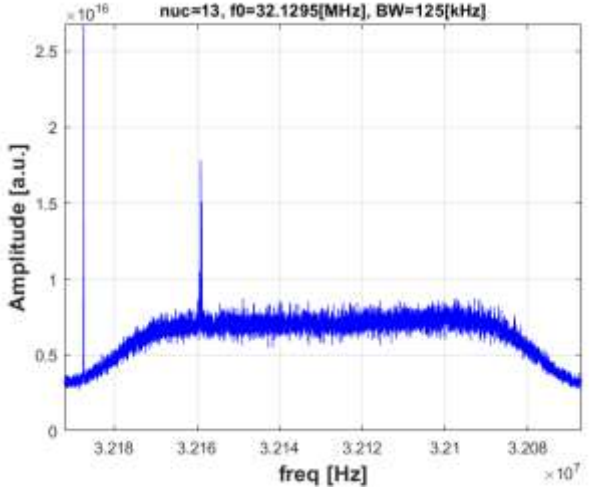
RF Interference: Example

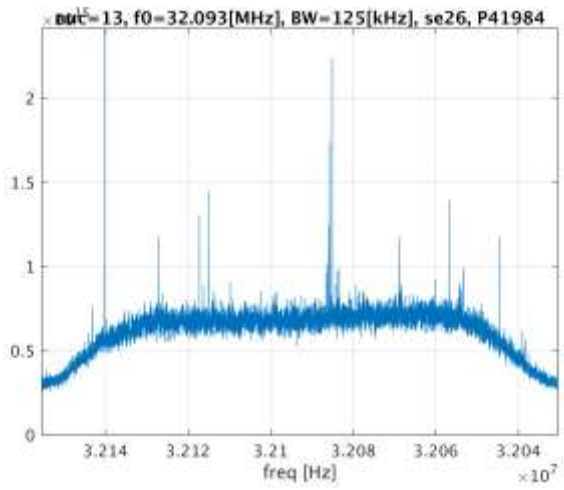
(electronic) power supply leaking RF noise inside MR scanner room

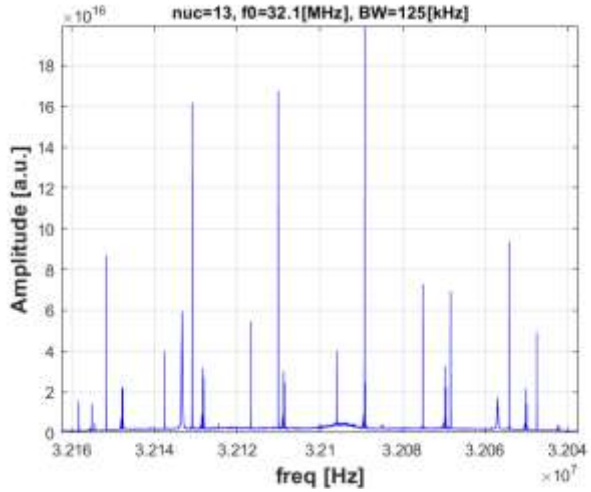


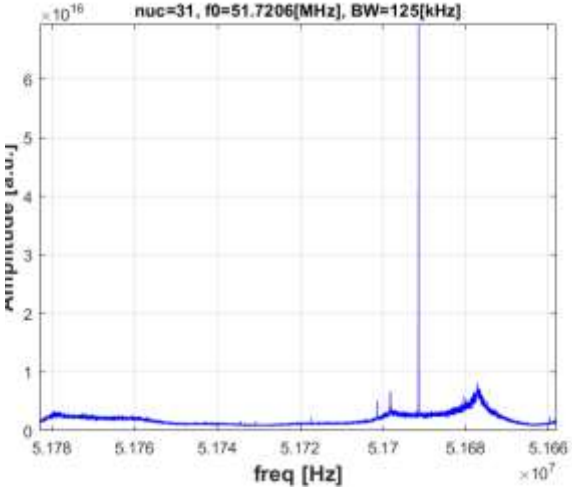
RF Interference: Systematic Noise Scan

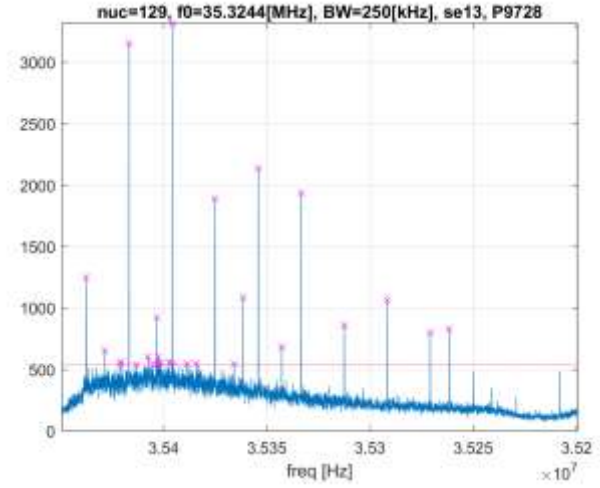
- Use large coil, no RF excitation
- BW=125kHz, #pts=8192, #reps=256
- Power spectrum = sum-of-squares spectrum
- Fidall manual 9.9

