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Proceedings Article

A concept for an MPI scanner with Halbach arrays

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Abstract

One of the major challenges of MPI is the upscaling of scanners. Typically, the magnetic fields are generated electromagnetically with immense power consumption, which becomes a severe issue for larger setups. However, electromagnets provide high flexibility in terms of adjusting the gradient strength of the selection field and providing quickly alternating drive fields. The scanner concept proposed here reduces the power consumption drastically, because both the selection field and the drive field are generated by rotating permanent magnets. In addition, it maintains the flexibility to adjust the gradient strength for different imaging sequences. The selection field consists of two concentric Halbach quadrupoles. Mutual rotation of the nested quadrupoles enables the variation of the gradient strength. The drive field is generated by two reversely rotating Halbach dipoles driving the field free point on a radial trajectory. To show the feasibility of the setup an exemplary image simulation with an additional excitation field is performed and the resulting reconstruction is discussed.

I Introduction

One of the major challenges for the upscaling of MPI scanners is the power consumption of electromagnetically generated fields. Already Gleich and Weizenecker [1] proposed two opposing permanent magnets for the generation of a field free point (FFP). A field free line (FFL) scanner was presented in [2], using permanent magnets in Halbach configuration. A scanner was demonstrated in [3], which generates an FFP by two opposing permanent magnet rings, which is then moved by two reversely rotating Halbach rings in dipole configuration. The main drawback of using permanent magnets in comparison to electromagnets is the adjustability of field and gradient strengths. Therefore, we propose a scanner concept, which uses two reversely rotating Halbach dipoles, generating the drive field and two nested Halbach quadrupoles, which generate the selection field [4, 5]. By choosing the angle between the quadrupoles the gradient strength can be adjusted. The superposition of the drive field and the selection field drives the FFP on a radial trajectory. We show the calculations of the Halbach configurations, numeric simulations of the proposed geometry as well as an exemplarily simulation of the MPI performance of the proposed system of magnets.

II Material and methods

The concept of the proposed MPI scanner is introduced, an equation for the analytic calculation of the expected flux density is derived and the applied simulation parameters are given.

II.I The concept for a Halbach design

The selection field is generated by two concentrically nested Halbach quadrupoles, each producing the same

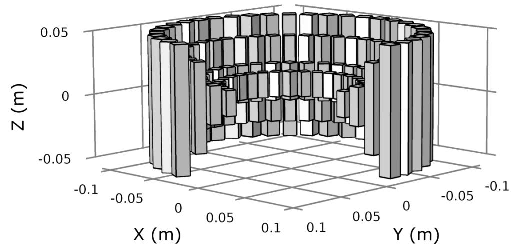

Figure 1: The proposed setup. The two innermost Halbach rings are in dipole configuration and generate the drive field via reverse rotation. The two outermost Halbach rings are in quadrupole configuration and generate the selection field with adjustable gradient strength.

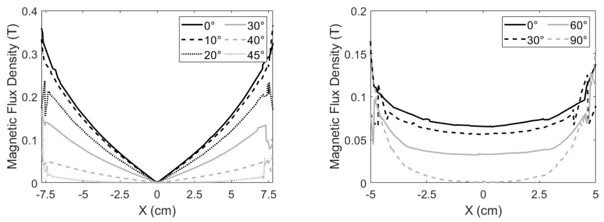

Figure 2: By changing the rotation angle between the two quadrupole rings, the gradient strength can be varied between 0 and 2.6 T/m (left). By rotating the two dipole rings a drive field with an amplitude of 65 mT is generated (right).

gradient strength G_{quad}. An FFL is generated along the cylinder axis, which is used as a 2D FFP in the x/y-plane. By rotating the quadrupole rings reversely, the gradient strength can be adjusted according to:

$$|G| = 2G_{quad}|\cos\alpha|, \tag{1}$$

with α the angle between the quadrupole rings. The drive field is generated by two concentrically nested Halbach dipoles, each producing a homogeneous magnetic field of the same flux density B_{dip}. When rotating the dipoles reversely, the time dependent flux density reads:

$$B_{drive} = 2B_{dip}\cos\omega t, \tag{2}$$

with $\omega = 2\pi f$ the angular frequency. When superimposing the drive field with the selection field, the FFP moves on a line. By a rotation of the whole setup a radial trajectory of the FFP is obtained.

