International Journal on Magnetic Particle Imaging
Vol 6, No 2, Suppl 1, Article ID 2009042, 3 Pages

Infinite Science Publishing

Proceedings Article

Iron core coil designs for MPI

F. Förger[1,2,*]· M. Graeser[1,2]· T. Knopp[1,2]

[1]Section for Biomedical Imaging, University Medical Center Hamburg-Eppendorf, Hamburg, Germany
[2]Institute for Biomedical Imaging, Hamburg University of Technology, Hamburg, Germany
[*]Corresponding author, email: f.foerger@uke.de

Abstract

In Magnetic Particle Imaging, much of the power consumed during an imaging sequence is used for the generation of the selection and focus fields. In today's MPI scanners three different concepts are applied to generate the gradient fields: Air coils, permanent magnets and coils with soft iron. Air coils and permanent magnets have the great advantage of good calculability by the Biot-Savart Law. On the way to a clinical imaging modality, the needed power for sufficient gradient strength demand the use of soft iron. In order to make good use of the ferromagnetic amplification properties, much more complex simulations have to be done. A recently published head scanner uses a soft iron yoke for field generation. In this study, we investigated different coil geometries with soft iron with respect to this head scanner.

I Introduction

The resolution of MPI scanners is strongly related to the gradient strength of the selection fields. For air coils, gradient strengths are mostly limited by the available power and the possibility to dissipate generated heat. As in Maxwell's equations the current density is the source term for magnetic fields, systems with the same need of power could have different gradient strengths. Thus, optimization of the coil configurations could lead to power efficient field generators. Depending on the system, mainly air coils [1] and permanent magnets [2] are used. The use of soft iron in MPI is rather rare [3]. Therefore, it is still an open question how soft iron can be used for field amplification and how it affects the needed power in the MPI context. In this study, we investigated three different coil designs with soft iron, which allow a locally variable generation of a field free point (FFP). These designs would make it possible to carry out imaging and force experiments with high gradient strengths.

II Material and methods

All soft iron simulations were done in COMSOL (COMSOL, INC., Burlington, MA, USA) which solves the underlying differential equations in finite elements. Calculations for air coils have been done with an in-house Biot-Savart software. To have a better comparison to an experimental setup the following simulations were performed with respect to a published head scanner [4]. In other words, each coil design, which is investigated, has comparable dimensions.

III Different iron shapes

The head scanners present gradient strength is about 0.22 $\mathrm{T m^{-1}}$ whereby a power of approx. 380 W is required. Simulations show that the gradient is increased by a factor of 5.2 due to the iron here. Hence, the yoke reduces the power by factor of 27. At this point the question arises whether it is possible to construct an even more efficient setup with iron coils. In order to investigate this question some simulations with different iron and coil geometries

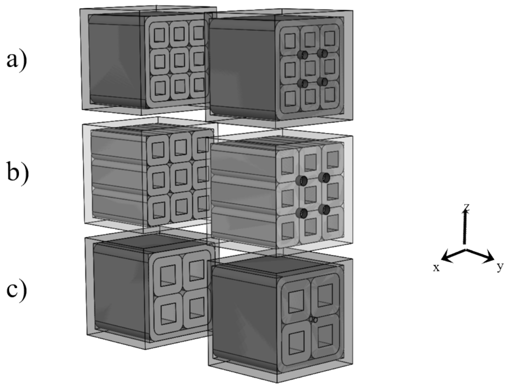

Figure 1: Iron geometries with different number of coils. Every inner coil has an iron core and the whole setup is covered with an iron layer on the outer sides respectively. Design a) consists of 20, design b) of 18 and design c) of 10 coils.

were performed. The gradient strength at the center of the setup was the optimization target while the power was kept to be constant. Because there are infinite options to arrange coils and shape iron cores, it was only possible to evaluate a few iron design concepts.

A coil enclosed in an infinitely large block of iron with the permeability μ_r ($\sim 10^2$ - 10^4) would generate a magnetic field that would be exactly by a factor of μ_r larger than the field of the corresponding air coil. From this point of view, it seems to make sense to choose an iron design, which encloses the coils as far as possible but leaves enough space for a human head. In the simulations, such designs generated the highest gradients too. By enlarging the coils of the head scanner and increasing the amount of iron it was possible to achieve gradients up to 1.25 Tm^{-1} with the fixed present power. But this would result in coils weighing about 2 tons per side, which is not feasible.

However, with higher gradients and limited excitation field amplitudes, the setup has to be modified to obtain an image of the whole brain again. This is why additional coils have to be added to be able to freely shift the FFP to every position.

IV Iron designs with multiple coils

One possible approach is to add three coils per side and a big coil which wrapped all four coils (see figure 1 c). Other designs, which were investigated for comparison, contain nine coils per side with (a) and without (b) a wrapping outer coil. Since the coils fully covered in iron gave the best results, iron-covered designs are chosen again. There is no iron between the coils, because the field lines should run back via the outer iron and not shortcut via inner iron. It is also a medical requirement to build the scanner as openly as possible. For this reason, the design is limited to coils placed on two sides of the patient.

A fair comparison between the different setups is a challenging task. We propose to limit the coil blocks to the same size. It is assumed that the dimensions of the coils and iron layers are decoupled degrees of freedoms and by varying them independently suitable values have been found. In order to get a first approximation this assumption is sufficient.

Since the aim of this setup is imaging and performing force experiments, it is of interest to determine the required power for different FFP positions. The average power required for FFPs on a 3D lattice seems to be a good measure of the effectiveness of a setup.

