

Proceedings Article

Comparison of human-scale MPI system concepts using a 3D arbitrary-waveform magnetic particle spectrometer

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Abstract

In the field of Magnetic Particle Imaging (MPI) hybrid methods are utilizing the simplicity and high SNR of magnetic particle spectrometers to complement imaging by characterizing particles and measuring system matrices for fast system calibration. In this contribution we utilize the flexibility of our 3D arbitrary-waveform magnetic particle spectrometer to measure the system matrices of three MPI scanner concepts inspired by clinical-scale head-sized MPI systems. Using these system matrices we are able to compare reconstructed images under the same noise, particle and reconstruction conditions gathering first insights into the imaging properties of different scanners.

I. Introduction

Magnetic Particle Imaging (MPI) is approaching its first clinical applications with multiple human-scale systems near the first in-human experiments. In contrast to established imaging methods like Magnetic Resonance Imaging, these systems utilize different concepts regarding selection and excitation field sequences, each with their distinct advantages. For future developments in the field of MPI it is therefore important to compare the approaches of the current MPI systems and evaluate the performance of these conceptual differences. However, differences in the respective receive chains, reconstruction methods, and used nanoparticles do not allow the isolated evaluation of the basic concepts by just comparing the imaging results of the completed scanners.

In this work, we utilized a three-dimensional arbitrary-waveform magnetic particle spectrometer (3D-AWMPs,

[1]) to measure the hybrid system functions of three different human-scale MPI scanner concepts. Using these system functions it is possible to perform hybrid imaging experiments under comparable conditions, including the same particles, SNR and reconstruction parameters, highlighting only the differences inherent to the different field sequences.

II. Methods and materials

The three investigated system concepts are based on the core principles used in different head-size MPI systems [2–5]. However, the sequences were modified to improve comparability. The first system features a one-dimensional excitation in x with two slow triangular shift fields to move the FFP in a cartesian trajectory [4, 5]. The second system employs a two-dimensional Lissajous-type excitation in the xz -plane with a slow triangular

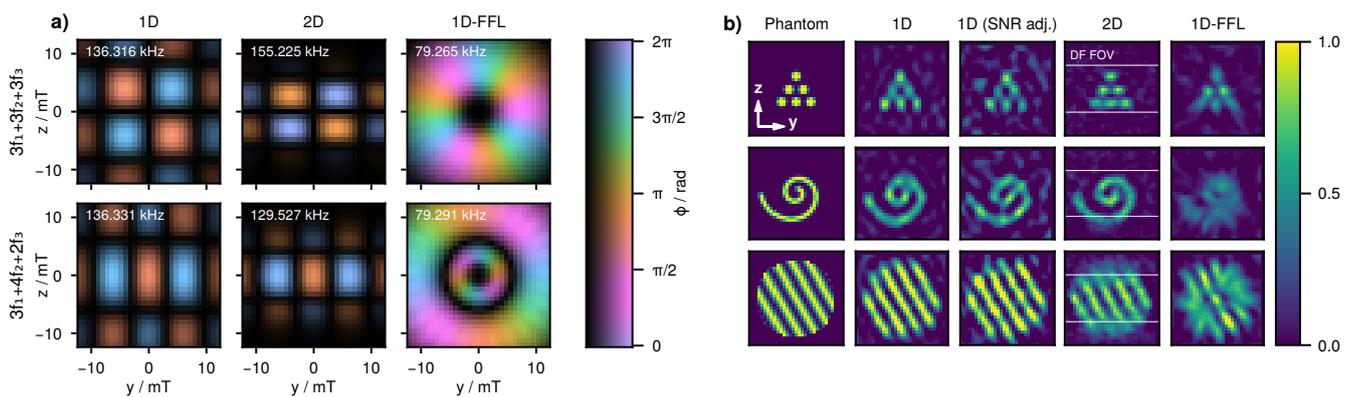


Figure 1: **a)** Representative complex-valued system matrix components visualizing the differences in FFP and FFL encoding. **b)** Reconstructions of three hybrid phantoms under identical noise conditions using the same reconstruction method. For column three, noise levels were increased by $\frac{46}{25} = 1.84$ to account for the SNR advantage of the higher excitation frequency.

Table 1: Overview of the parameters used for the selection field (SF), drive field (DF) and focus field (FF) of the three systems

	1D	2D	1D-FFL
SF	FFP	FFP	FFL, yz-plane
DF	x: 46 kHz, sin	x: 26 kHz, sin z: 25.7 kHz, sin	x: 26 kHz, sin
FF	y: 8 Hz, tri z: 1 Hz, tri	y: 1 Hz, tri	trans: 27 Hz, tri rot: 1 Hz

shift in the y-direction [2]. The third system features an FFL instead of an FFP, which is translated and rotated to scan the yz-plane, in addition to a 1D excitation in x [3]. All frequencies are listed in Table 1. With the slowest frequency set to 1 Hz, the volume scan time is 1 s in all cases. For comparison reasons all drive fields were set as 6 mT and all shift fields as 12 mT.

