Signal Enhancement in Magnetic Particle Imaging by a passive Dual Coil Resonator (pDCR)

Bachelor Thesis Defence Talk

Jonas Philipps

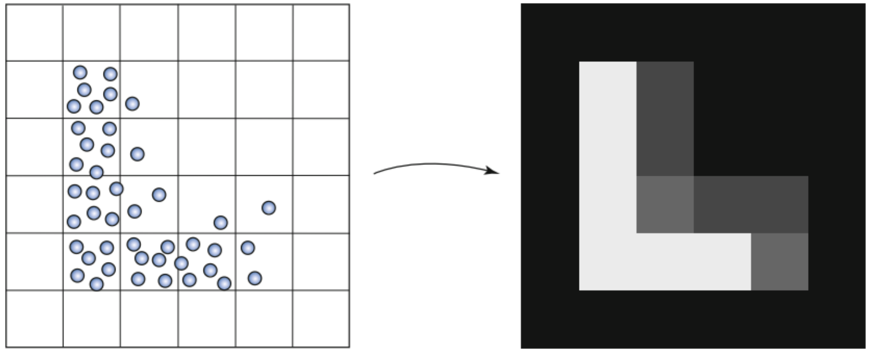
16.02.2021

Contents

Basics – Magnetic Particle Imaging (MPI)

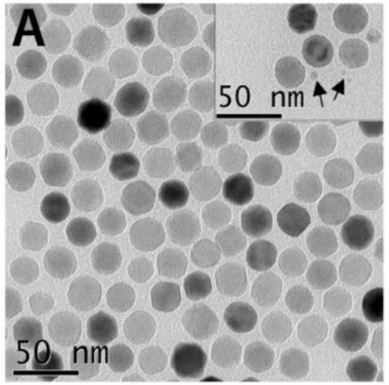
- Novel tracer-based imaging technique
- Determination of the spatial distribution of a tracer by stimulation with magnetic fields
- Tracer: Material to be imaged
  - Superparamagnetic iron oxide particles (SPIONs)
- Advantages:
  - High temporal resolution → Real-time imaging
  - High sensitivity
  - Good spatial resolution
  - Quantitative
  - No use of harmful ionizing radiation

(a)

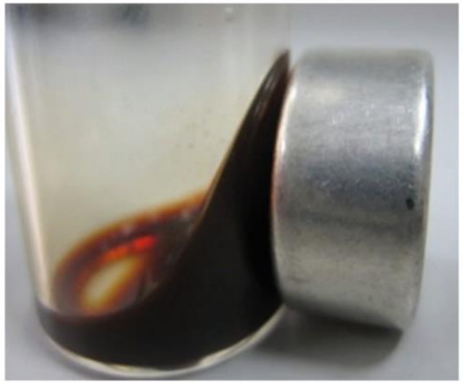


[1]

(b)



[2]

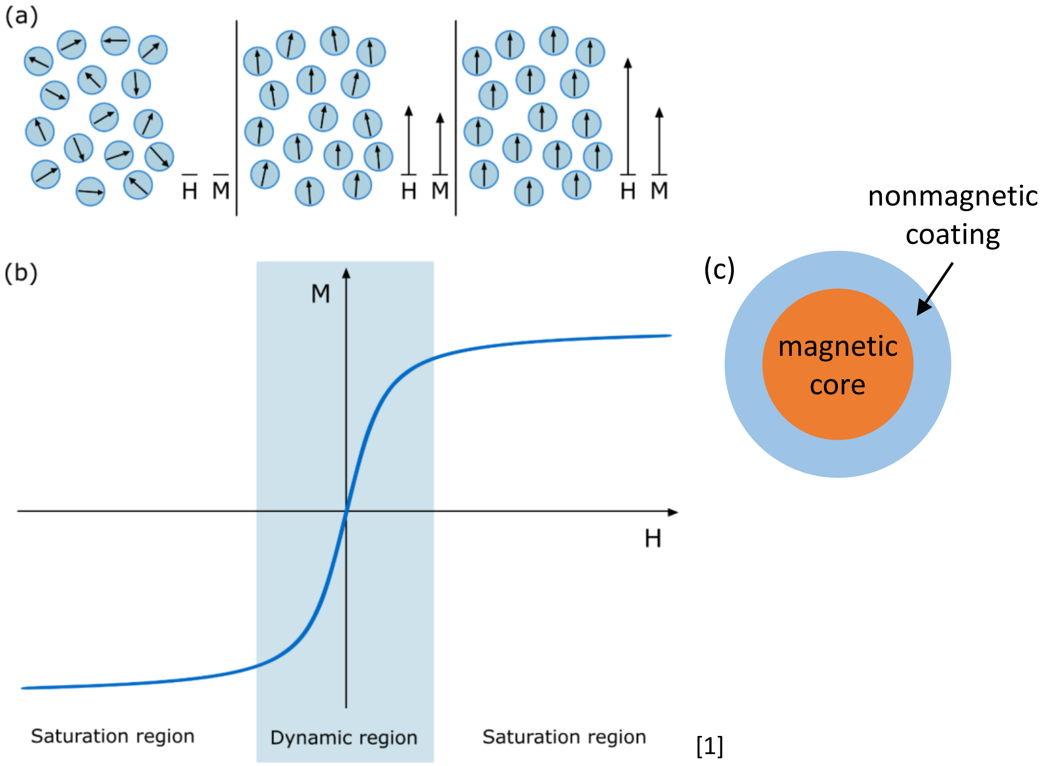


[3]

Basics – SPIONs and Signal Generation

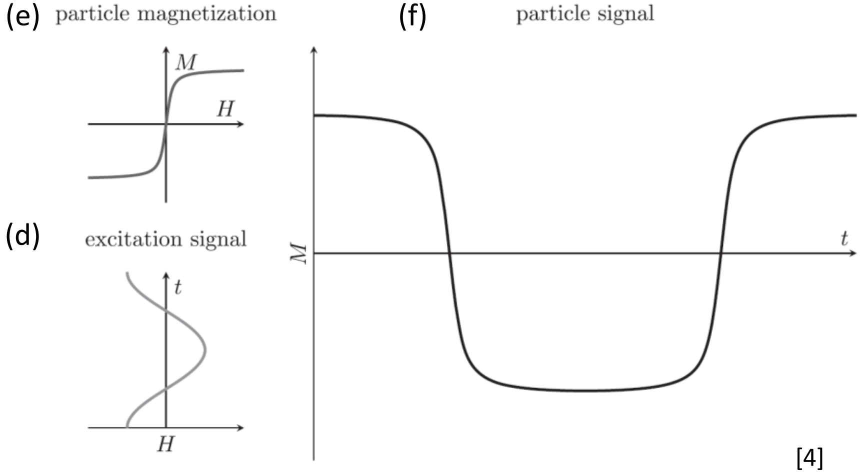
SPIONs

- Superparamagnetism → ferromagnetism + single domain
  ⇒ no particle-particle interactions
- Nonlinear magnetization behavior → Langevin function

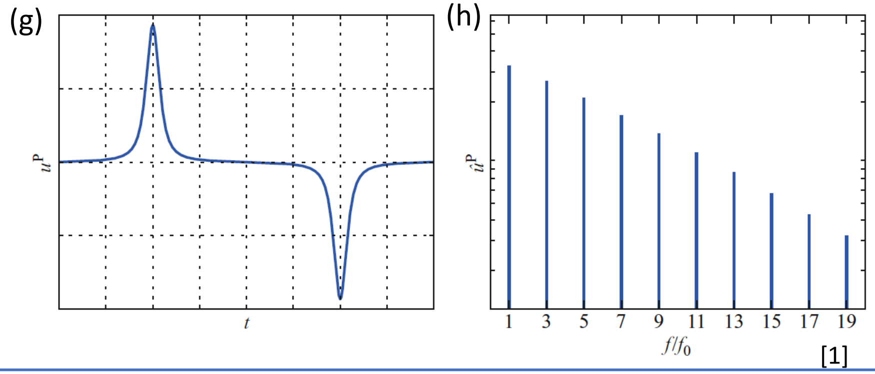


Signal Generation

- Excitation with a sinusoidal magnetic field (drive field)



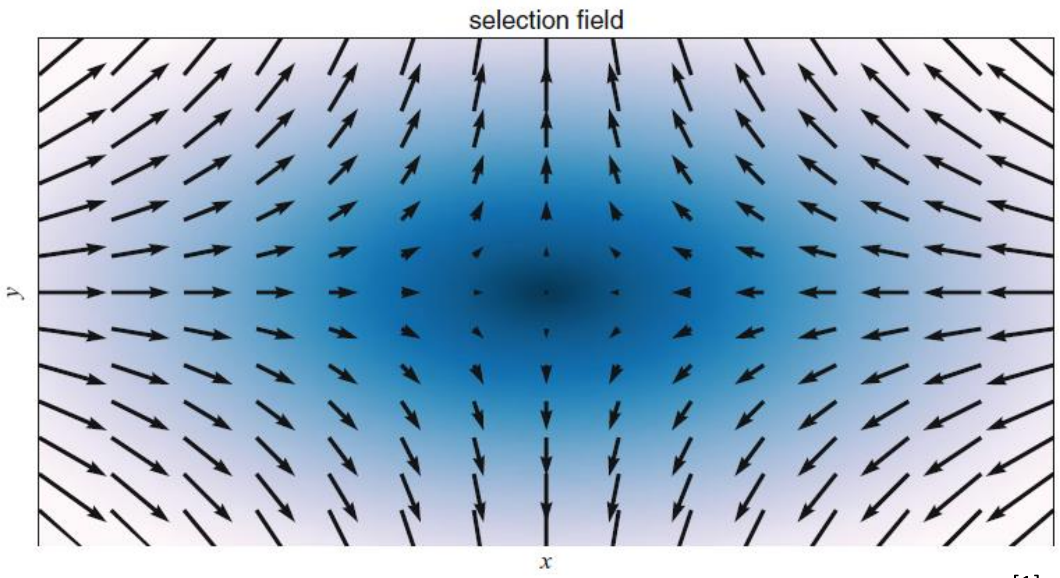
- Detection via voltage induced into receive coils



Basics – Spatial Encoding and Image Reconstruction

Spatial Encoding

- <u>So far</u>: Magnetization response of all particles
  → Mean concentration
- <u>Wanted</u>: Particle distribution
  → Local concentration
- <u>Solution</u>: Superposition of a gradient field (selection field) featuring a field free point (FFP)



[1]

