

Permanent Magnet Arrangements for Low-Field NMR

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1 Introduction

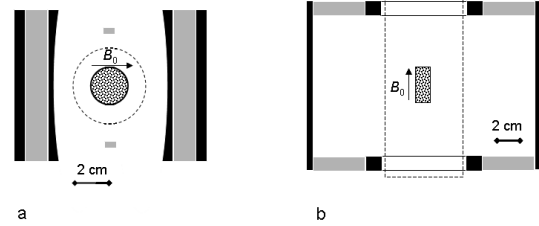


Figure 1: Schematics of the parallel (a) and the circular (b) arrangement of NdFeB magnets (gray) and iron yokes (black) for two NMR magnets. Sample and access volumes are indicated in the centers of both magnets.

Nuclear magnetic resonance (NMR) studies with fluids contained in the void space of porous materials such as natural sediments (rocks, soils), cements, concretes, catalyst particles etc. are a modern non-destructive method in porosimetry. In order to determine pore structure parameter such as porosity, pore size, fluid saturation and fluid-matrix interactions, representative sample volumes (a few cm) of the fluid-saturated porous materials need to be introduced into a homogeneous magnetic field of relatively low magnetic flux density ($0,02 < B/T/m < 0,2$). For such studies, commercial NMR systems are often not well suited since they offer much too high magnetic flux densities and too small accessible sample volumes. Last but not least, purchase and operating costs for commercial magnet systems are generally high. Therefore, we designed two low-cost NMR magnets, which utilize modern FeNdB permanent magnets as source for the required magnetic flux. They are arranged together with iron yokes in such a way that a low but homogenous magnetic flux density B_0 over a large cylindrical sample volume is generated (see Figure 1). Simultaneously, these new magnet systems provide sufficient free space to access the samples enabling, e.g., NMR studies at high variable carbon dioxide and methane gas pressures, which are currently performed in our lab.

2 Use of COMSOL Multiphysics

The aim is to find the right dimension to obtain the homogeneous field within the sample volume. Therefore the lengths and the distances are varied. All problems are solved by magnetostatic models. The boundary condition "magnetic isolation" is set as shell much larger than the model. The parallel arrangement (Figure 1 a) is simulated by the 2D model "Perpendicular Induction Currents, Vector Potential"

$$\nabla \times (\mu_0^{-1} \mu_r^{-1} (\nabla \times A - B_r)) - \sigma v \times (\nabla \times A) = A_z e_z \quad (1)$$

The problem is split into two 2D slices perpendicular to each other. The solution of one slice is shown in Figure 2.

For the circular arrangement the 2D axial symmetry model "Azimutal Induction Currents, Vector Potential"

$$\begin{aligned} \nabla \times (\mu_0^{-1} \mu_r^{-1} (\nabla \times A - B_r)) - \sigma v \times (\nabla \times A) \\ = (A_{\phi,red} + A_{\phi,ext}) e_{\phi} \end{aligned} \quad (2)$$

and the 3D model "Magnetostatics, No Currents" are used.

$$\nabla \cdot (\mu_0^{-1} \mu_r^{-1} \nabla V_m - \mathbf{B}_r) = 0 \quad (3)$$

The value $B_r = 1.3T$ is set to the residual magnetism and $\mu_r = 1.07$ to the relative permeability of the permanent magnets in the particular subdomains. No currents appear in the model, so $v = 0$. For subdomains of yokes the predefined material "Iron" is used.

In the simplified 2D model the homogeneity is investigated. Then the 3D model (figure 3), with the calculated dimensions of the 2D model, yields the correct field strength. Additionally the magnetostatic forces are calculated to find the appropriate supports for the permanent magnets and the yokes.

3 Results

In the parallel arrangement (Figure 1 a), a good homogeneity of the B_0 field is achieved by using shaped iron yokes at the inner pole faces and small additional shim magnets. Figure 2 shows the residual relative deviation of the magnetic flux density for the optimized design.

In the circular arrangement (see Figure 1 b) 32 NdFeB magnets are combined. The homogeneity is optimized by varying the length and the diameter of the iron yokes connecting the individual magnets. Figure 3 shows the magnetic flux density in this arrangement.

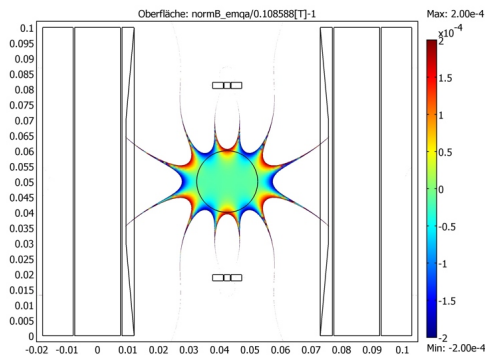


Figure 2: Residual relative magnetic flux in parallel arrangement.

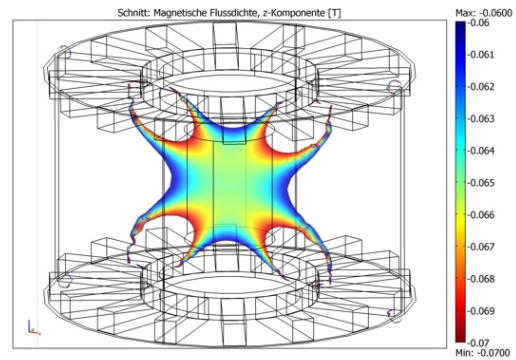


Figure 3: Magnetic flux in circular arrangement.

4 Conclusion

Simulations of magnetic flux densities are a useful approach in magnet system design for low-field NMR applications. The absolute values and the spatial variations of magnetic field predicted by COMSOL were found to agree very well with the corresponding quantities measured by NMR with the constructed magnets. Small differences between measurements with the constructed magnets and predictions by COMSOL result mainly from uncertainties in the manufacturing of the mechanical parts of the magnet.

Necessary simplifications in the COMSOL models have to be made carefully. Therefore the physics behind the model and the simplifications have to be taken into account and their influences on the result have to be rated by comparing different simulations and experiments.