II.II Calculations of the magnetic fields

The magnetic field strength of an ideal Halbach dipole is given by [6]

$$B_{dipole}^{ideal} = B_r \ln\frac{r_i}{r_o}, \tag{3}$$

with B_r the remanence of the used permanent magnetic material, r_o the outer, r_i the inner and r the radius of the Halbach ring. When using N bar magnets with edge

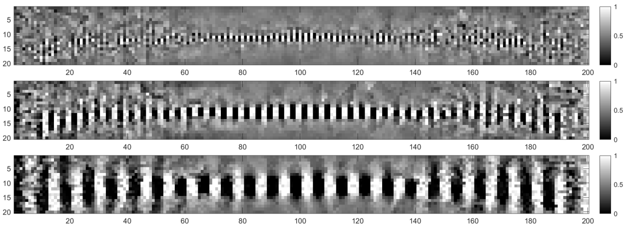

Figure 3: The image reconstruction using line phantoms of 0.5 mm (top), 1.0 mm (middle) and 2 mm (bottom) line width. The lengths of the phantoms and the images are 10 cm.

length a and length l, the flux density of a Halbach dipole decreases accordingly [5]:

$$B_{dipole} = \frac{l(6r^2+l^2)}{(4r^2+l^2)^{3/2}}\frac{Na^2}{\pi(r_o^2-r_i^2)}B_r\ln\frac{r_i}{r_o}. \tag{4}$$

With this equation two Halbach dipoles were found, producing the same flux density. Halbach quadrupoles can be calculated accordingly [4], so that two rings give the same gradient strength.

II.III Simulations

Numeric simulations are performed with COMSOL Multiphysics for the proposed geometry. With the results from the numeric simulation the MPI performance is evaluated with 2D line phantoms of 0.5, 1.0 and 2.0 mm line width for maximum gradient strength. The FFP is driven on a 1D line trajectory by rotating the dipoles and an additional 1D excitation field with a frequency of 25 kHz and an amplitude of 5 mT is applied. The simulation is based on the ideal Langevin particle model. A system matrix based reconstruction was performed by using a Thikonov regularized Kaczmarz algorithm.

III Results and discussion

The design derived from the analytic description is presented. The numeric simulations for the drive field and the selection field are demonstrated, followed by the simulation results of the MPI performance.

III.I The geometry

Figure 1 shows the proposed geometry. The system has an accessible inner bore of 10 cm. It is surrounded by two dipole rings consisting of 32 bar magnets each (with $l_1 = 2$ cm, $l_2 = 3$ cm, $a_1 = 8$ mm, $a_2 = 9$ mm). From equation 4 we expect a drive field amplitude of 67 mT. The two quadrupole rings consist of 40 bar magnets each (with $l_3 = 7$ cm, $l_4 = 10$ cm, $a_3 = 9$ mm, $a_4 = 11$ mm). According to the equation in [4] we expect a maximum gradient strength of 2.3 T/m.

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III.II Numeric simulations

Figure 2 left shows that the gradient strength can be varied between 0 and 2.6 T/m by changing the angle between the quadrupole rings. The analytic calculation in [4] underestimates the gradient strength by 15 %. The gradient strength changes as expected with the cosine of the angle between the quadrupoles. The gradient strength was determined by a linear fit. Figure 2 right shows the flux density produced by two counter rotating Halbach dipoles. A maximum drive field amplitude of 65 mT was measured in the center. The amplitude matches the analytic calculation in equation 4 with a deviation of 3 %. The amplitude varies with the cosine of the rotation angle.

III.III Simulations of the MPI performance

Figure 3 shows the results of the simulated MPI performance. All line phantoms can be resolved within 30 mm around the center. For the line distances of 1 and 2 mm the resolution gets worse at distances beyond 40 mm from the center, because the expected size of the FOV at maximum gradient strength is 48 mm.

IV Conclusions

A scanner concept is presented, which generates the selection field by using two nested Halbach quadrupoles. The gradient strength can be chosen via the angle between the two quadrupoles. The drive field is proposed as two reversely rotating Halbach dipoles, driving the FFP on a radial trajectory. An equation was found to estimate the expected magnetic fields of Halbach rings, when using bar magnets of finite length (equation 4). A numerical simulation followed the analytic calculations for the proposed geometry. The simulations of the MPI performance showed, that an image reconstruction of at least 0.5 mm is feasible within a FOV of 30 mm and 1 mm can be resolved within a FOV of 40 mm, when applying maximum gradient strength.

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Author's Statement

Conflict of interest: Authors state no conflict of interest.

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