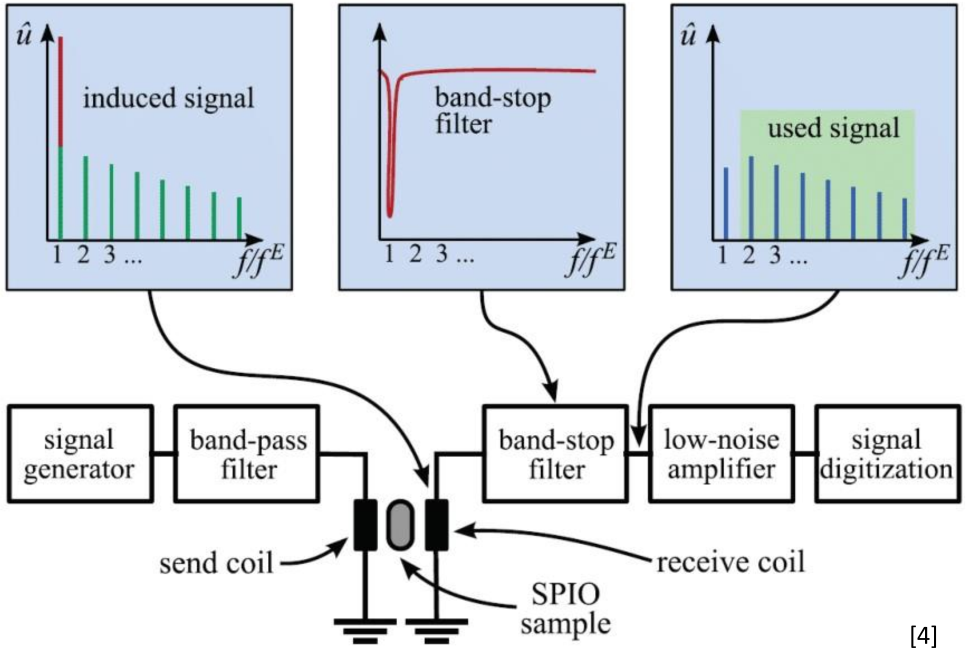
Image Reconstruction

- $\boldsymbol{Sc} = \boldsymbol{\hat{u}}$
  - $\boldsymbol{c}$: particle concentration
  - $\boldsymbol{\hat{u}}$: induced voltage
  - $\boldsymbol{S}$: System matrix
    - Describes the spectra of a delta sample being placed at every position in the volume to be imaged
- In true measurements: $\boldsymbol{\tilde{u}}$ distorted by noise
  - $\|\boldsymbol{Sc} - \boldsymbol{\tilde{u}}\|_2^2 \xrightarrow{\boldsymbol{c}} min$
  - Solve with an iterative solver (Kaczmarz method)
- $\boldsymbol{S}$ also noisy
  - Denoising: Fourier or cosine transformation will compress the true signal but not the noise
    → Noise can be separated by thresholding

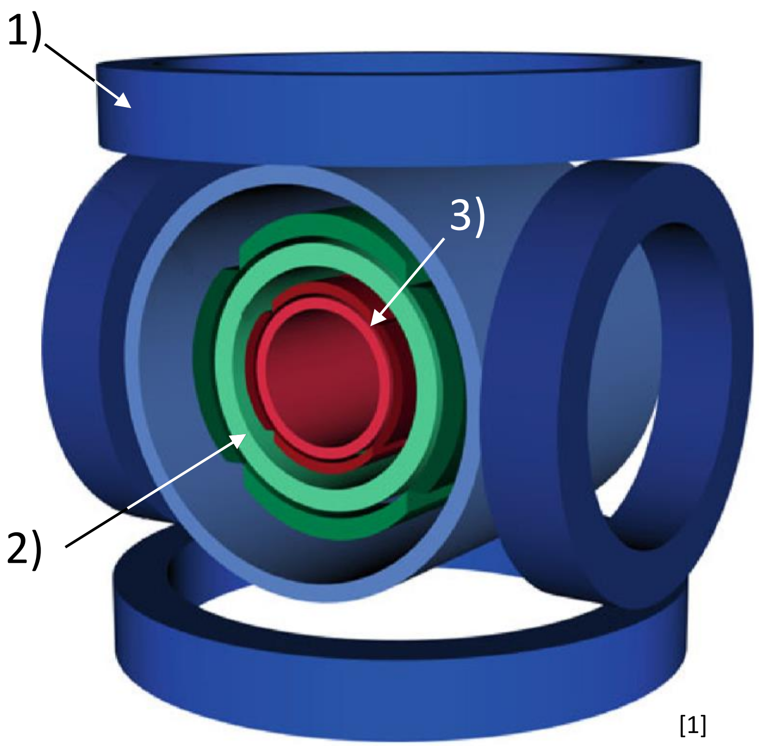
Basics – Scanner Setup

- **Scanner:**
  1) selection field coils (blue): generate the FFP
  2) drive field coils (green): generate the excitation field
  3) receive coils (red): pick up the particles' magnetization response

- **Signal chain:**



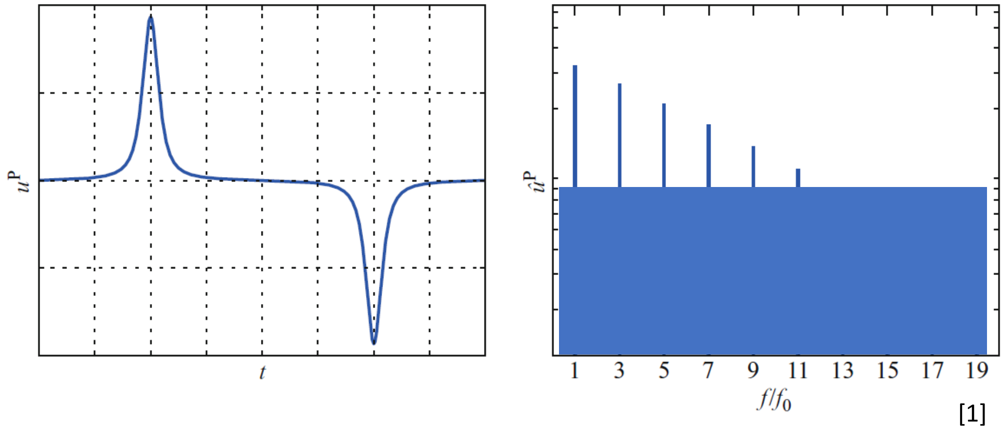
[4]



[1]

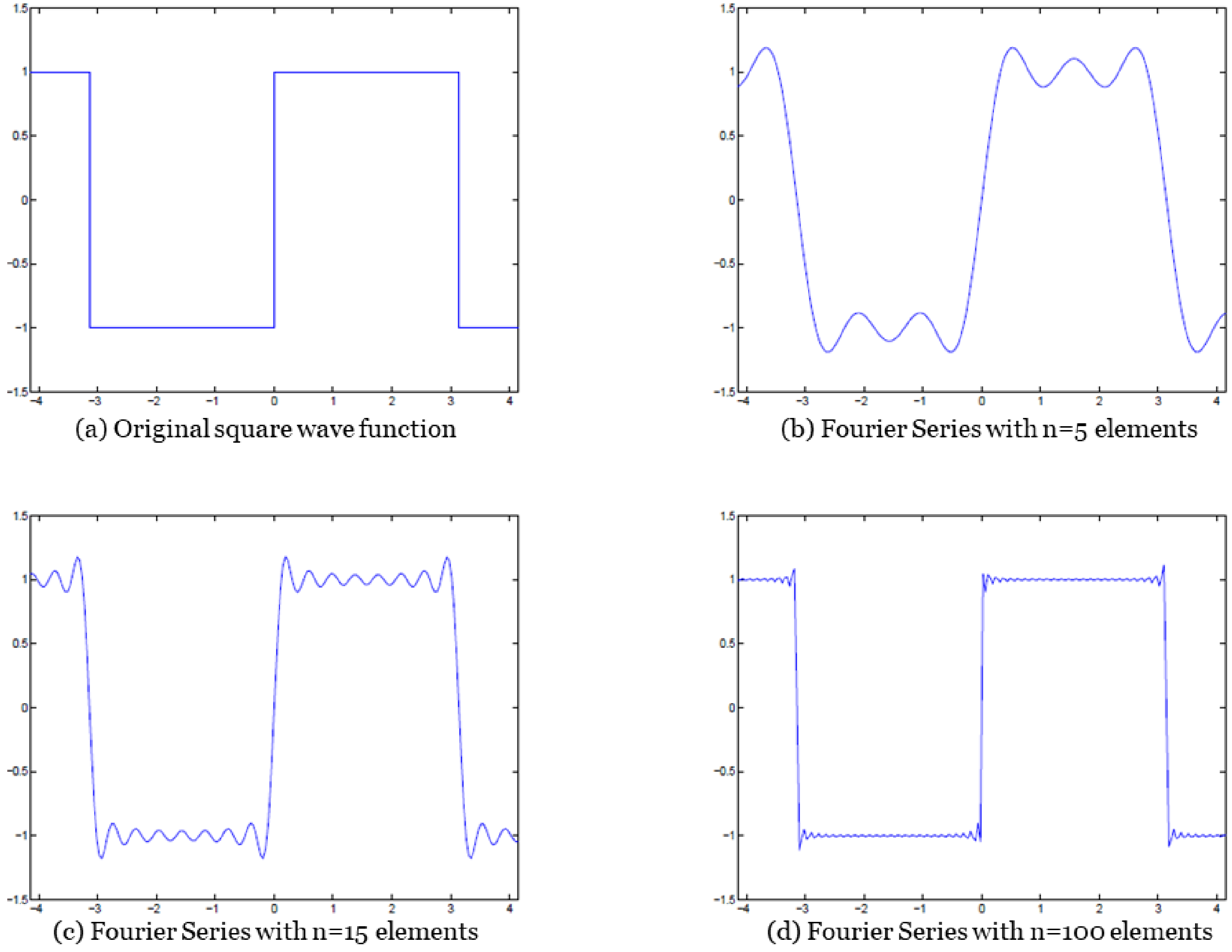
Motivation – Signal Enhancement

- <u>True measurements</u>: Noisy signal
  → Higher harmonics disappear in a noise floor



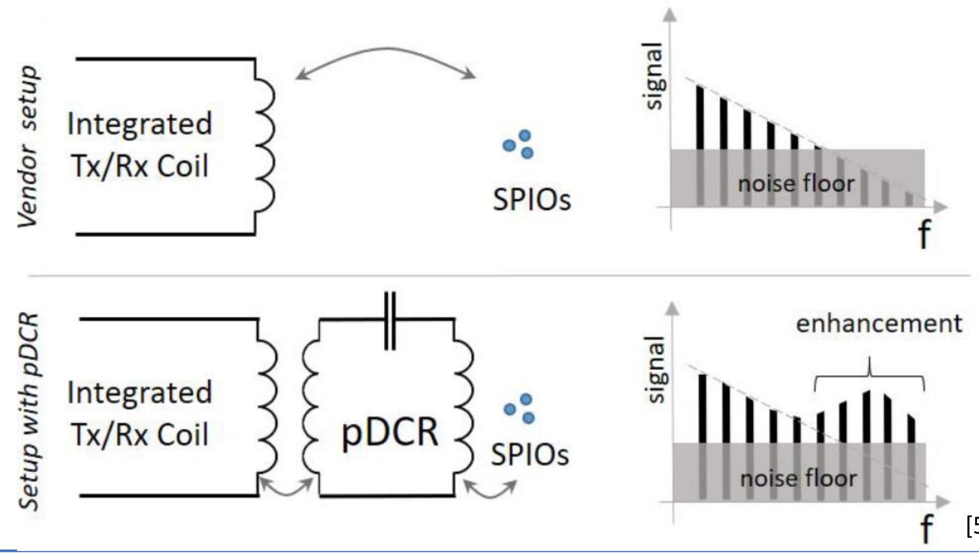
[1]