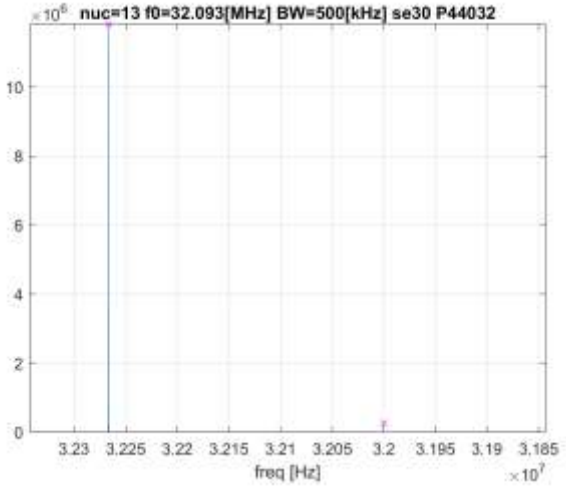


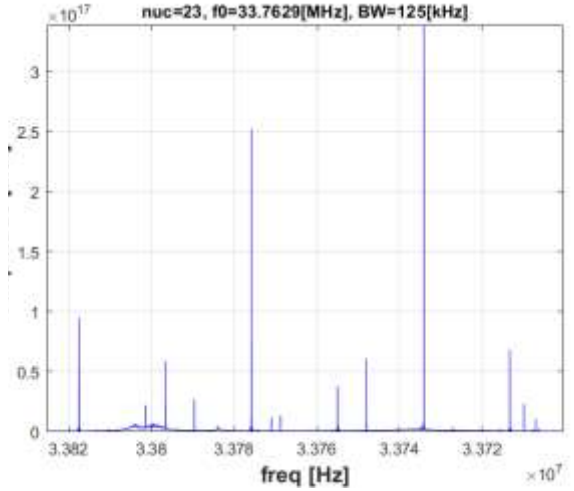


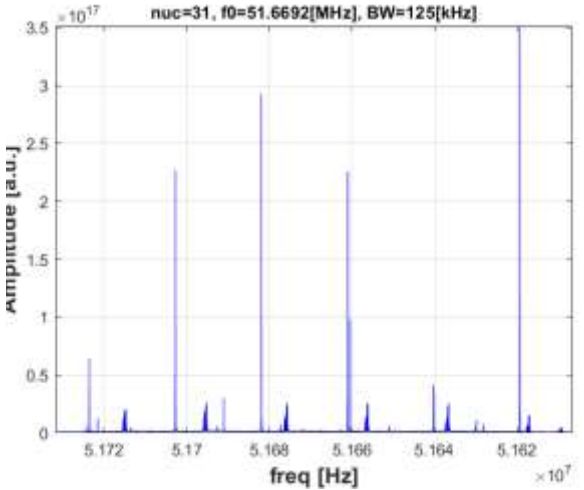










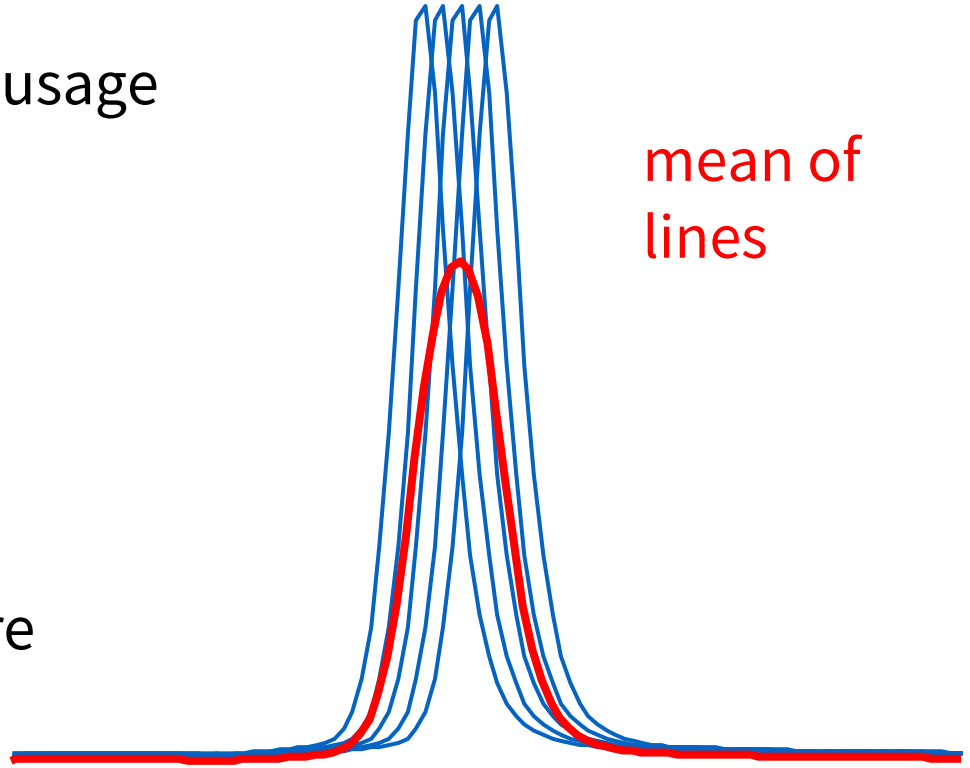


Frequency Drift

- Short-term ≈10-200 Hz/h after excessive gradient usage (eg after fMRI/EPI session)
- Long-term: 10-1000 Hz/years
- Long measurements with many averages: centre frequency shifts → peaks smear out
- Patient motion

Remedies

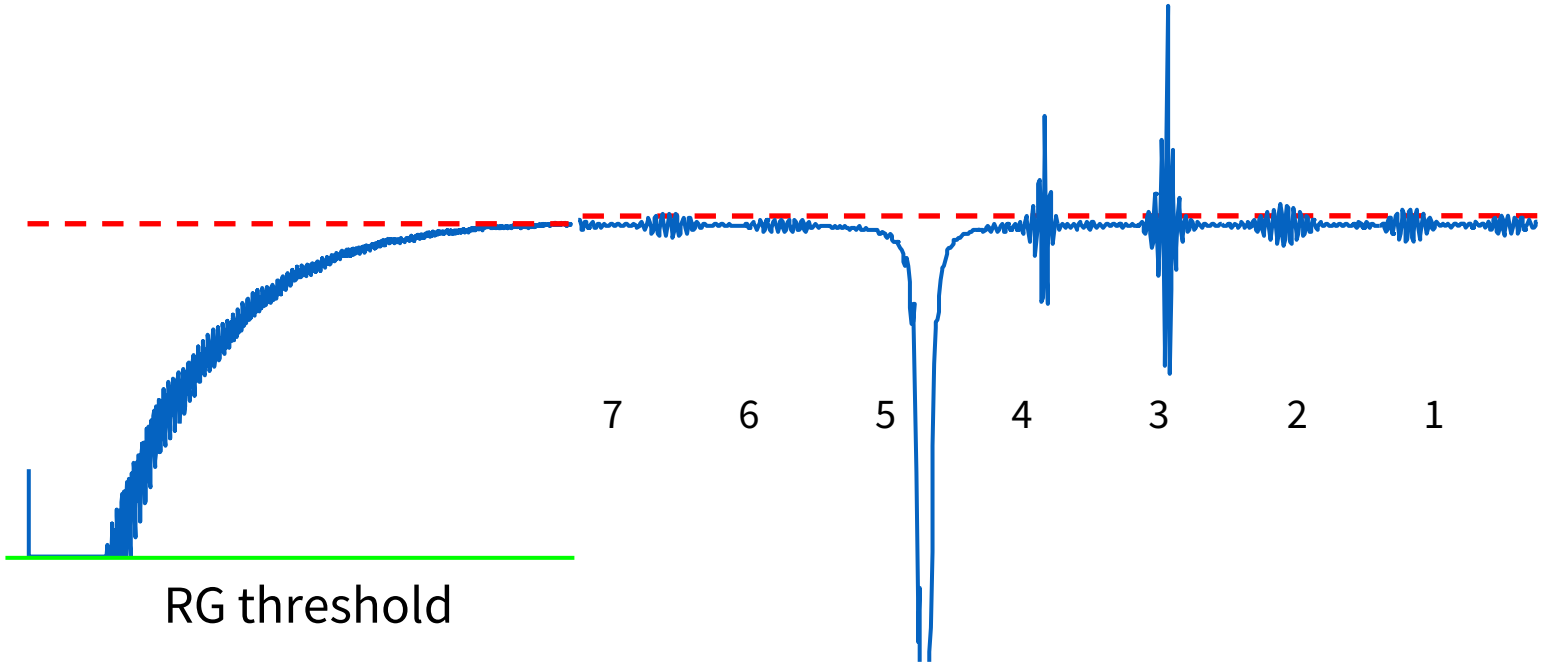
- Newer scanners with water cooled amplifiers more stable
- Avoid MRS after EPI scans
- f_0 determination before each scan
- Save + correct raw data
- Measure and correct f_0 in every repetition



