ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO26

DESIGN AND SIMULATION OF MINIATURIZED PERMANENT MAGNET ARRAYS FOR COMPACT DIAGNOSTIC APPLICATIONS*

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Abstract

This paper presents the design and simulation of miniaturized permanent magnet configurations for Nuclear Magnetic Resonance (NMR) applications where compactness and field quality are critical. Traditional NMR systems require large and costly equipment to achieve high magnetic field uniformity, which limits portability and broader diagnostic use. We investigate compact magnet geometries, including H-type and Halbach arrays, evaluating their field strength and homogeneity. Special attention is given to the trade-off between device miniaturization and achievable field uniformity, a key factor in measurement sensitivity. Through computational modelling, we establish a framework for quantifying and optimizing magnetic field homogeneity, providing design strategies relevant for portable diagnostic instrumentation and potential applications where in-situ, non-invasive measurements are required.

INTRODUCTION

The development of compact and precise diagnostic instrumentation often depends critically on the design of strong, homogeneous magnetic fields. Compact permanent magnet assemblies could support portable NMR-based field probes [1] or calibration devices for accelerators [2], where diagnostic magnets must be small, stable and cost-effective.

Nuclear Magnetic Resonance (NMR) techniques, in particular, require high field strength and uniformity to achieve accurate and reproducible measurements. Conventional high-field NMR magnets are heavy, bulky, expensive, [3] and hence limited to fixed laboratory installations, which restricts their applicability in portable diagnostic devices.

In order to overcome these limitations recently there have been efforts [4] to design miniaturized NMR systems that reduce magnet size while maintaining adequate field quality. Achieving this balance is challenging: strong and homogeneous magnetic fields typically require larger magnet volumes, which runs counter to portability.

As a result, compact NMR devices must adopt innovative magnet geometries and optimization techniques to deliver both sufficient field strength and uniformity to perform reliable diagnostics.

The aim of this paper is to introduce a simulation and analysis methodology to compare and assess different magnet assembly designs based on magnetic field strength and uniformity within manufacturing constraints.

* Work supported by STFC Impact Acceleration Award
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MODEL

Two types of permanent magnet configurations were considered in this study: H-shaped magnet and Halbach Cylinder shown in Fig. 1.

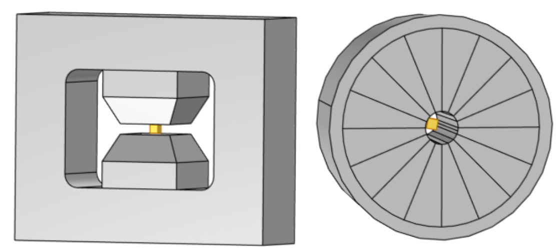

Figure 1: Magnets configurations: H-shaped magnet (left) and Halbach cylinder (right). ROI is highlighed by yellow color.

Magnetic field calculations have been performed using COMSOL software Magnetic Fields, No Currents (mfnc) physics interface [5], where following set of magnetostatic Maxwell equations [6] have been solved under the assumption of no free currents ($\mathbf{J} = 0$) using Finite Element Method stationary study:

Gauss's law for magnetism:

$$\nabla \cdot \mathbf{B} = 0. \quad (1)$$

Constitutive relation between the magnetic flux density and magnetic field:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r, \quad (2)$$

where $\mathbf{B}_r$ is the remanent flux density;

Ampère's law:

$$\nabla \times \mathbf{H} = \mathbf{J}. \quad (3)$$

Since $\nabla \times \mathbf{H} = 0$, the magnetic field $\mathbf{H}$ can be expressed as the gradient of a scalar potential V_m:

$$\mathbf{H} = -\nabla V_m. \quad (4)$$

Equations are completed by magnetic insulation as boundary condition which enforces that the normal component of the magnetic flux density vanishes at the boundary:

$$\mathbf{n} \cdot \mathbf{B} = 0. \quad (5)$$

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HOMOGENEITY DEFINITIONS

Magnetic field homogeneity is a measure of the magnetic field uniformity over a defined region of interest [7]. It is measured in parts per million (ppm) difference from nominal magnetic field B_0 over a certain diameter of spherical volume (DSV). Vendors usually measure homogeneity using field mapping techniques. There are different methods for calculation homogeneity including peak-to-peak and volume-root-mean-square (VRMS) homogeneity [8, 9].

