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Traveling Wave MPI utilizing a Field-Free Line

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Abstract

Field-free line (FFL) Magnetic Particle Imaging (MPI) scanners are of high interest for fast and accurate scanning of 3D samples because of the higher signal-to-noise ratio due to the enlarged encoding scheme. Until now, only magnetic field generators have been presented providing an electrical rotation and displacement of an FFL within a 2D slice. Utilizing double-helix coils and the Traveling Wave approach, a full 3D FFL MPI scanner can be introduced, providing fast 3D imaging with less hardware efforts.

I. Introduction

Since the first publication of Magnetic Particle Imaging (MPI) in 2005 by B. Gleich and J. Weizenecker [1], multiple different scanner designs have been presented [2]. The basic idea behind MPI is to measure the non-linear magnetization response of superparamagnetic iron-oxide nanoparticles (SPIONs) to time-varying magnetic fields. For encoding, a strong magnetic field gradient is rapidly moved through the field of view (FOV) inducing MPI signal in the receive coil by the change of the SPION magnetization. Two different encoding schemes have been presented: field-free point (FFP) and field-free line (FFL).

Originally, FFP scanners used either permanent magnets [1, 3] or electromagnets [4, 5, 6] assembled in Maxwell configuration for the generation of a static FFP in the center of the system. Using additional drive-coils in Helmholtz configuration, the FFPs can be steered on specific trajectories covering the entire FOV. For scanning FOVs of the size of a whole rodent, the Traveling Wave MPI scanner has been presented in 2014 using a dynamic linear gradient array (dLGA) generating and moving multiple FFPs dynamically along the scanner [7, 8]. All FFP scanners provide high acquisition speed [9, 10], high sensitivity [11] and good spatial resolution [12].

FFL scanners firstly have been introduced in 2008 [13]. Their more complex setup using permanent or electro magnets allows the generation, movement and rotation of an FFL, which provides the acquisition of projections of the sample with a higher signal-to-noise ratio (SNR) [14, 15, 16, 17, 18]. However, the complex hardware requirements for magnetic field generation only allow for fast 2D signal acquisition. For 3D scanning, additional mechanical parts are required, i.e., a mechanically rotated gantry.

In this abstract, a novel MPI scanner design is presented, which provides dynamic 3D projection imaging using an FFL entirely generated by electro magnets.

II. Material and methods

The basic idea behind this novel approach is the dLGA concept used in TWMPI scanners [7, 8]. In a dLGA-4 system four solenoids, fed with the same sinusoidal current with frequency f_1 and a phase shift between adjacent coils of 90°, are used to generate traveling FFPs along the symmetry axis. By replacing the four solenoids in the dLGA-4 by a double-helix dipole coil design (DHD or cross-coil – CC) [19], a field-free line traveling along the

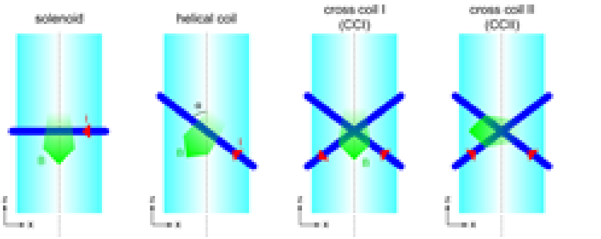

Figure 1: Evolution from single solenoid to cross-coil concept.

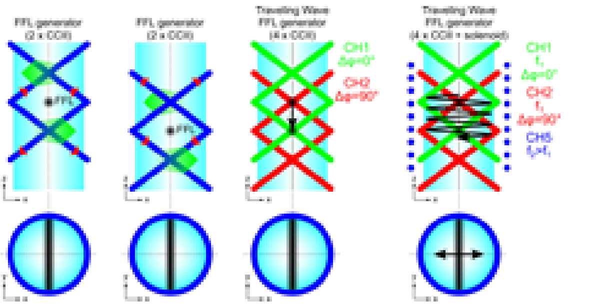

Figure 2: Concept of the Traveling Wave FFL generator. The dark regions at the bottom indicate the FFL.