- More harmonics detectable
  → Better image reconstruction possible
- Spatial information is encoded in higher harmonics
  → Exemplarily shown by the Fourier series of the square wave function

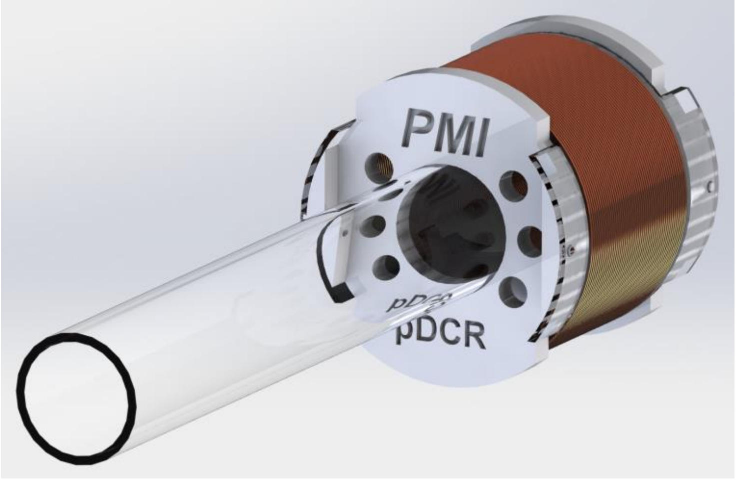


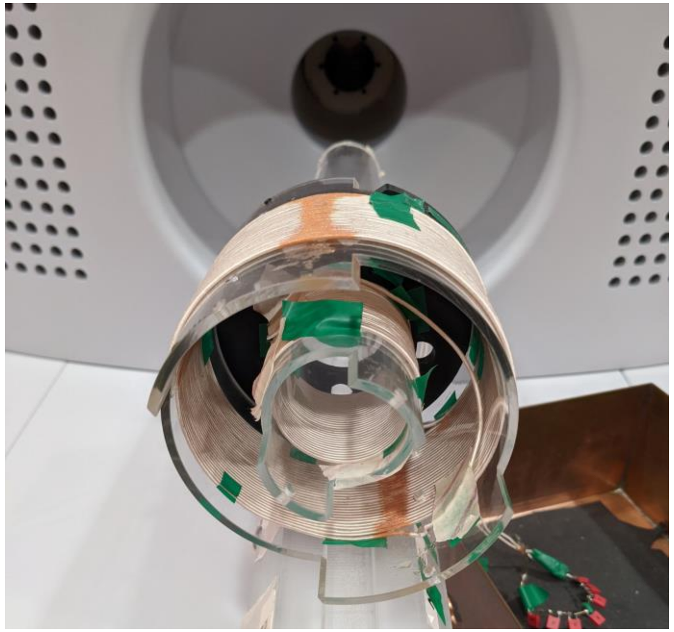
Basics – The passive Dual Coil Resonator (pDCR)

- Goal: Enhancement of SNR at a high frequency band → improve spatial resolution
- Implementation: Passive coaxial dual coil resonator
  - Inner coil (50 mm) to receive SPION signal with high sensitivity
  - Outer coil (110 mm) coupled into native receive coil → combined inductance 210 µH
  - Coils connected via a capacitor (0.314 pF) → resonance at 608 kHz

(a)


[5]

(b)


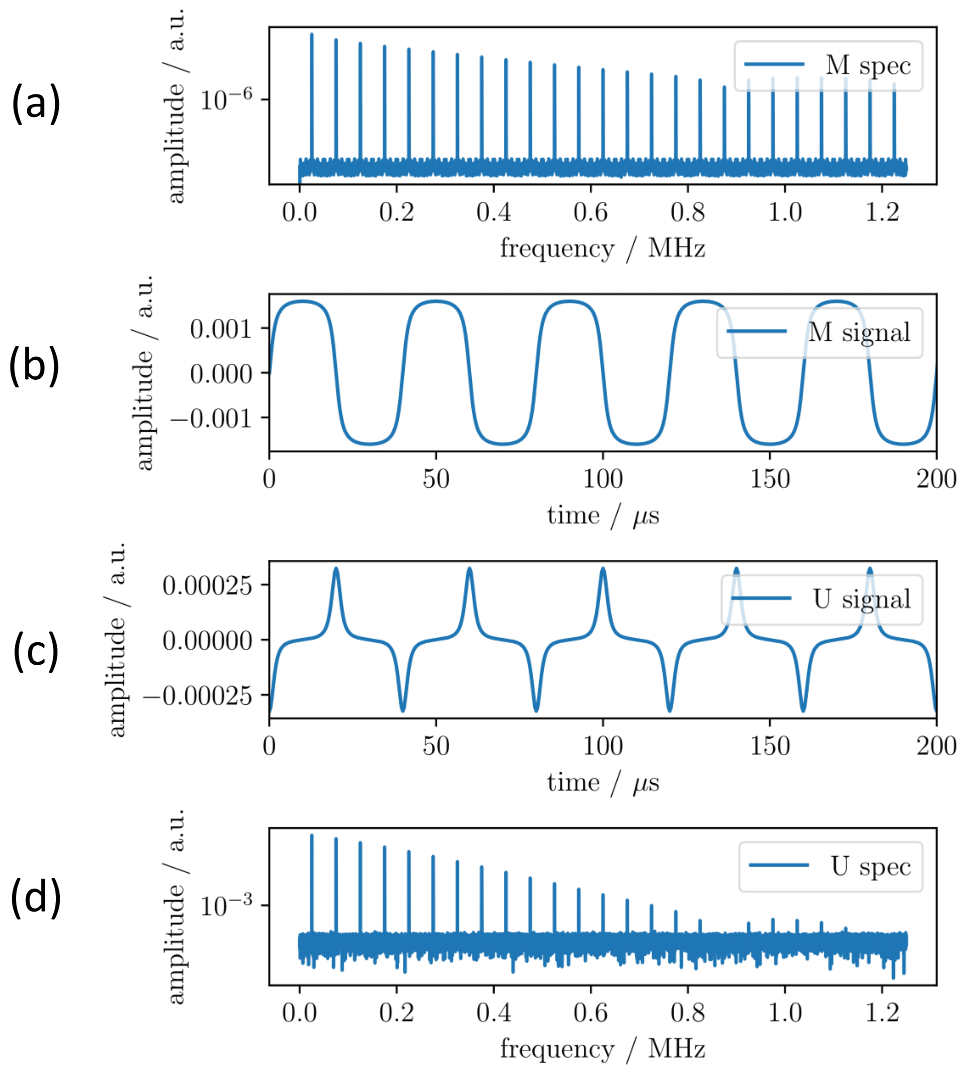
(c)


Impact of the pDCR – Simulations 1D

- System matrix simulation:

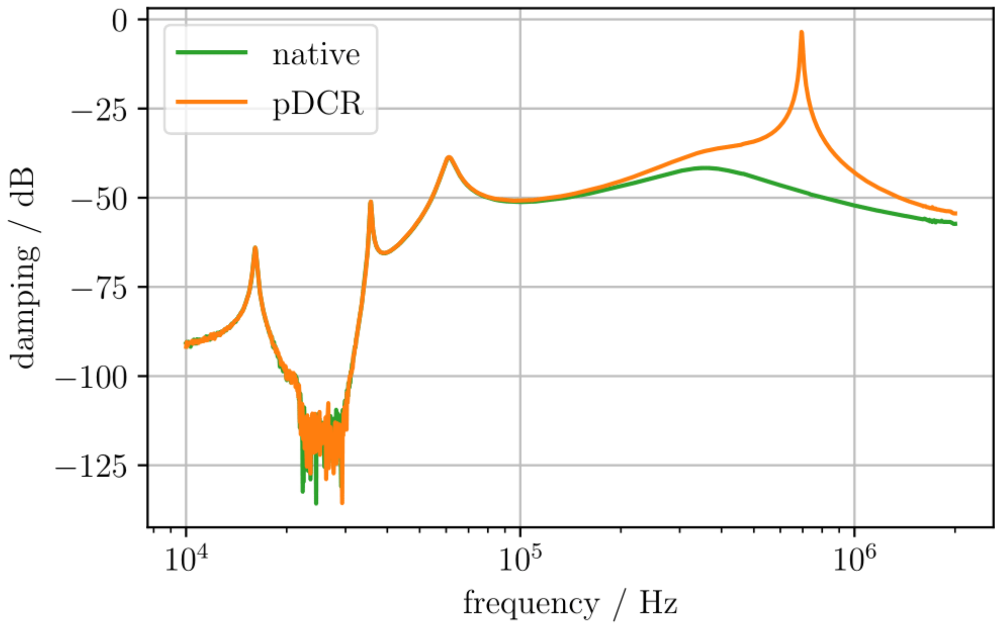
$$\mathbf{S}_{ij} = \mathrm{i}\omega_i \mu_0 m \mathbf{R} \frac{V}{N} \mathcal{F}\left[\mathcal{L}(\mathbf{r}(t) - \mathbf{x}_j)\right](\omega_i) \cdot \hat{\Gamma}(\omega_i)$$

- Signal simulation:
  - (a) Magnetization signal in frequency domain
  - (b) Magnetization signal in time domain
  - (c) Voltage signal in time domain
  - (d) Voltage signal in frequency domain



Impact of the pDCR – Transfer Function and SNR

- <u>Transfer function</u>:
  - Transfer function of receive chain incl. pDCR
  - Increased sensitivity at high frequency band
  - Peak at 694 kHz
    - inside scanner: coupling with scanner elements
      → resonance frequency shifts