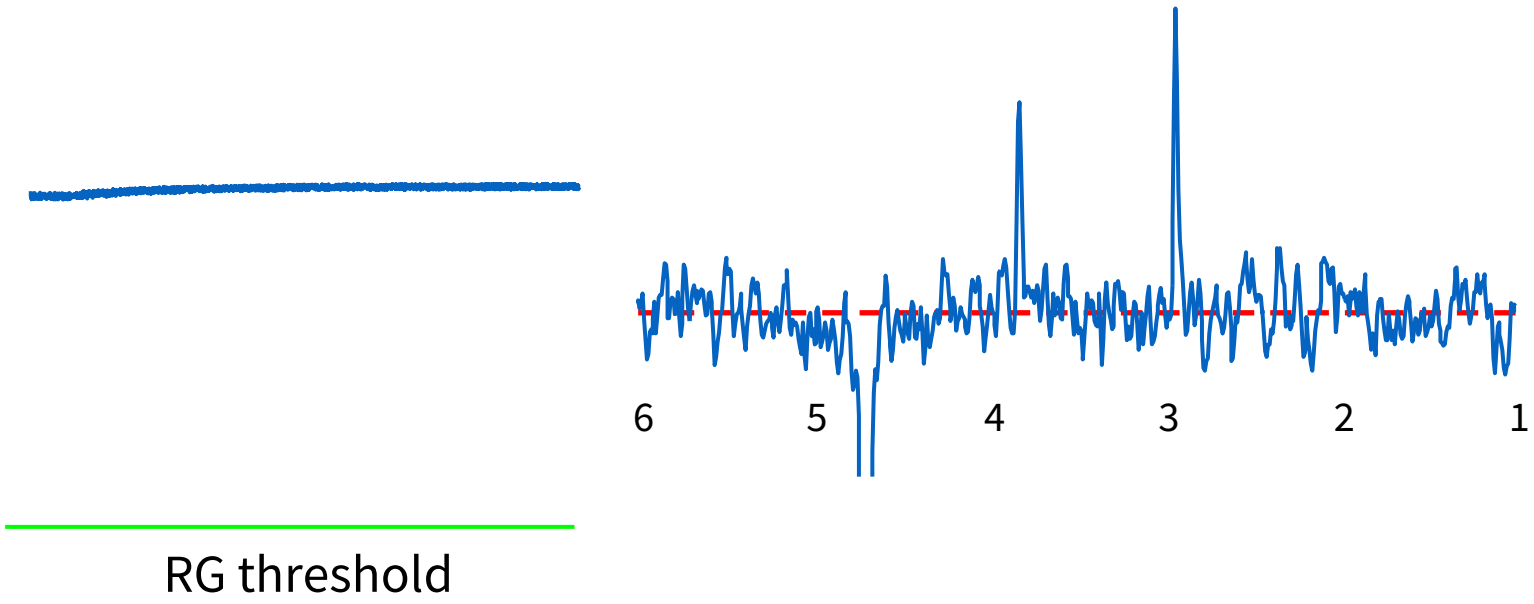
Receiver Gain

Pre-amplification:

- Too high:
  signal overflow &
  saturation of receiver



- Too low:
  digitisation noise



Receiver Gain on GE

- R1: analogue receiver gain: pre-amplification
  depends on signal level and coil pre-amplification
- R2: digital receiver gain: digitisation
- Normal MRI: Automatically determined in auto prescan
- Hyperpolarised studies: signal level unknown
  beforehand