While the sequences already provide 3D encoding, this preliminary study only investigates the transverse (yz) plane. For that, a 31×31 hybrid system matrix (SM) [6] was recorded in our custom 3D-AWMPS [1] using Reso-tran. The identical hybrid selection fields cover a FOV of 24×24 mT (i.e. 48×48 mm @ 0.5 T m^{-1}). Representative frequency components of these SMs are shown in Figure 1a, highlighting the encoding differences of FFP and FFL imaging and the strong similarities between the 1D and 2D excitation.

For hybrid imaging experiments, the SMs were multiplied with software-defined phantoms, superimposed with white noise to avoid inverse crime and reconstructed using the original SM and the l_2 -regularized Kaczmarz method from MPIReco.jl [7].

III. Results and discussion

The reconstruction results are shown in Figure 1b. While the 2D sequence shows the best resolution in z (direction of the additional excitation field), the lower amplitude in that direction limits the usable FOV, resulting in smeared reconstructions of the phantom with larger extension in z. The reconstructions of the FFL sequence are less resolved compared to the other two sequences at the same noise level, especially the spiral phantom is barely visible. The 1D sequence provides sharp reconstructions with a large FOV, partially due to the increased SNR from the higher excitation frequency, as the reconstruction performs worse when noise levels are adjusted.

Note that these first, qualitative results are valid for the system matrix reconstruction. It is possible that other reconstruction methods fine-tuned for each sequence might further influence the performance. Additionally, we used the ideal field profiles without taking into account inhomogeneities and system specific noise characteristics which further influence the imaging results in a real-world system. To translate the hybrid results to spatial domain the gradient strength of the different systems needs to be applied.

IV. Conclusion

We have shown that the 3D-AWMPS can be a useful tool in comparing MPI scanners, showing first insights into the differences of the concepts of current clinical-scale MPI systems. In the future this enables many more detailed analyses to aid the decision-making in MPI scanner development and the design of imaging trajectories and reconstruction methods and their performance with different nanoparticle types.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

References

- [1] J. Ackers, J.-P. Scheel, S. Ilbey, F. Jochen, T. Buzug, and M. Graeser. A three-dimensional arbitrary waveform MPS for MPI scanner concept evaluation. *International Journal on Magnetic Particle Imaging IJMPI*, 11(1 Suppl 1), 2025.
- [2] F. Thieben, F. Foerger, F. Mohn, N. Hackelberg, M. Boberg, J.-P. Scheel, M. Möddel, M. Graeser, and T. Knopp. System characterization of a human-sized 3D real-time magnetic particle imaging scanner for cerebral applications. *Communications engineering*, 3(1):47, 2024, doi:[10.1038/s44172-024-00192-6](https://doi.org/10.1038/s44172-024-00192-6).
- [3] E. Mattingly, M. Śliwiak, E. Mason, J. Chacon-Caldera, A. Barksdale, F. H. Niebel, K. Herb, M. Graeser, and L. L. Wald. Design, construction and validation of a magnetic particle imaging (MPI) system for human brain imaging. *Physics in Medicine & Biology*, 70(1):015019, 2025, doi:[10.1088/1361-6560/ad9db0](https://doi.org/10.1088/1361-6560/ad9db0).
- [4] Z. Wei, Y. Liu, S. Liu, X. Yu, H. Zhang, T. Zhu, B. Zhang, Y. Zhang, H. Huang, Y. Fan, *et al.* First nonhuman primate-sized magnetic particle imaging system based on digital-scanned focus field. *IEEE Transactions on Instrumentation and Measurement*, 73:1–11, 2024, doi:[10.1109/TIM.2024.3418109](https://doi.org/10.1109/TIM.2024.3418109).
- [5] E. E. Mason, E. Barcikowski, J. Carl, M. Chandeeing, B. Davison, B. Fellows, W. Fetsch, K. Fields, J. Greve, J. J. Konkle, *et al.* Preliminary results: Large bore clinical mpi system imaging human head-sized fovs. *International Journal on Magnetic Particle Imaging IJMPI*, 10(1 Suppl 1), 2024.
- [6] A. Von Gladiss, M. Gräser, P. Szwargulski, T. Knopp, and T. M. Buzug. Hybrid system calibration for multidimensional magnetic particle imaging. *Physics in Medicine & Biology*, 62(9):3392, 2017.
- [7] T. Knopp, P. Szwargulski, F. Griesse, M. Grosser, M. Boberg, and M. Möddel. MPIReco.jl: Julia package for image reconstruction in MPI. *International Journal on Magnetic Particle Imaging IJMPI*, 5(1), 2019, doi:[10.18416/ijmpi.2019.1907001](https://doi.org/10.18416/ijmpi.2019.1907001).