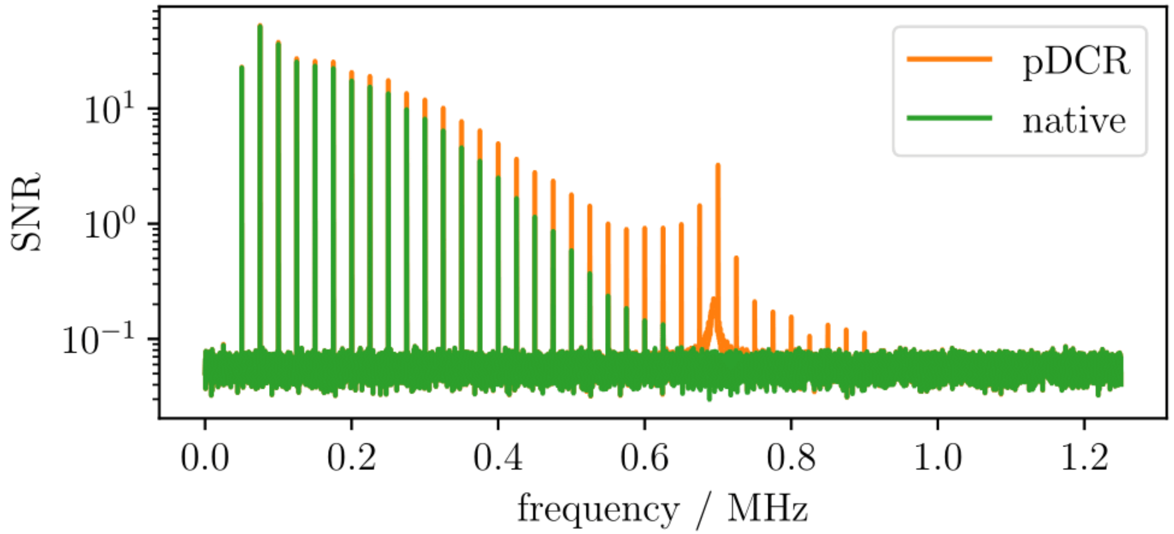


- <u>Signal-to-noise ratio</u>:

$$SNR = \frac{S(f) - BG(f)}{\sigma(BG(f))}$$

  - SNR of system matrix used for threshold determination in image reconstruction

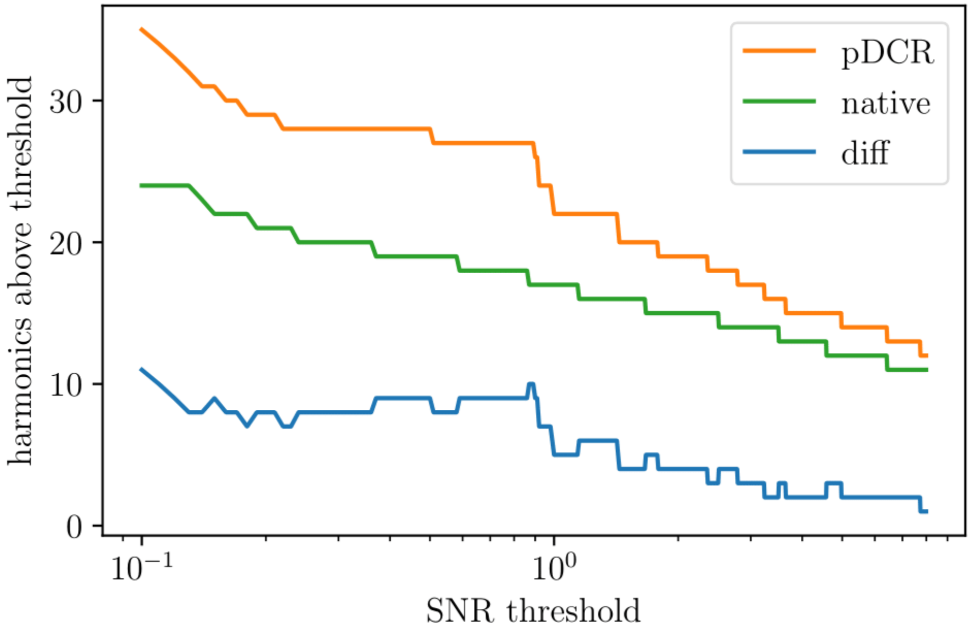
SNR of system matrix tuned with transfer function



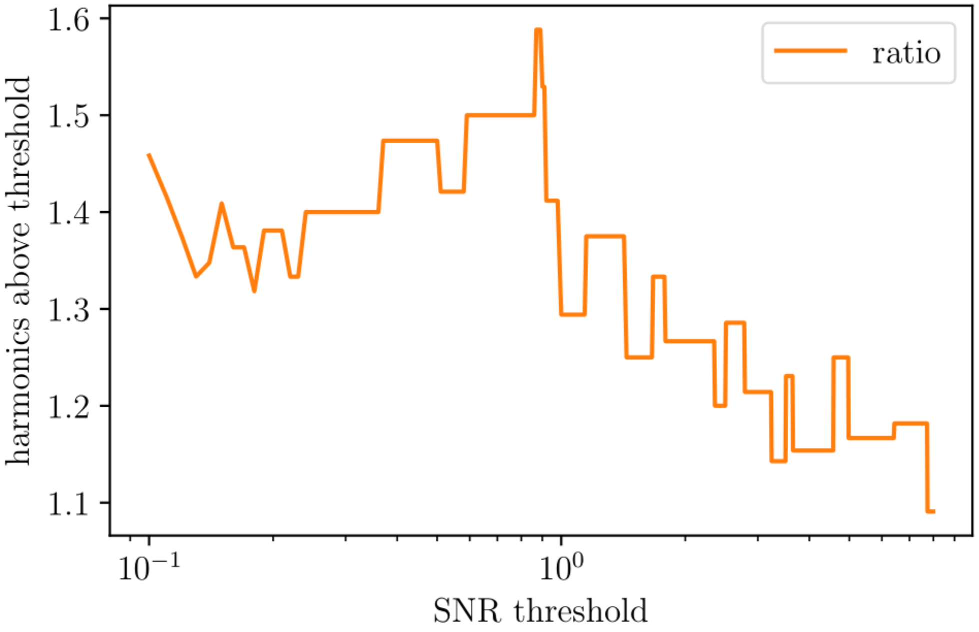
Impact of the pDCR – SNR Threshold

- Threshold variation
- Determination of number of harmonics with amplitude above threshold
  - (a) pDCR gives advantage for all thresholds
  - (b) Ratio $n_{\mathrm{h}}(\mathrm{pDCR})/n_{\mathrm{h}}(\mathrm{native})$ peaks at a threshold of 0.8

(a)

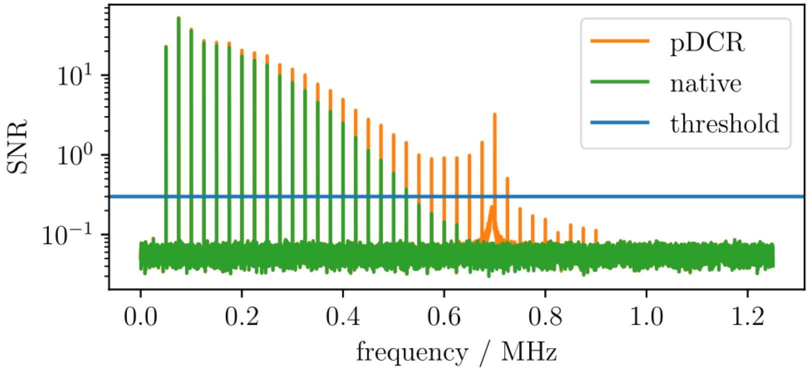


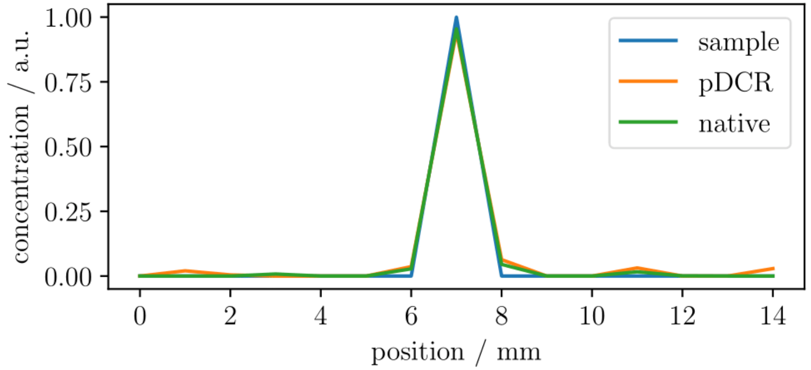
(b)



Impact of the pDCR – Threshold and Image Reconstruction

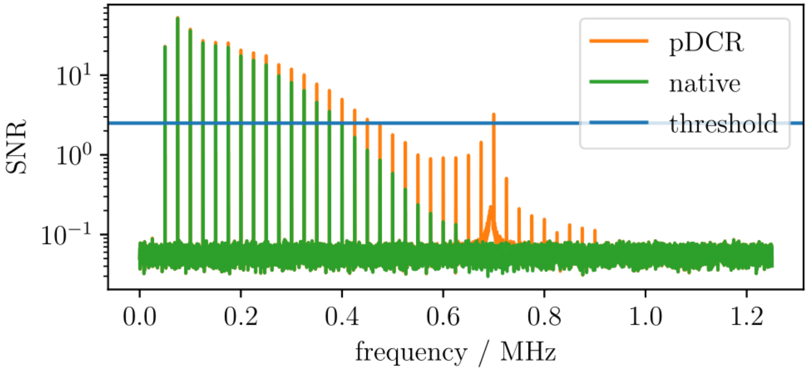
Threshold: 0.3

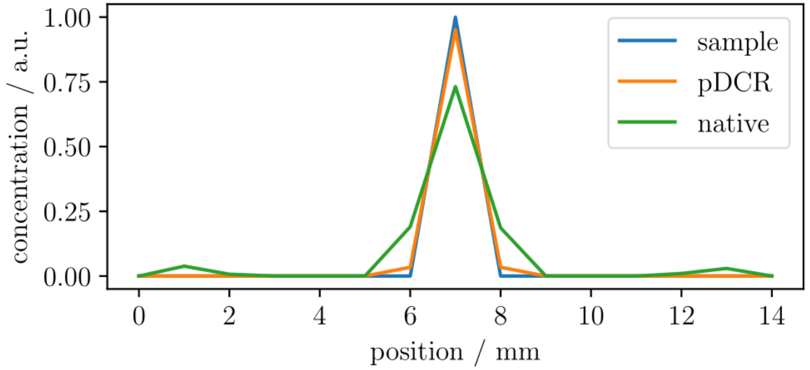




- Low threshold: No difference, both reconstructions perform well

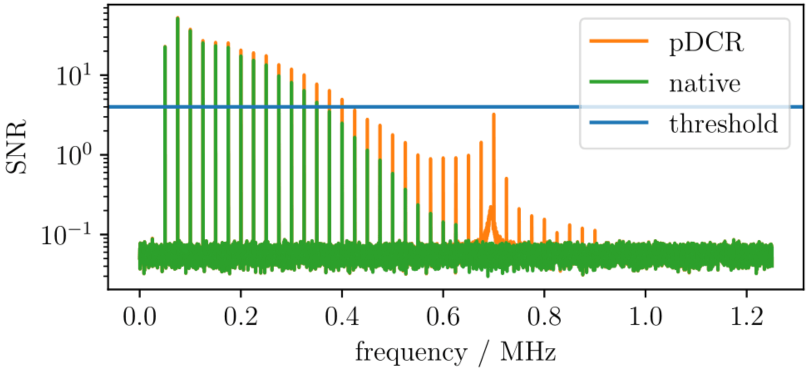
Threshold: 2.5

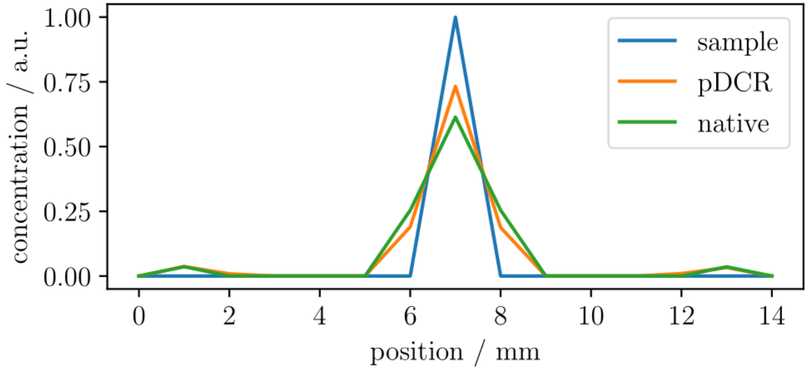




- Medium threshold: pDCR reconstruction performs well, while native gets worse

Threshold: 4.0





- High threshold: pDCR reconstruction gets worse, but still better than native

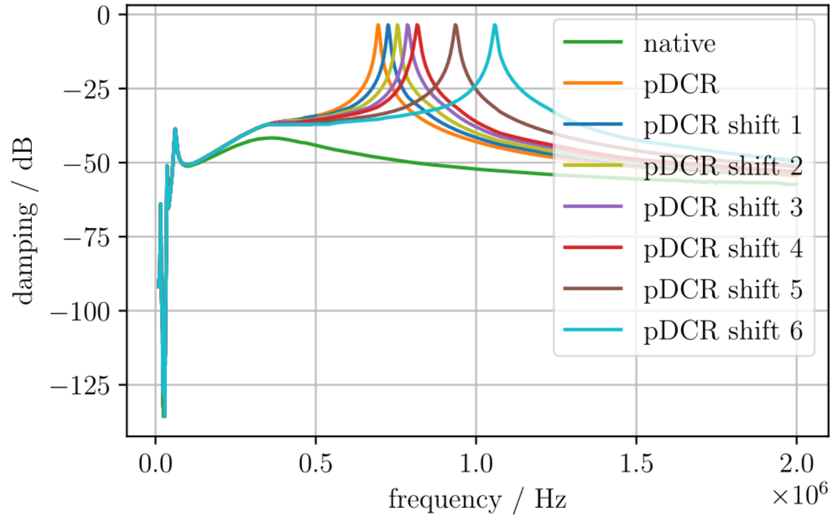
Impact of the pDCR – Shift of Resonance Frequency