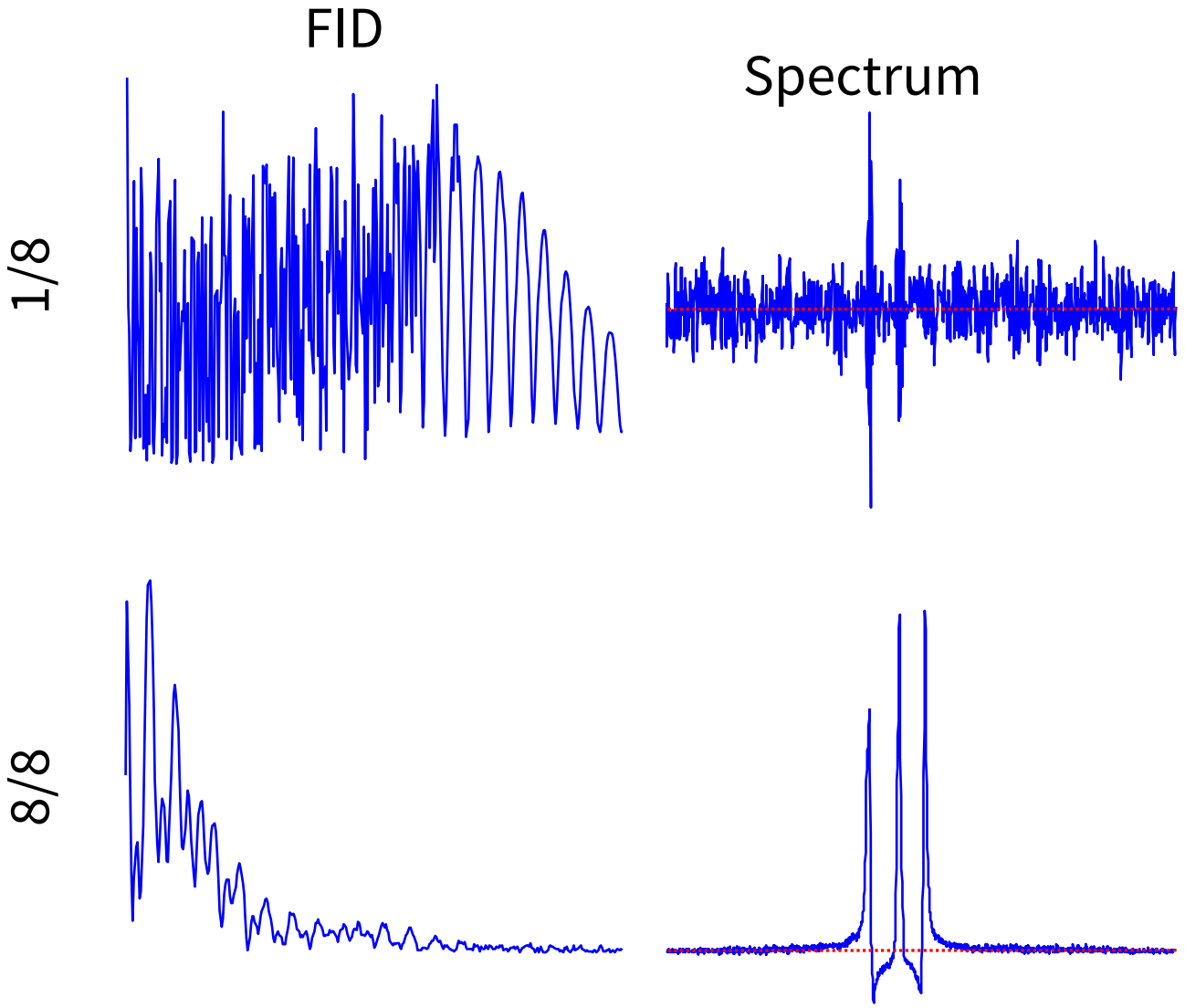
Remedies

- Always observe system error log for over-range
  warnings (≥MR30: requires key)
- Adjust R1 properly, establish safe ranges
- R2=maximum: (digital receive gain)
  EDR off=15, EDR on=30

```
1724757572      0       1       Tue Aug 27 11:19:32 2024        104702  2
        LISE    LxMxConsumer
ICEDataReceiverThread.cpp               454
Server Name: ADS
Signal overrange detected (R1 analog).
EN 173
SR 214
1724757572      1       1       Tue Aug 27 11:19:32 2024        2270060 1
        LISE    LxMxConsumer
ICEDataReceiverThread.cpp               478
Server Name: ADS
MR Signal over-range. Re-scan with Auto Prescan or Manual Prescan (reduce
R1).
EN 214
SR 511
```

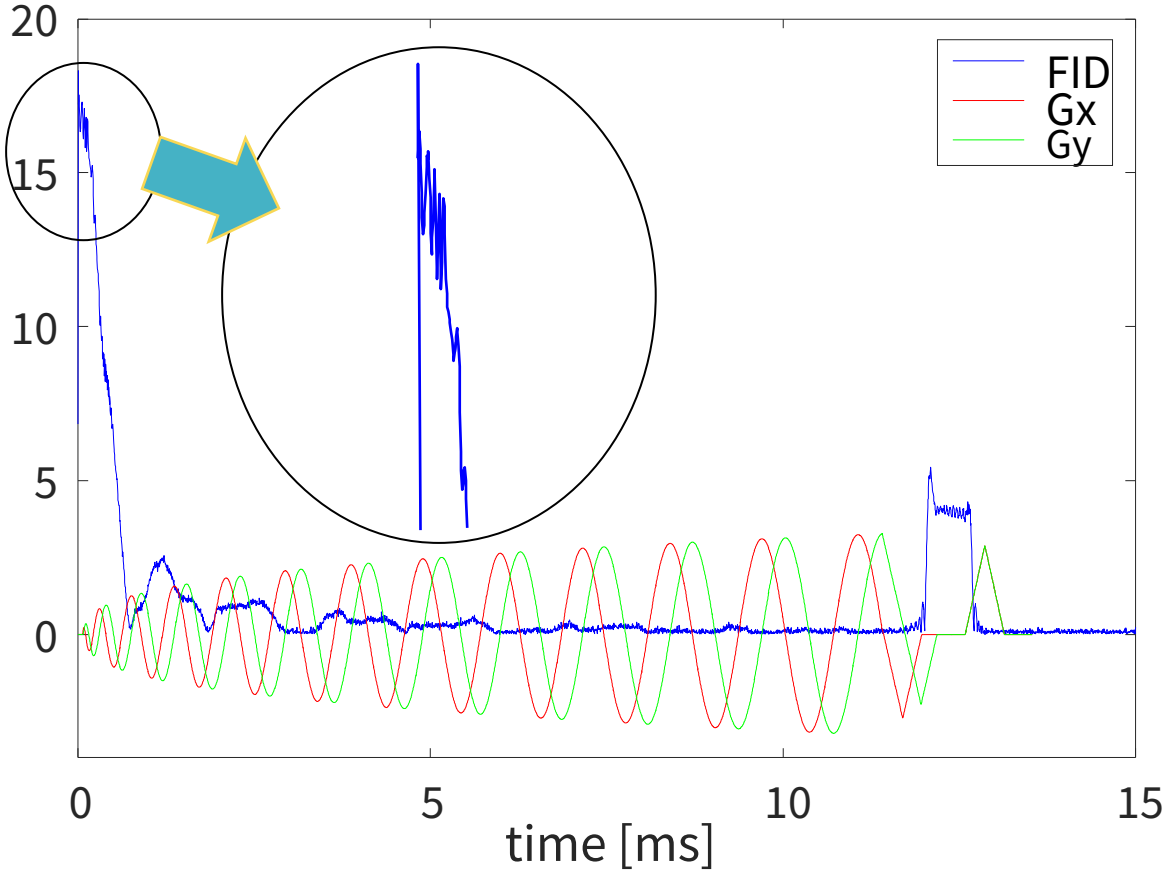
Receiver Gain: 13C Example

- Liquid-state polarisation measurement
- [1-13C]pyruvate syringe
- Saturation of receiver chain
- 1st acquisition: signal level too high
- 8th acquisition: signal level OK

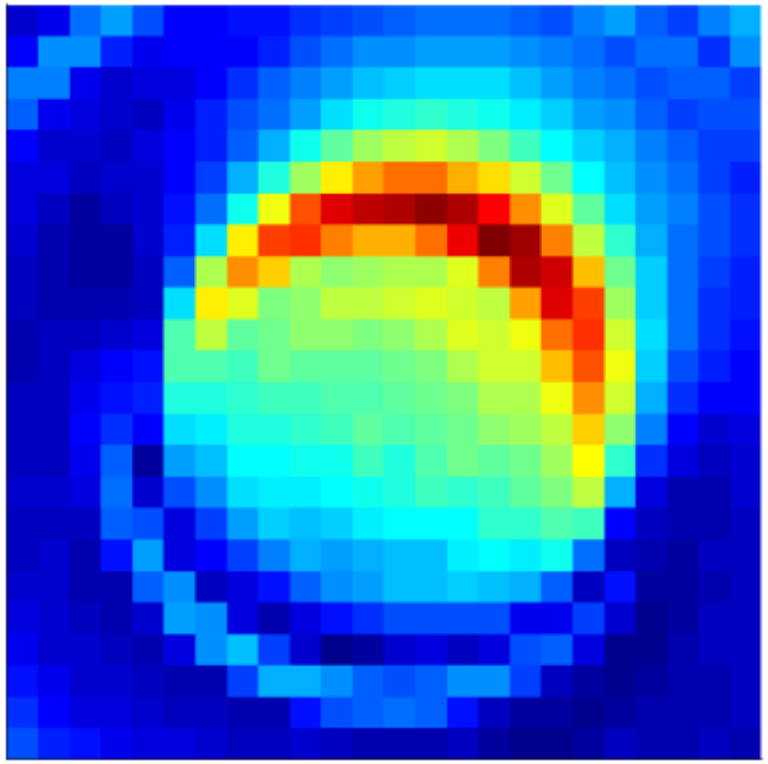


Receiver Gain: 19F example

FID + gradients



Image



- 19F spiral imaging of Perfluorocyclobuthan
- R1=11, R2=30
- Extensive averaging is summing up data