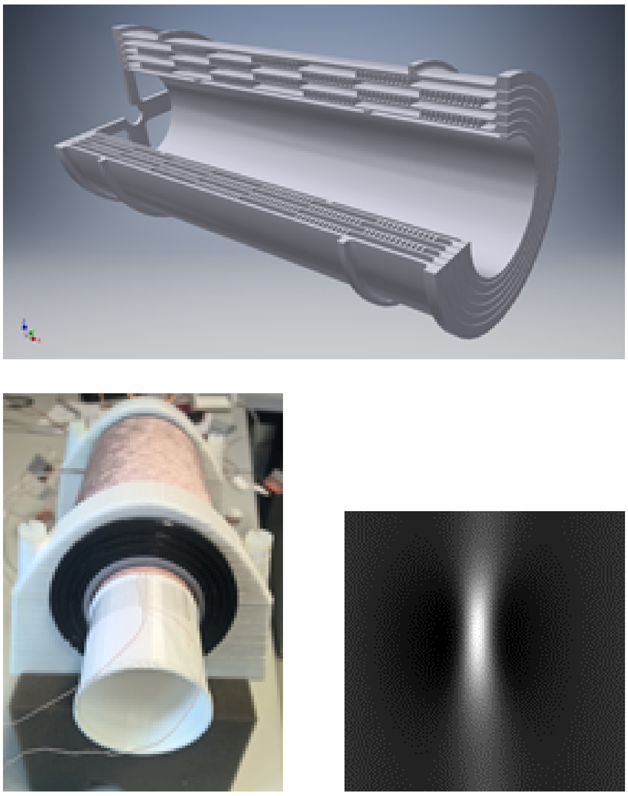

Figure 3: Top: CAD rendering of the 3D printable coil holders. Bottom left: photo of the first prototype of the TWMPI FFL scanner. Bottom right: first measurement of a point-like sample.

symmetry axis can be generated.

In Fig. 1 the concept is shown: a single solenoid is tilted and complemented by a second one to form a cross-coil. Depending on the direction of current (CCI and CCII), the magnetic field direction can be adjusted in x- and z-direction.

Assembling two cross-coils with configuration II (CCII) along the z-axis, where the magnetic field direction is inverted (compare Maxwell configuration of two solenoids), a static field-free line is generated in their center (see Fig. 2). Adding a second pair of CCII coils and feeding both with a sinusoidal current and a phase shift of 90°, the FFL travels along the symmetry axis (Traveling Wave approach [7]).

A solenoid assembled around the entire system allows to translate the FFL in the x-y-plane regardless of its orientation. With this generator, a full projection through the FOV can be provided. For FFL rotation around the z-axis an additional Traveling Wave FFL Generator (4×CCII coils) is assembled in perpendicular orientation (90° rotated around z-axis). At the end, five independent channels (CH1..CH4 feeding the cross-coils and CH5 feeding the solenoid) running at three frequencies ($f_1 \dots f_3$) are required to move the FFL within the 3D volume (see Table 1).

Table 1: Overview about the channels and frequencies driving a full 3D FFL scanner.

Channel	
CH 1	$A \cdot \sin(2\pi f_1) \cdot \sin(2\pi f_2)$
CH 2	$A \cdot \sin(2\pi f_1 + \pi/2) \cdot \sin(2\pi f_2)$
CH 3	$A \cdot \sin(2\pi f_1) \cdot \sin(2\pi f_2 + \pi/2)$
CH 4	$A \cdot \sin(2\pi f_1 + \pi/2) \cdot \sin(2\pi f_2 + \pi/2)$
CH 5	$B \cdot \sin(2\pi f_3)$

III. Results and discussion

In initial simulation studies with a home-built simulation framework [20], the geometry and field performance of the TWMPI FFL scanner has been determined for a FOV with length 70 mm and 30 mm diameter and gradient strength of about 1.5 T/m. In Fig. 3 top, a CAD rendering of the 3D printable coil holders can be seen providing multiple layers for the cross-coils and the solenoid.

In Fig. 3 bottom left, a photo of the first TWMPI FFL scanner is shown. For an easy fabrication and space-saving assembling of the cross-coils, a special winding technique is used providing compact dimensions of the entire scanner of 158 mm in length and 70 mm in diameter.

In Fig. 3 bottom right, the first result of a 2D scan of a point-like sample is demonstrated (frequencies: f_1=220.4 Hz, f_2=0.0 Hz, f_3=9329.9 Hz).

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IV. Conclusions

The TWMPI FFL scanner design uses a novel approach for the dynamic generation, movement and rotation of a field-free line. This allows scanning full 3D samples with short acquisition times and the advantages of a higher SNR. Since the hardware requirements are small, compact scanners can be built, which can revolutionize preclinical usage of MPI.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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