- <u>Goal</u>: Increase the total number of harmonics above threshold
- Shifting the resonance frequency of the pDCR to higher frequencies

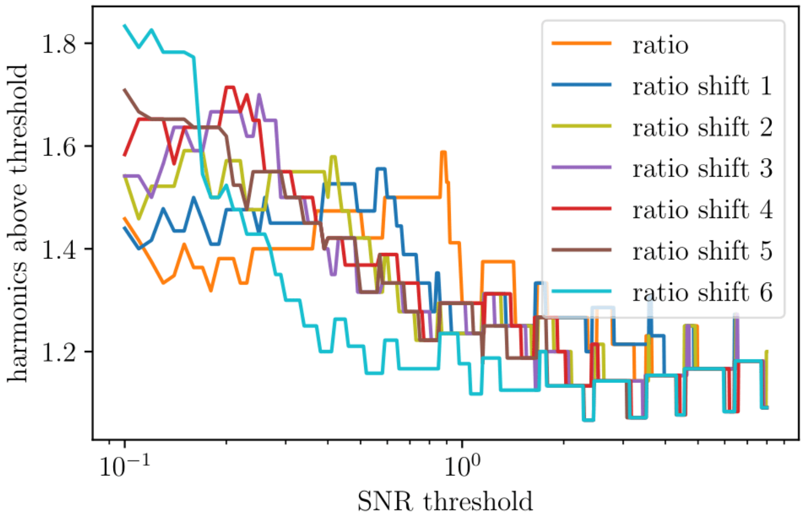
- <u>Results</u>:
  - Higher resonance frequency
    → Higher maximum ratio
    → Lower threshold at which the maximum is reached

⇒ Shifting the resonance frequency can optimize the performance of the pDCR
⇒ It depends on the threshold, which resonance frequency performs best

(a)



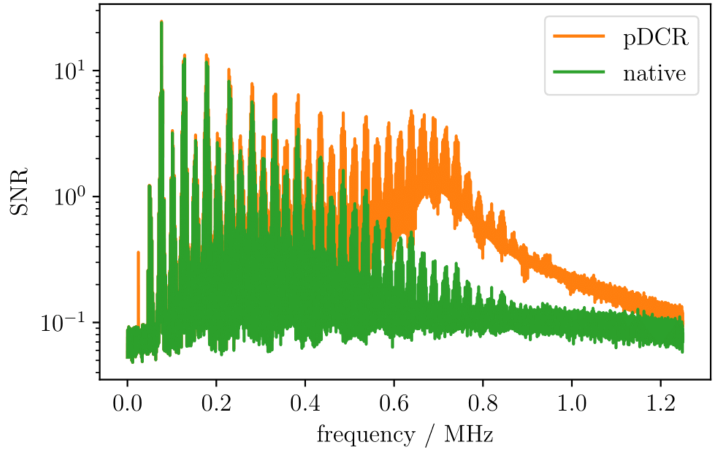
(b)



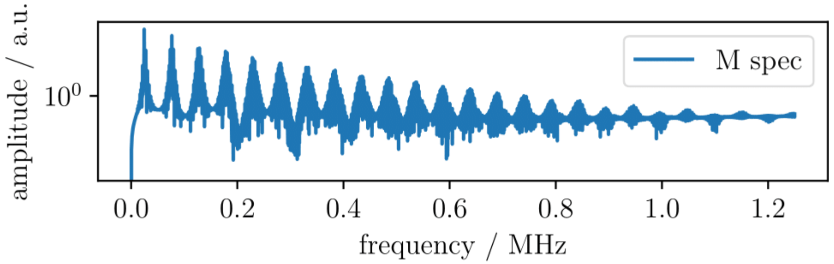
Impact of the pDCR – Simulations 3D

- 3D drive field
- Only signal induced in x-channel used
- Signal simulation:
  - (a) Magnetization signal in frequency domain
  - (b) Magnetization signal in time domain
  - (c) Voltage signal in time domain
  - (d) Voltage signal in frequency domain
- Transfer function of receive chain for signal tuning

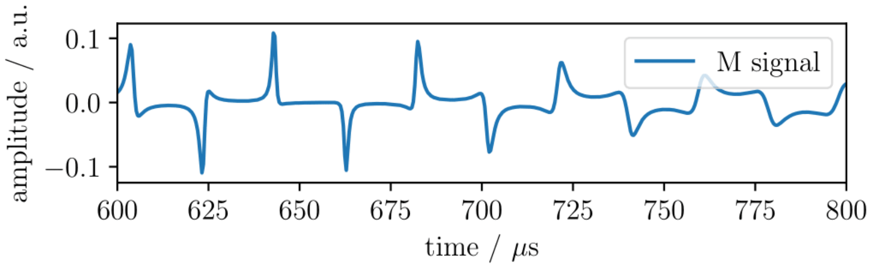
SNR of system matrix



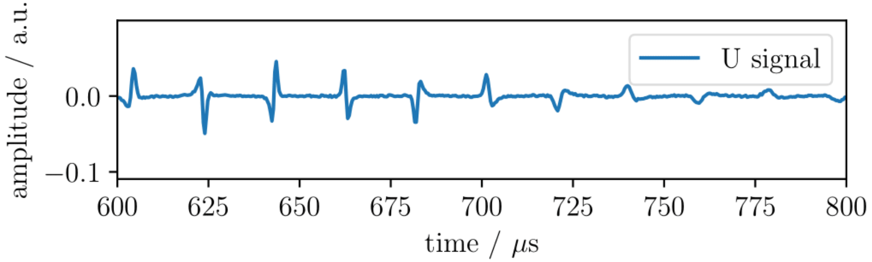
(a)



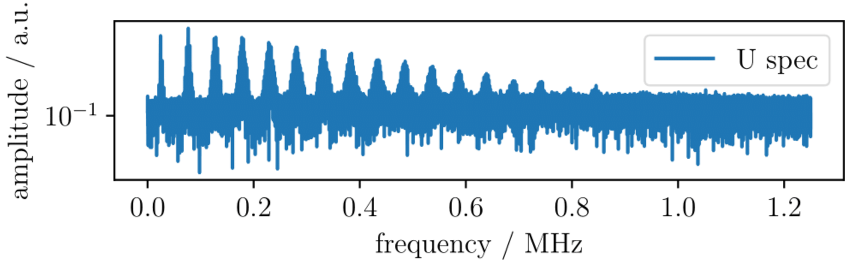
(b)



(c)



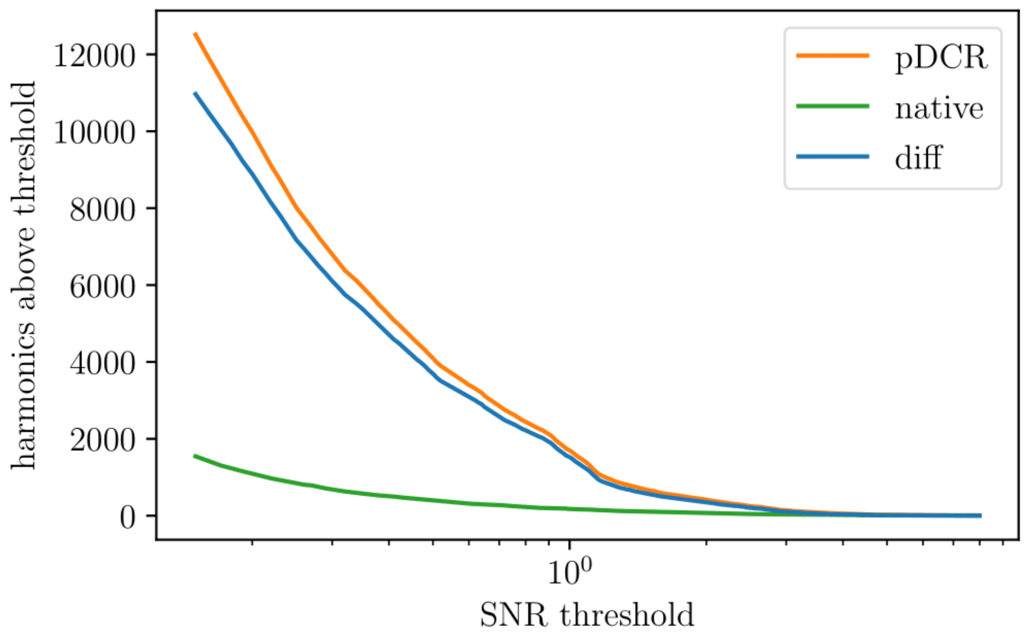
(d)



Impact of the pDCR – Threshold and Image Reconstruction

- Threshold variation
- Determination of number of harmonics with amplitude above threshold
  - (a) pDCR gives advantage for all thresholds
  - (b) Ratio $n_\mathrm{h}(\mathrm{pDCR})/n_\mathrm{h}(\mathrm{native})$ peaks at 0.9