Spike Noise (Time Domain)

- Acquisition contaminated by spikes
- Severity: increased noise to data unusable
- Sources:
  - Moving metal: quad-hybrid in gradient FOV, gradient cables, coin/splinter in bore, loose body coil capacitor, …
  - Poor electrical contact: gradient cables not tightened enough
  - Broken gradient amplifier
  - …

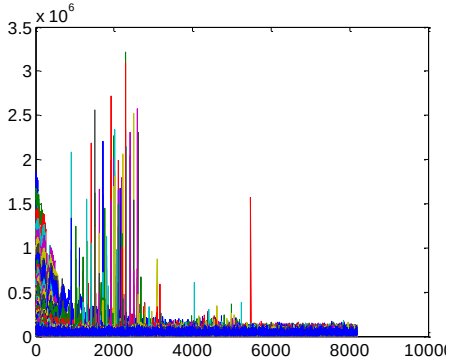
Remedies

- Locate source and remove
  - helpful tool: sniffer coil
- Null contaminated data
  - in matlab: look for outliers
  - on scanner: pickup loop connected to detector

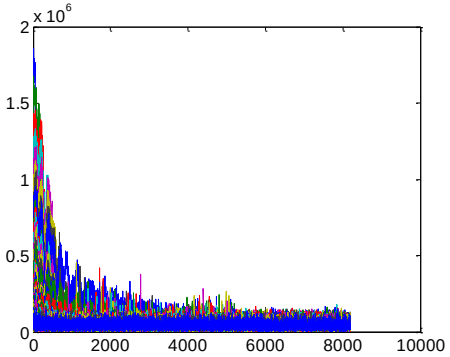
  → Warning: can also null regular MNS (eg 2H) data

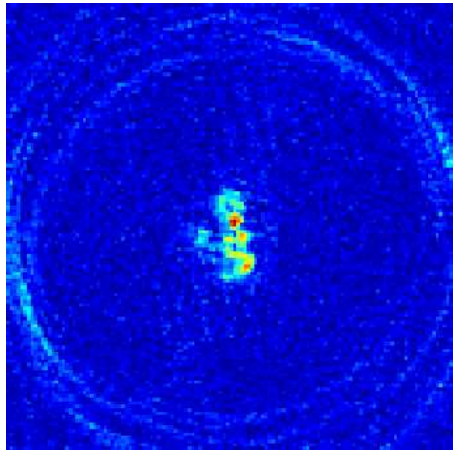
Pickup antenna at MR scanner for “Universal Transient Noise Suppression”

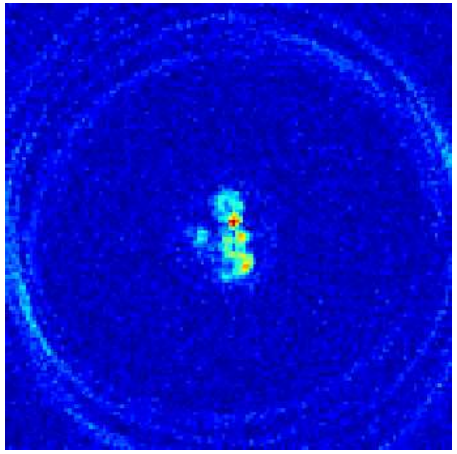
Spike noise



After removal







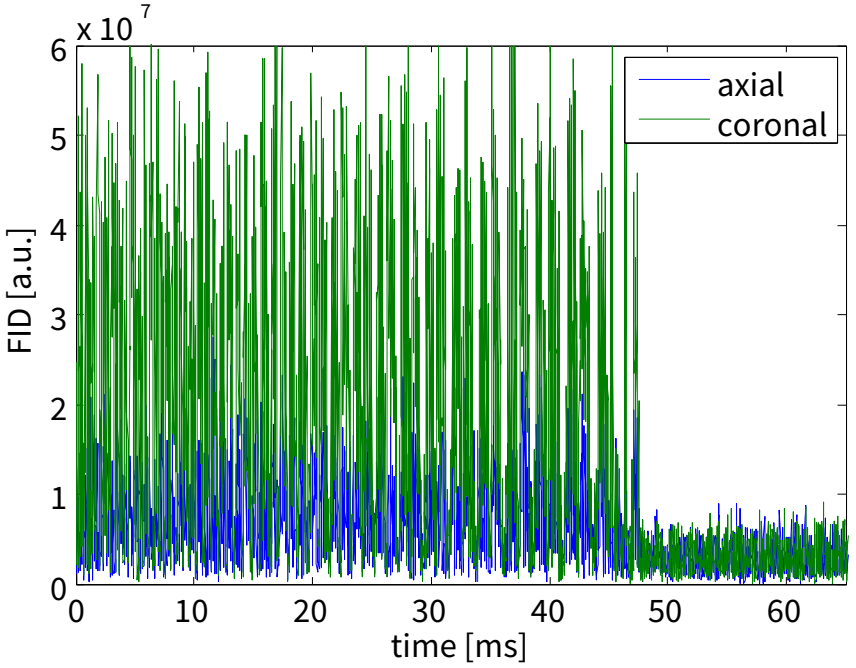
Gradient Artefacts

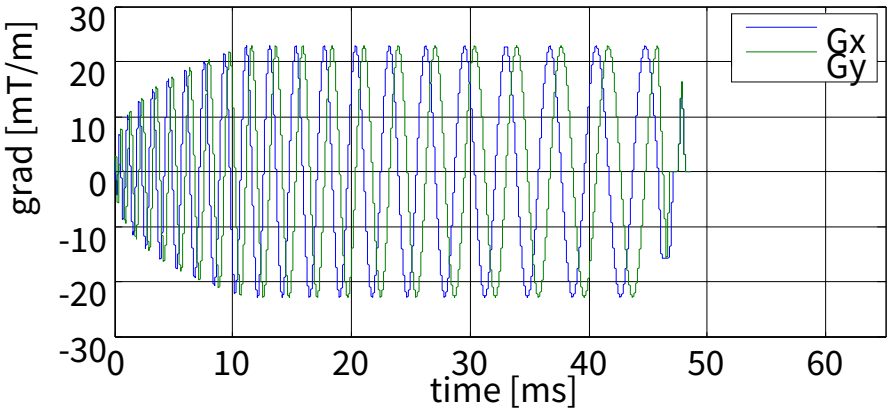
- Noise elevated by gradients (particularly z-axis)
- Can be present even if gradients not used (eg Deuterium)
- Sources:
  - Gradient amplifiers and power supplies produce high frequency noise
  - Insufficient low-pass filter for gradient cables in penetration panel
  - Large Rx RF coils close to gradients