The required currents for different FFP positions are calculated under the assumption that the sensitivity of an iron coil changes by only one factor compared to an air coil. With Tikhonov regularization, small deviations of the gradient or the desired FFP positions are allowed if the needed power would be too high. Therefore, the following minimization problem has to be solved, were x is the desired FFP position:

$$||\mathbf{S}(\mathbf{x})\cdot\mathbf{I}-\mathbf{G}||_2^2-\lambda_I\cdot||\mathbf{I}||_2^2 \rightarrow \min$$

with

$$\mathbf{S}(\mathbf{x})=\begin{pmatrix} \lambda_p\cdot S_{1,x}(\mathbf{x}) & \dots & \lambda_p\cdot S_{N,x}(\mathbf{x}) \\ \lambda_p\cdot S_{1,y}(\mathbf{x}) & \dots & \lambda_p\cdot S_{N,y}(\mathbf{x}) \\ \lambda_p\cdot S_{1,z}(\mathbf{x}) & \dots & \lambda_p\cdot S_{N,z}(\mathbf{x}) \\ \lambda_d\cdot\partial_x S_{1,x}(\mathbf{x}) & \dots & \lambda_d\cdot\partial_x S_{N,x}(\mathbf{x}) \\ \frac{1}{2}\lambda_d\cdot\partial_y S_{1,y}(\mathbf{x}) & \dots & \frac{1}{2}\lambda_d\cdot\partial_y S_{N,y}(\mathbf{x}) \\ \lambda_d\cdot\partial_z S_{1,z}(\mathbf{x}) & \dots & \lambda_d\cdot\partial_z S_{N,z}(\mathbf{x}) \end{pmatrix}$$

$$\mathbf{I}=\begin{pmatrix} I_1 \\ \vdots \\ I_n \end{pmatrix},\mathbf{G}=\begin{pmatrix} 0 \\ 0 \\ 0 \\ \lambda_d\cdot G_x \\ \frac{1}{2}\lambda_d\cdot G_y \\ \lambda_d\cdot G_z \end{pmatrix}$$

$S_{n,i}(\mathbf{x})$ is the i'th component of the sensitivity of the n'th coil at the position $\mathbf{x}$ and λ_p, λ_d, λ_I are the regularization parameters for the position, derivative and current respectively. I_i represents the current in the i'th coil. The target gradients in x, y and z directions are G_x, G_y and G_z.

One can solve this minimization problem by calculating the solution to the following regularized system of equations:

$$(\mathbf{S}^T\mathbf{S}+\lambda_I\cdot\mathbb{1})\cdot\mathbf{I}=\mathbf{S}^T\mathbf{G}$$

With suitable regularization parameters it can be influenced how far the actual values for the gradient and the FFP position deviate from the target values for the solution.

In table 1, some calculated power values for the iron setups are summarized (Only steady state. Additional

10.18416/ijmpi.2020.2009042

Table 1: Calculated power values for three different iron coil designs with a block distance of 31 cm. The gradient strength in the FFPs is set to 0.22 Tm−1.

	10 coils	18 coils	20 coils
Maximal power in volume [W]	3140	240	200
Mean power in volume [W]	540	140	170
Power center FFP [W]	100	140	140
Maximal power single coil [W]	880	70	140
Mean gradient error	6 %	6 %	6 %

power would be required for fast shifting of the FFP, e.g. due to eddy currents). As with the head scanner the gradient is set to 0.22 Tm^{-1} and the coils distance is 31 cm which makes human brain imaging applications possible. The outer dimensions are 34 cm × 34 cm × 31 cm per block. This results in a weight of approx. 300 kg per side. The irons permeability is set to $\mu_r = 1000$. A total of 31× 31 × 31 evenly distributed FFPs are generated in a volume of size 20 cm × 20 cm × 20 cm around the center of the setup for the calculated power values.

One has to keep in mind that the assumption that the field of the iron coils is only altered by a constant factor compared to the air coils is not valid. In reality, the nonlinear magnetization curve and magnetically couplings between the coils are not negligible. For field calculations very close to the coils this assumption collapses completely. However, as a first approximation, these calculations seem to be a good starting point for further investigation.

V Discussion and Conclusion

The iron coil design with 18 coils is a very promising and effective design for the generation of freely movable FFPs. With this design it would be possible to reduce the need of power by about a factor of three compared to the head scanner with additional flexibility. A challenge of this design could be the large inductances of the coils which limit the operation speed. On the way to a human sized MPI system the use of soft iron is a key step to reduce the need of power to manageable dimensions. If one would take into account how the sensitivities are altered for different combinations of currents and would include the coupling between the coil parameters it might be possible to build even more effective setups.

Author's Statement

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

References

[1] B. Gleich, Tomographic imaging using the nonlinear response of magnetic particles, Nature 435, 1214–1217, 2005, doi:10.1038/nature03808

[2] M. Weber, Novel Field Geometry Using Two Halbach Cylinders for FFL-MPI, International Journal on Magnetic Particle Imaging, [S.l.], v. 4, n. 2, 2019, doi: 10.18416/IJMPI.2018.1811004

[3] J. Rahmer, Remote magnetic actuation using a clinical scale system, PLoS One. 13:e0193546, 2018. doi: 10.1371/journal.pone.0193546..

[4] M. Graeser, Human-sized magnetic particle imaging for brain applications, Nat Commun 10, 1936 (2019). doi:10.1038/s41467-019-09704-x