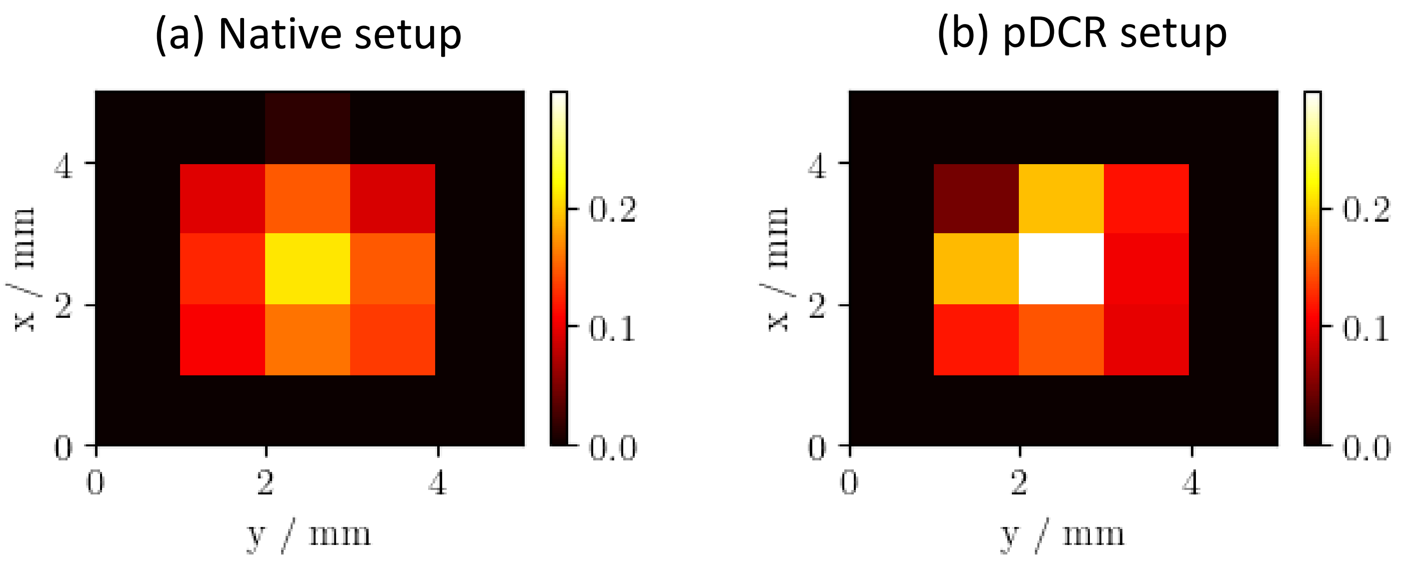
(a)



(b)

Impact of the pDCR – Threshold and Image Reconstruction

- Image reconstruction of a delta sample with a threshold of 0.9

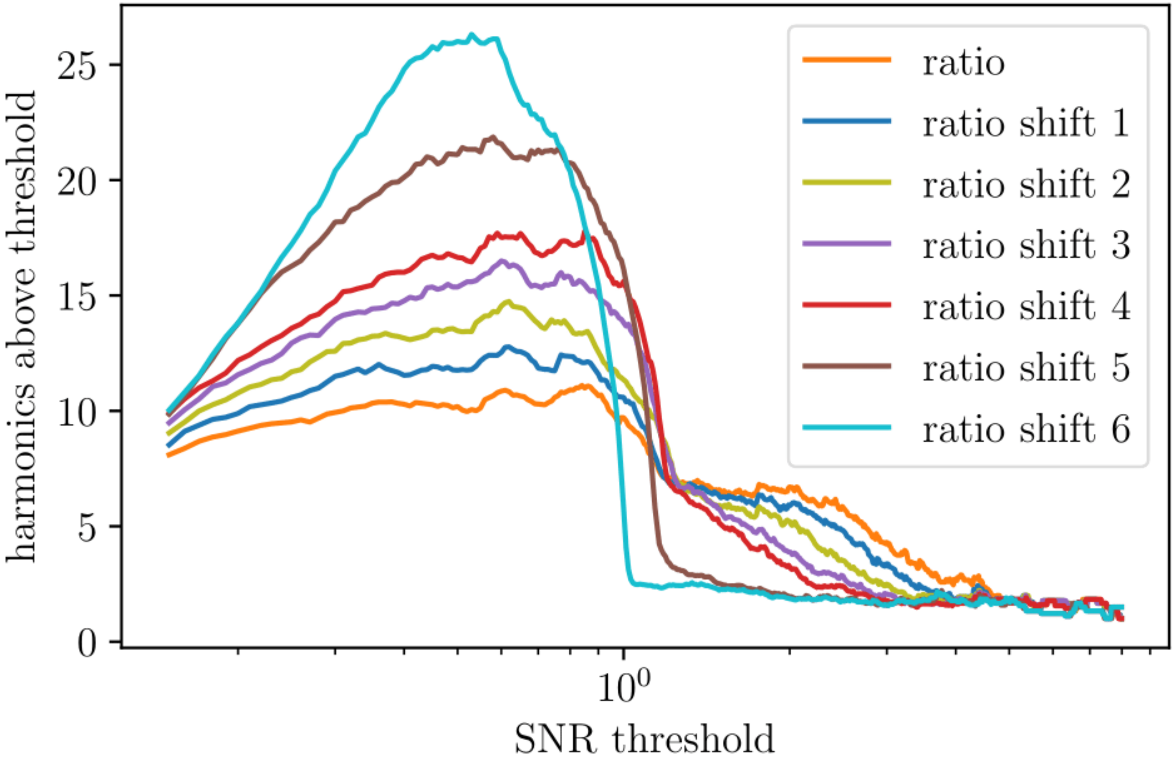


- Reconstructed intensity increased
- Signal flattens faster
  ⇒ Spatial resolution has improved

Impact of the pDCR – Shift of Resonance Frequency

- Goal: Increase the total number of harmonics above threshold
- Shifting the resonance frequency of the pDCR to higher frequencies

- Results:
  ⇒ Shifting the resonance frequency can optimize the performance of the pDCR
  ⇒ It depends on the threshold, which resonance frequency performs best



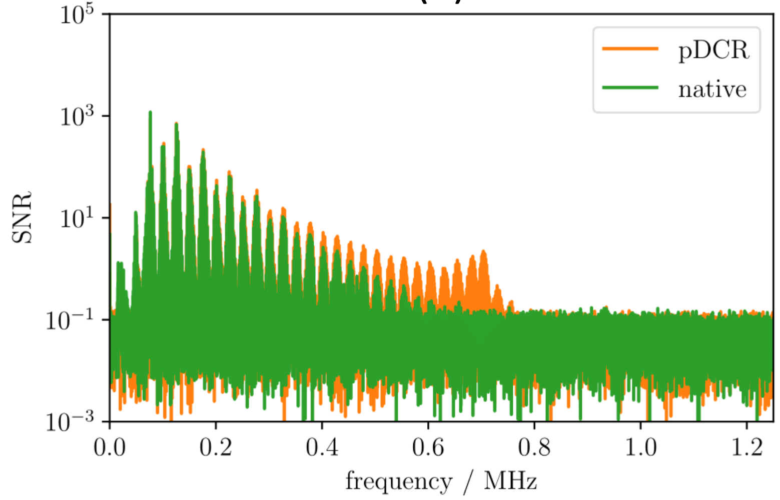
Impact of the pDCR – Measurements

- **Scanner**: Bruker Preclinical MPI system
  - Drive field amplitude: 14 mT
  - Drive field frequencies: 24.5 kHz, 26 kHz, 25.3 kHz
  - Max. magnetic field gradient: 2.5 Tm^{-1}

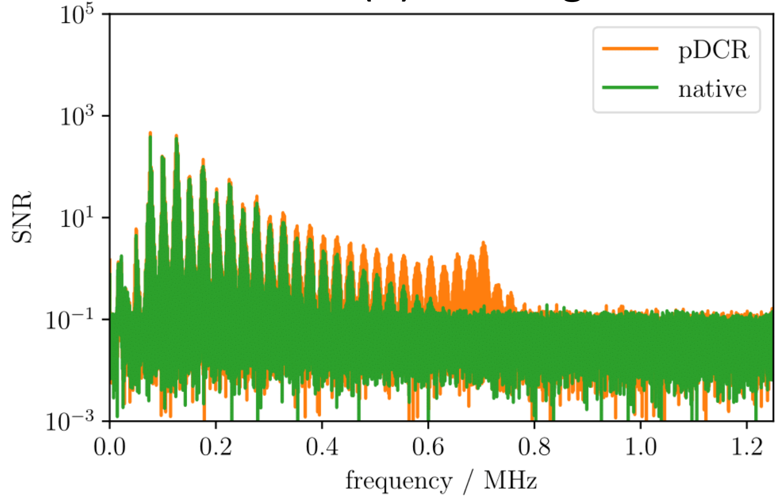
- **Tracer**:
  - C2 (in-house, hydrod. diameter: 49.4 nm, iron concentration: 8.5 mg/ml)
  - Perimag (commercial, hydrod. diameter: 130 nm, iron concentration: 8.5 mg/ml)

- **Measurements**:
  - SNR measurements
    - (a) C2
    - (b) Perimag
  - Resolution measurements