Remedies

- Impossible to filter out after data acquisition
- Improve low-pass filter of gradient cables
  → add ferrites
- Improved gradient filters

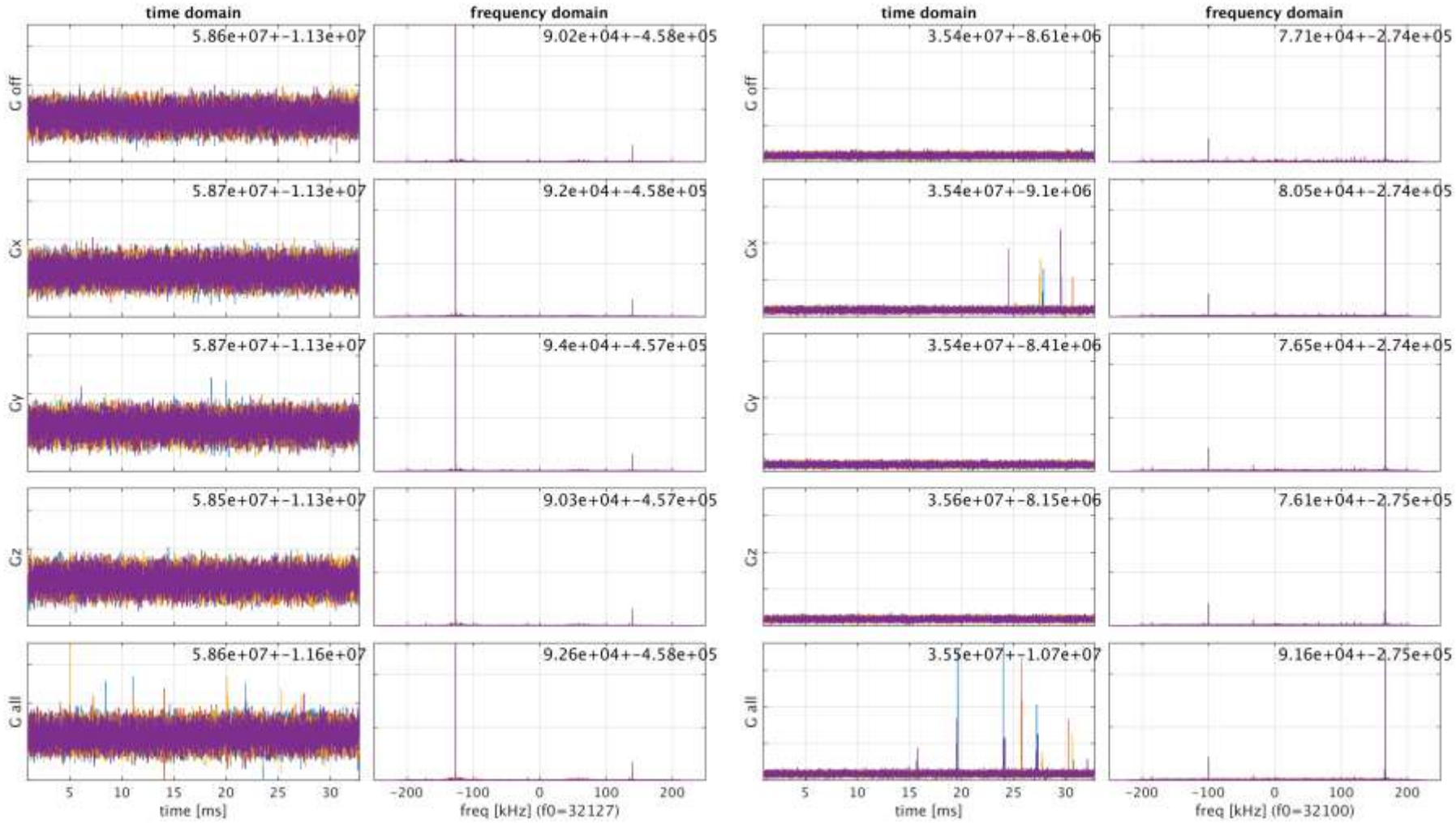
13C spiral data acquired in different orientations without phantom





Spike Noise Artefact: Systematic Test

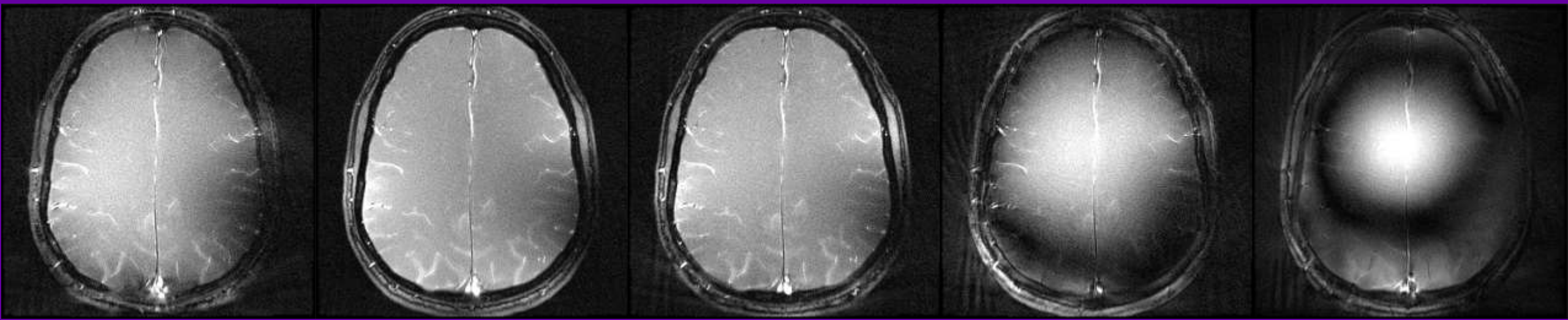
- Run strong spiral gradient waveform along different axes
- No RF excitation, large bandwidth
- Display time and frequency domain
- Fidall manual 9.1



Gradient Delay

- Gradient amplifiers switching large currents in very short time spans
  → different delays between gradients (100-200µs) and RF (1-5µs)
- System calibration: compensates most
- Small deviations (few µs) remaining
- Problematic mostly for Non-Cartesian acquisitions
- Spiral: rotation of object
- Radial: low frequency intensity variations
- EPI & SPSP (with bi-directional gradients): ghosting
- Fidall manual: 9.8, 8.5

2D full-spoke radial reconstructed with different gradient delay times

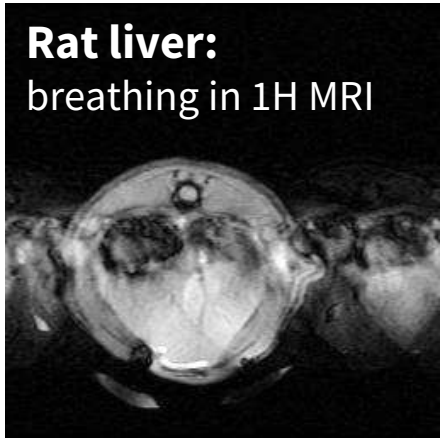


Motion Artefacts

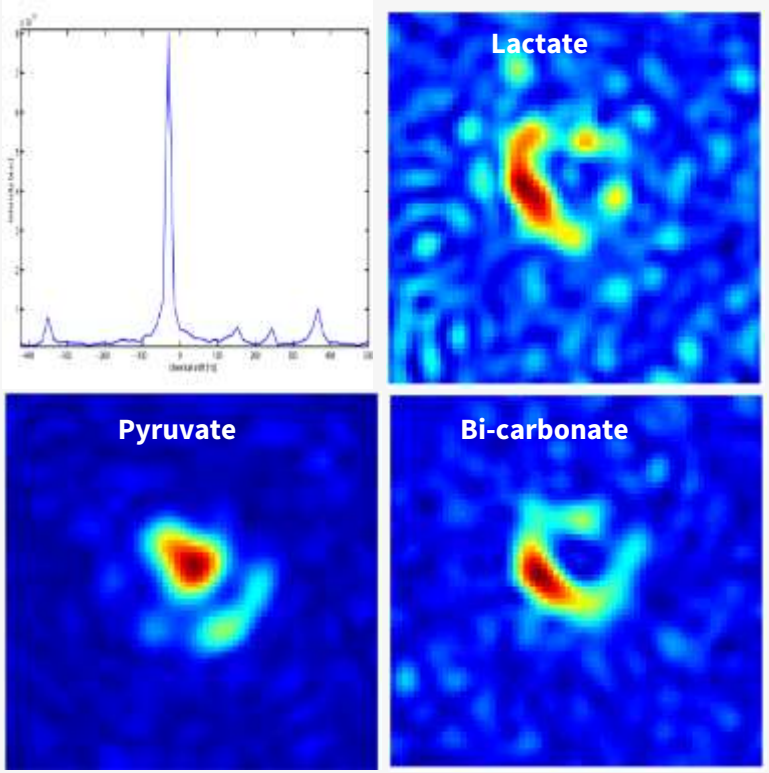
- Motion corrupts data consistency
- Blurring, loss of signal, smearing out
  (particularly for non-Cartesian difficult to predict)

Remedies

- Acquire faster
- Breath hold/intubation
- Cardiac triggering
- Correction in reconstruction



^{13}C IDEAL Spiral CSI in Pig Heart
(courtesy to CNR Pisa)



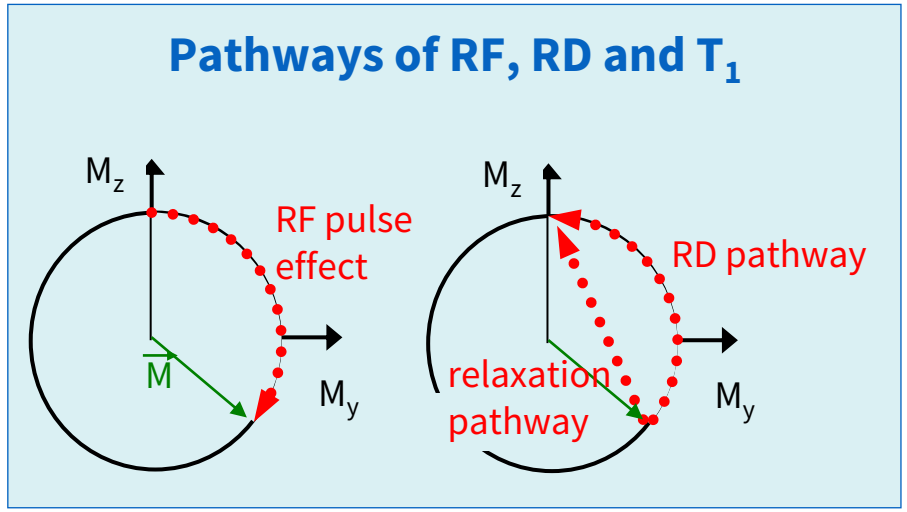
Radiation Damping

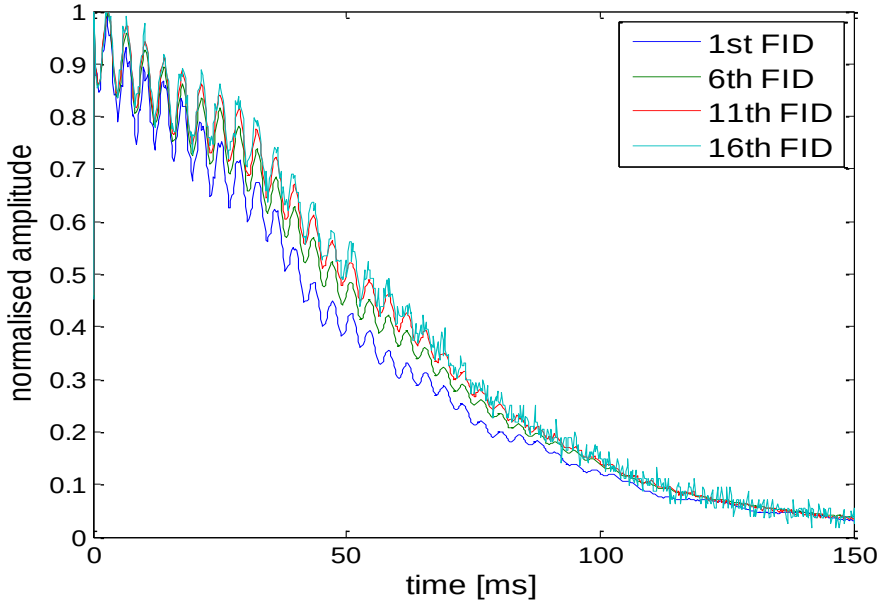
Strong sample signal
→ induces strong current in coil
→ induces again flip in sample

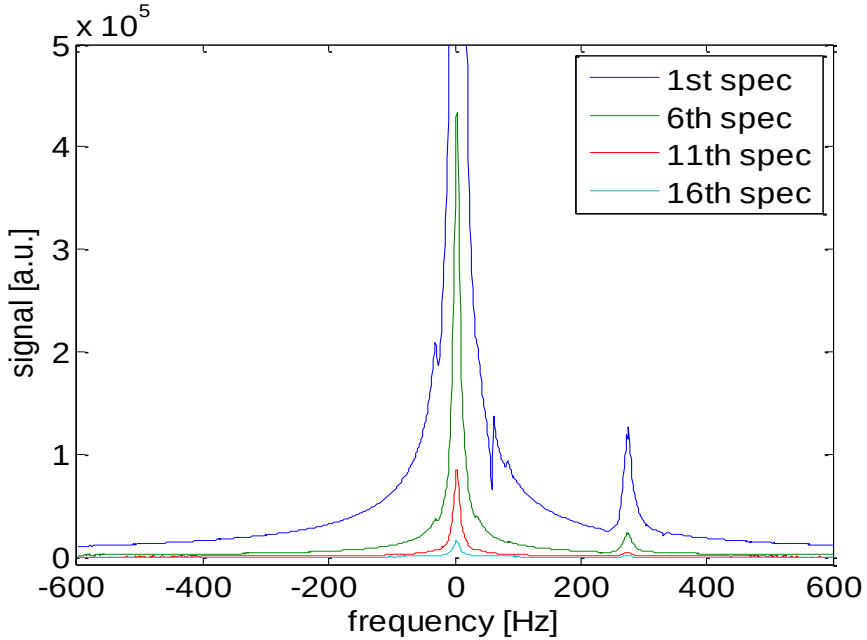
$$\tau_{rd} = \left(\gamma \eta m_0 Q \mu_0 / 2\right)^{-1},$$