(a) C2

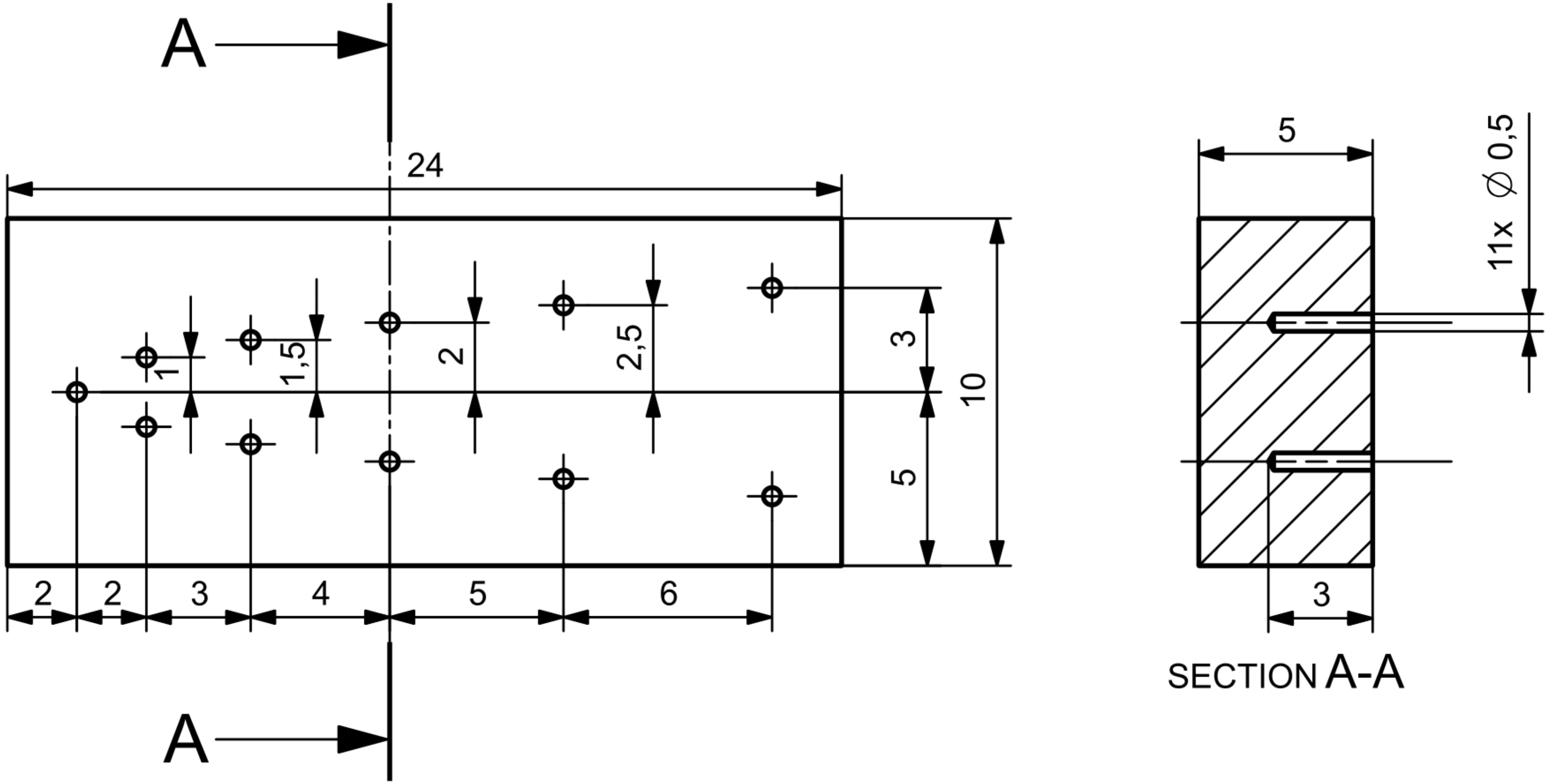


(b) Perimag



Impact of the pDCR – Resolution Phantom

MPI Resolution phantom
Material: Acrylic glass (unpolished)
All dimensions in mm

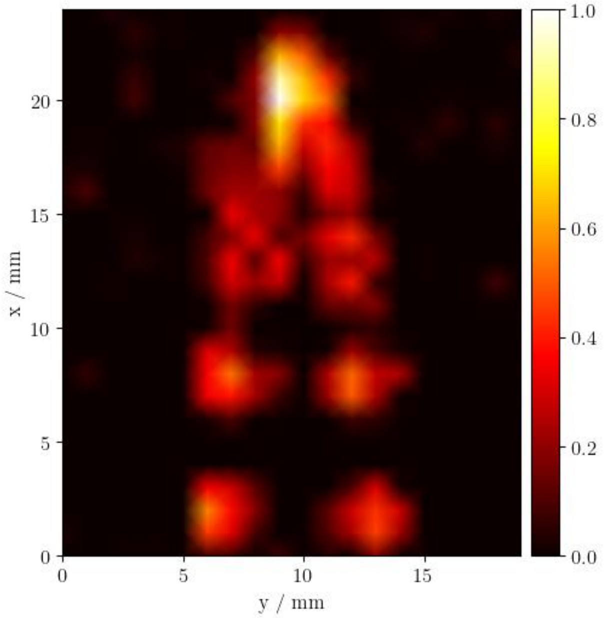


Impact – Reconstructed Images (C2, ParaVision)

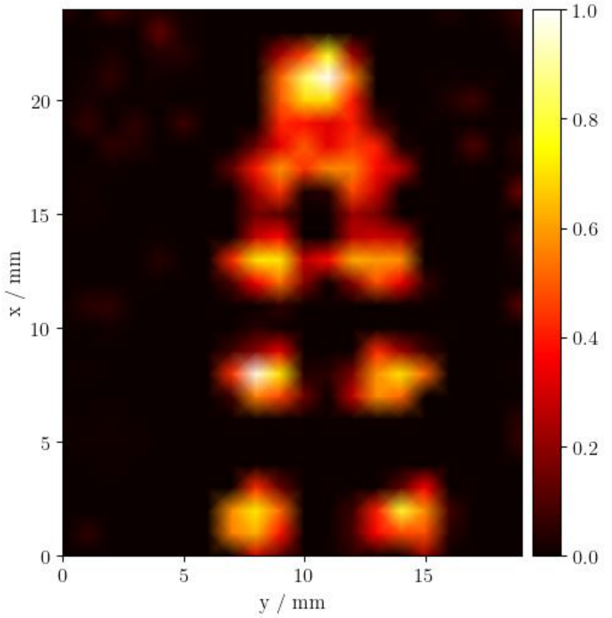
- Signal normalized
  → No comparison of reconstructed intensities possible
- No system matrix denoising → 500 averages for SM

⇒ Spatial resolution improved by the pDCR
- Points in clusters can be better resolved
- Individual points have an increased intensity compared to a cluster (mainly observable in the prominent plane)

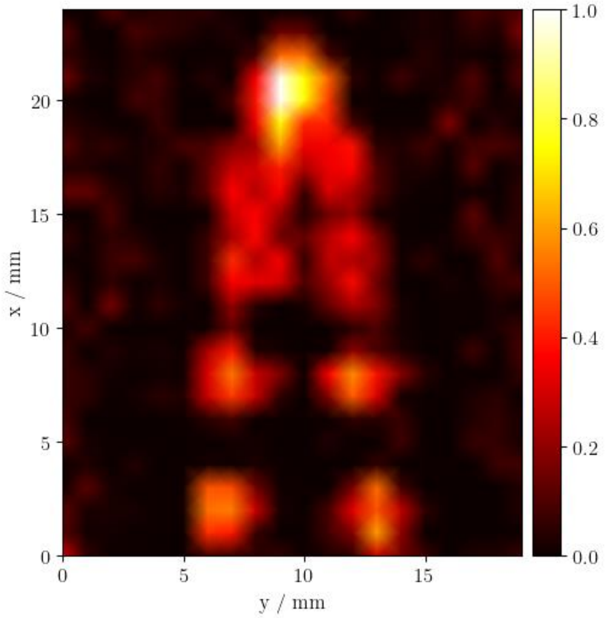
(a) Native – prominent plane



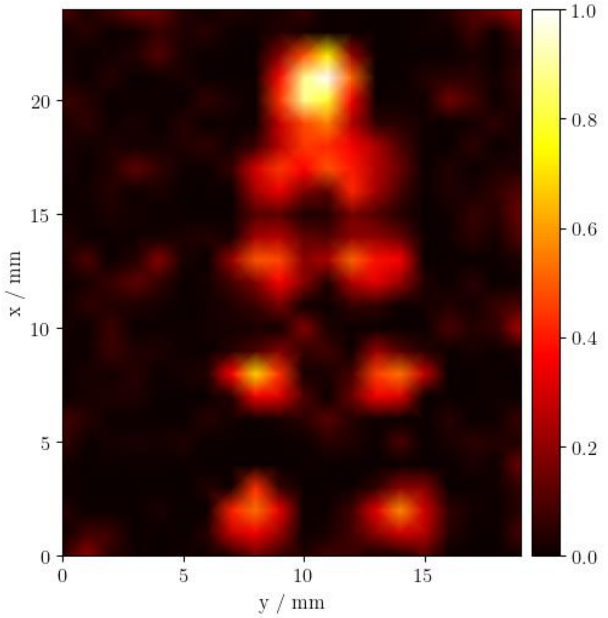
(b) pDCR – prominent plane



(c) Native - overlay



(d) pDCR - overlay

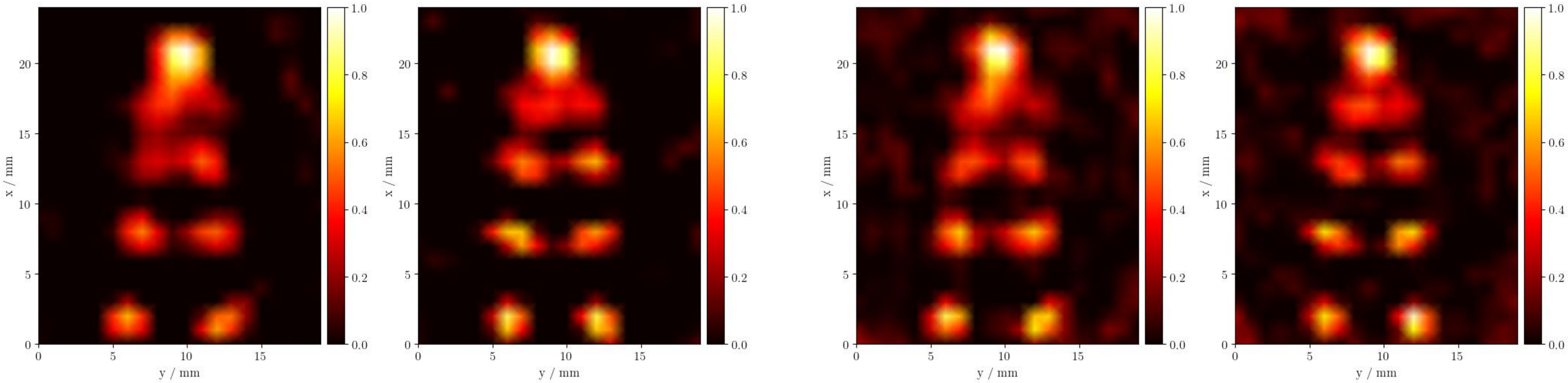


Impact – Reconstructed Images (Perimag, ParaVision)

- Signal normalized
  → No comparison of reconstructed intensities possible
- System matrix denoising → number of averages reduced to 300

⇒ Spatial resolution improved by the pDCR
- Points in clusters can be better resolved
- Individual points have an increased intensity compared to a cluster (mainly observable in the prominent plane)

(a) Native – prominent plane (b) pDCR – prominent plane (c) Native - overlay (d) pDCR - overlay

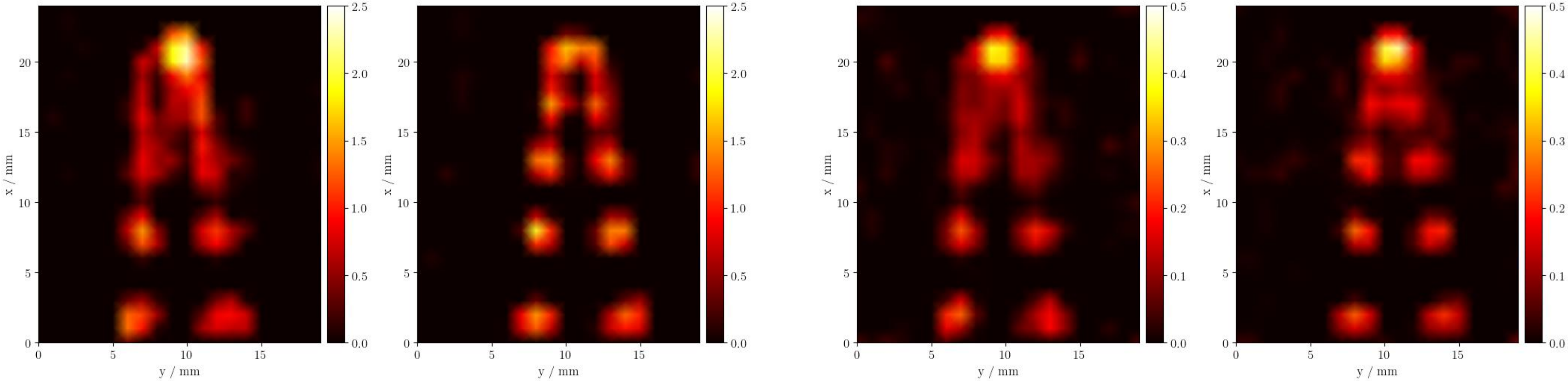


Impact – Reconstructed Images (C2, Python)

- Signal not normalized
  → Comparison of reconstructed intensities possible
- System matrix denoising

⇒ Spatial resolution improved by the pDCR
- Points in clusters can be better resolved
- Individual points have an increased intensity (mainly observable in the prominent plane)

(a) Native – prominent plane (b) pDCR – prominent plane (c) Native - overlay (d) pDCR - overlay

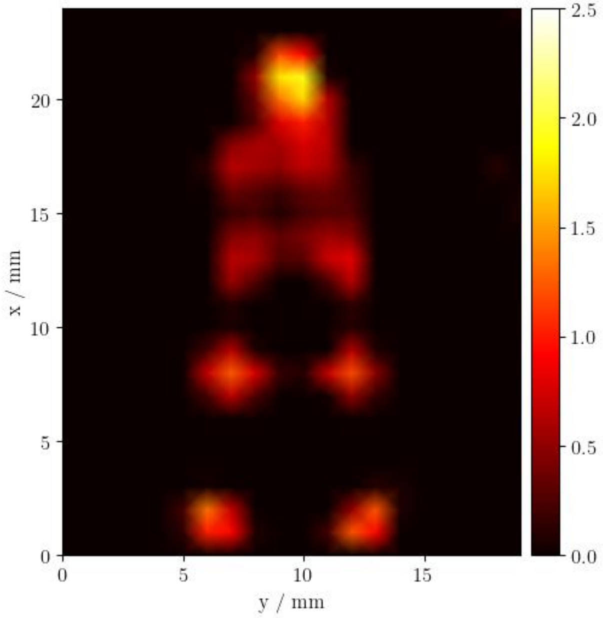


Impact – Reconstructed Images (Perimag, Python)

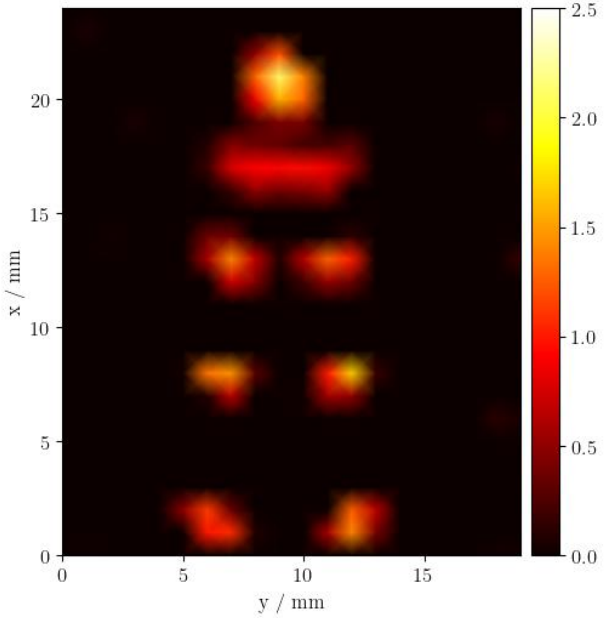
- Signal not normalized
  → Comparison of reconstructed intensities possible
- System matrix denoising

⇒ Spatial resolution improved by the pDCR
- Points in clusters can be better resolved
- Individual points have an increased intensity (also observable in the overly)

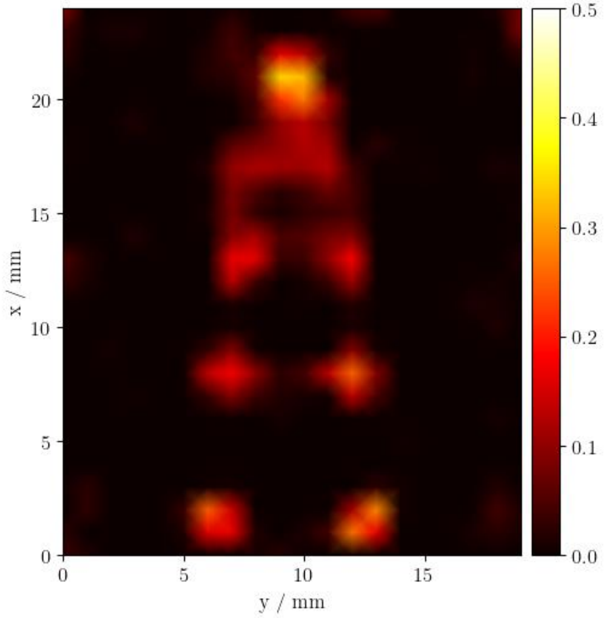
(a) Native – prominent plane



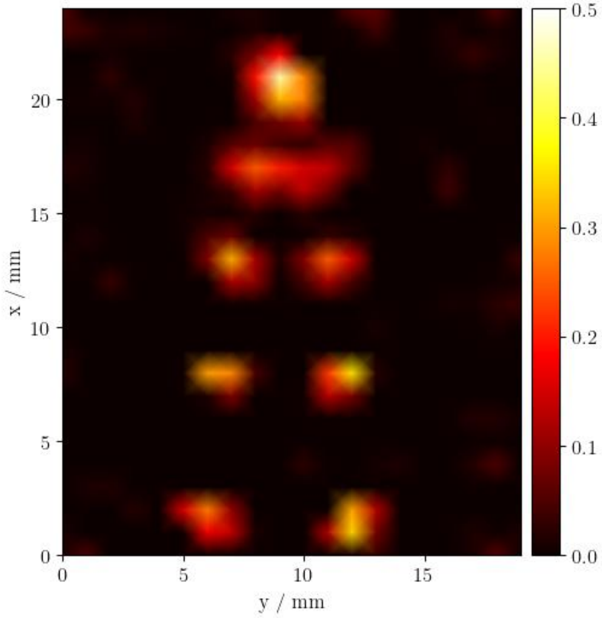
(b) pDCR – prominent plane



(c) Native - overlay



(d) pDCR - overlay



Conclusion and Outlook

- **Conclusion**:
  - Simulation (1D and 3D drive field):
    - ✓ pDCR enhances the SNR of higher harmonics
    - ✓ FWHM of PSF (spatial resolution) is increased by pDCR
    - Shifting the resonance frequency to higher harmonics:
      - ✓ Number of harmonics above threshold increases
      - ✓ Ratio $n_{\mathrm{h}}(\mathrm{pDCR})/n_{\mathrm{h}}(\mathrm{native})$ depends on threshold
  - Measurements (at Bruker scanner):
    - ✓ SNR enhancement of higher harmonics validated (Perimag and C2)
    - ✓ Resolution phantom: spatial resolution and absolute intensities increased with the pDCR (Perimag and C2)

- **Outlook**:
  - ➢ Optimizing noise modelling (especially in 3D simulation)
  - ➢ Using all three channels in 3D simulation
  - ➢ Different pDCR designs:
    - Tunable pDCR
    - 3D pDCR
    - Mini pDCR

Thank you for your attention!

Any questions?

References

[1] Tobias Knopp and Thorsten M. Buzug. Magnetic Particle Imaging: An Introduction to Imaging Principles and Scanner Instrumentation. Heidelberg: Springer, 2012

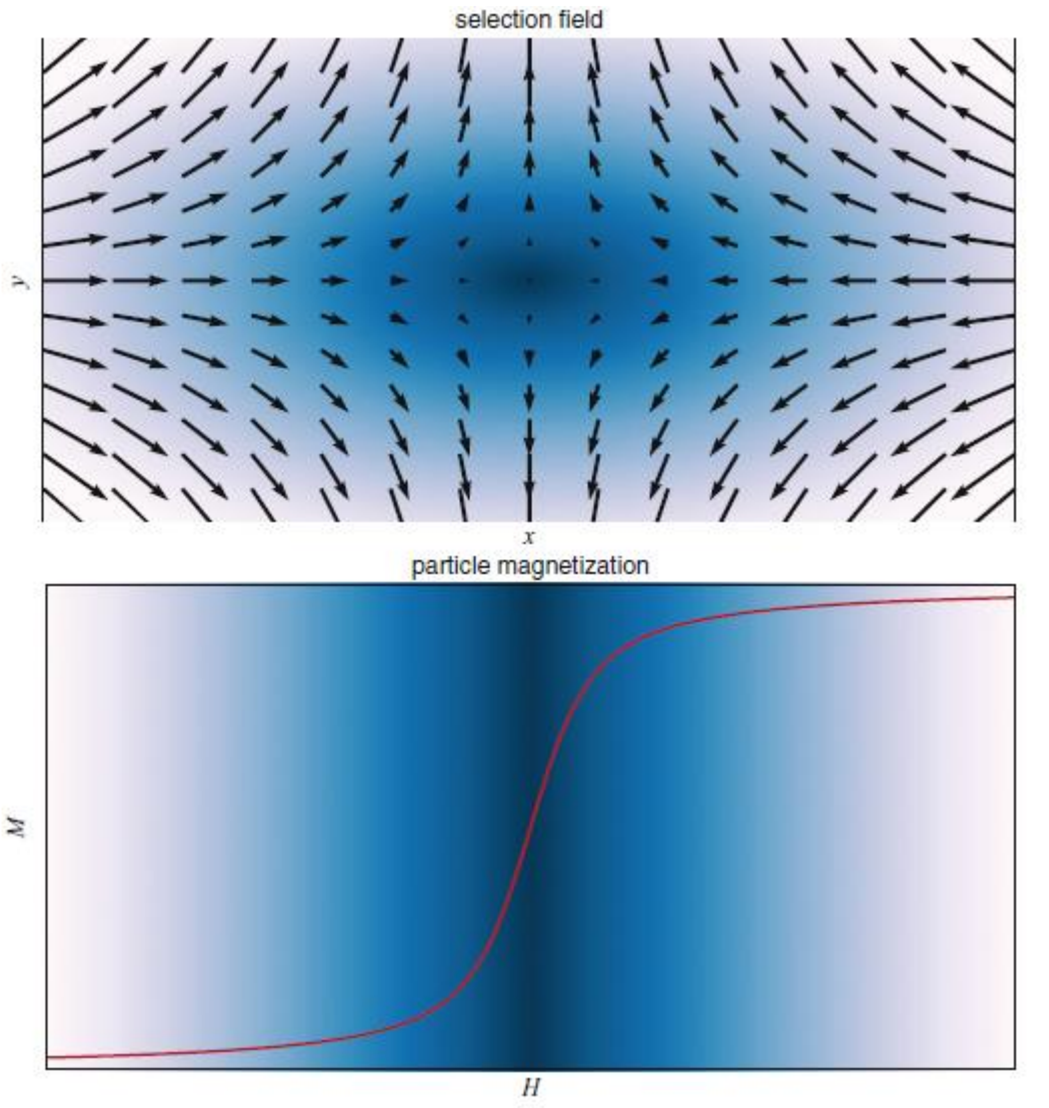
[2] L. W. E. Starmans & H. Gruell, PLOS, 2013

[3] Kerstin Lüdtke-Buzug, University of Lübeck

[4] T Knopp, N Gdaniec, and M Möddel. “Magnetic Particle Imaging: From Proof of Principle to Preclinical Applications”

[5] S D Reinartz et al. “Feasibility of a Spatial Resolution Enhancement by a Passive Dual Coil Resonator (pDCR) Insert for Large Bore MPI Systems”

Selection Field and Nonlinear Magnetization Behavior



V-Phantom Carrier