$$signal = M_0 \exp\left(-\frac{t}{T_2^*}\right) \cdot \mathrm{sech}\left[\frac{t}{\tau_{rd}} - \ln\left(\tan\frac{\theta_0}{2}\right)\right],$$

- Occurs in syringes, e.g. liquid state polarisation
- In vivo: signal level typically too low



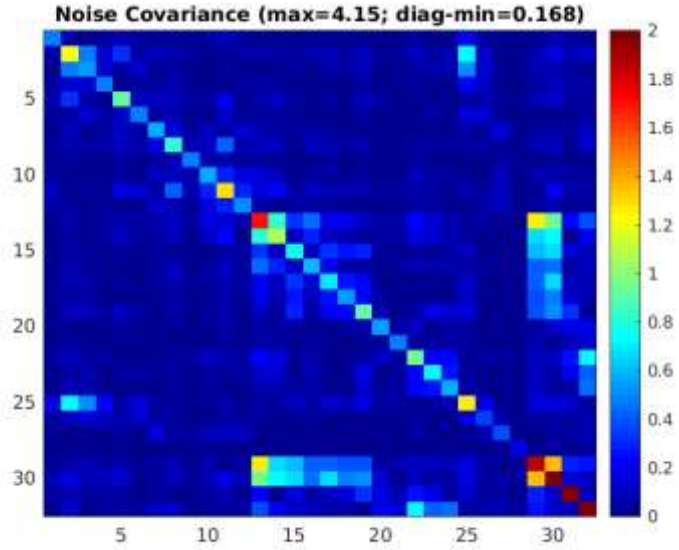




RF Coils

- 1H MRI (@3T): sample noise dominated
  → even lousy coils yield good images
- x-Nuclear MR: mixed regime
  → coil noise matters much more
  → good coils essential
  → too many, small receive elements: SNR penalty (inside object)
- Transmit-receive surface coils: inhomogeneous B1+/- fields
- Body coil: 1H
  → x-nuclei require transmit coils
- Multi-channel Rx coils: good isolation required
  (noise covariance part of fidall MNS prescan, also fidall manual 9.7)

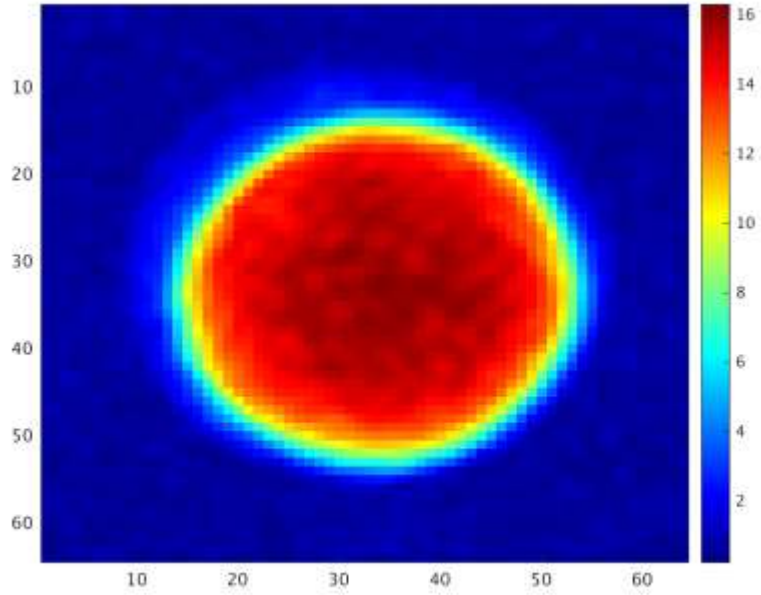
31P at 7T



SNR Scan

- SNR impacted by phantom, coil, MRI scanner, measurement
- Difficult to assess performance of setup
- Establish SNR standards across different sites, scanners, coils
- MNS phantom (WIP: Gold Standard Phantoms, Rapid): versatile, standardised, commercially available phantom containing 1H, 2H, 13C, 23Na and 31P spins
- Pink silicone oil phantoms: good for 13C
- Braino 1H MRS phantom: good for 31P
- Use standardised MRSI acquisition and reconstruction
- Fidall manual 9.2

31P 2D MRSI SNR Map



Discussion and Conclusion

- Always save and look at raw data
- Look at both FID & image/spectrum
- Be suspicious
- *“Garbage in garbage out”*
  → time on tracking down artefacts usually well spent

Literature (Spectroscopy Focused)

1. Kreis R. Issues of spectral quality in clinical 1H-magnetic resonance spectroscopy and a gallery of artifacts. NMR Biomed. 2004 Oct;17(6):361-81. Review.
2. Hurd RE. Artifacts and pitfalls in MR spectroscopy. In: Clinical MR neuroimaging. Cambridge Uni Press.
3. de Graaf RA. *In vivo* NMR spectroscopy. Wiley, 2nd edition.
(plus many sub-references)

Hands-on Course for Advanced Research on GE MR

Target Attendees: MR Physicist, Researcher, Scientist.

Learning objectives: The aim of the course is to allow research partners to get familiar to the GE MR scanners and how to effectively perform research on it. That includes an introduction to system architecture (hard- and software), how to interface to the system, pulse sequence programming, reconstruction, obtaining raw data, troubleshooting and more. Hands-on sessions on the MRI will provide direct learning experience.

Requisites: valid research key, Linux, C/C++, MATLAB, Python, knowledge of MR theory, operation of GEHC MR scanner

Course Teachers: Applied Science Laboratory Europe Team

Location: GE HealthCare, Oskar-Schlemmer-Str. 11, 80807 Munich

Date: January 20-23, 2025

Registration Fee; Deadline: 650€; Dec. 1, 2024

Costs: Registration fee includes VAT, lunch, dinner and refreshments. Participants are expected to cover their own travel expenses (flight, hotel, etc).

Organizers:

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Rolf Schulte: rolf.Schulte@gehealthcare.com

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Info: https://weconnect.gehealthcare.com/

Registration: https://axtravel.eventsair.com/ge-1st-hands-oncourse-for-advanced-research-on-ge-mr-2025/gehc/Site/Register

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