For simulated magnetic field the same definition can be applied. In this case, the magnetic field values can be extrapolated over grid as B_i over from the finite element mesh within a defined region of interest (ROI) with m points.

In addition to the standard approaches, alternative metrics may be used in simulations, such as the mean absolute error (MAE) from the center, which provides a more robust measure of average inhomogeneity and is less sensitive to extreme outliers [10]:

$$\eta = \frac{\sum_i^n \frac{|(B_i - B)|}{B}}{m} 10^6 \tag{6}$$

In this work, in order to compare magnet assemblies for field uniformity, heatmaps of homogeneity are used. For ViBo Health scanner, it is essential to have high strength and uniform magnetic field in the region inside of the bore or in the air gap between dipoles of H-type magnet with volume of approximately human finger. Therefore, 8 mm diameter cube has been chosen and segmented into volumetric voxels, each value of MAE corresponds to pixels value on a 3D homogeneity heatmap.

We have used two approaches to calculate MAE: 1) the value of B in Eq. (6) is defined as the magnetic field at the center of the bore - bore heatmap (in case of H-type dipole the center if the region between dipoles has been used); 2) B is determined by the field value at the center of each voxel - voxel heatmap. Figure 2 shows comparison of central XY slices of both heatmaps for a same dataset - single layer Halbach with layer thickness $H = 120$ mm.

SIMULATION RESULTS AND DISCUSSION

First, the results of the developed COMSOL model has been verified in 2D with the simulations performed using Finite Element Method Magnetics software (FEMM) and its interface to python pyFEMM which is a free finite element package for solving 2D planar and axisymmetric problems in low frequency magnetics and electrostatics [11]. Once results have been validated, COMSOL models have been extended to 3D. The data analysis tool written in Python has been developed which capabilities are visualization of the exported simulation results, masking for regions of interest, calculation single value metrics for homogeneity, handling 3D results and calculations 3D heatmaps. The COMSOL model has been linked to the developed script using python module MPh [12] which allowed to perform simulation and analysis within a single python code, allowing to do geometry parameter optimization.

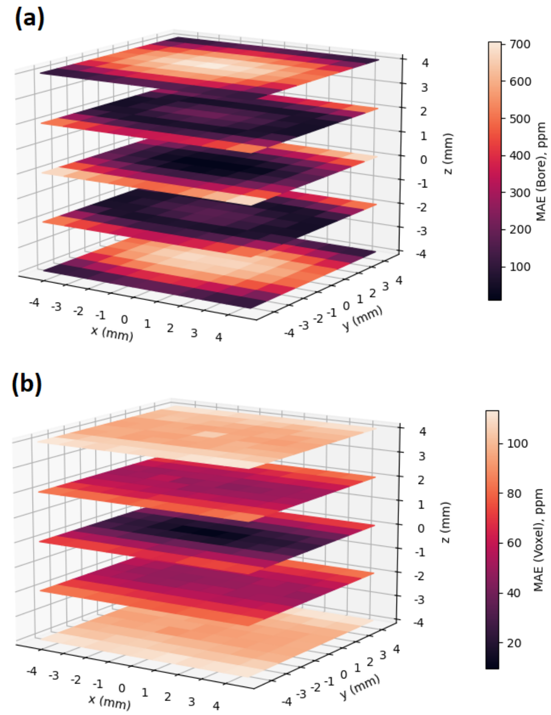

Figure 2: 3D homogeneity heatmaps calculated using Eq. (6) with two different values meanings of B in the formula: a) B is magnetic field at the center of the ROI which is for Halbach is aligned with the center of the bore; b) B is calculated at the center of each voxel.

Example of the Halbach layer thickness effect on the magnetic strength is shown in Fig. 3. A number of designs and their variations of designs were simulated and analyzed for field strength and uniformity. The designs also include variation of segments, as well as double staggered and multiple layers Halbach.

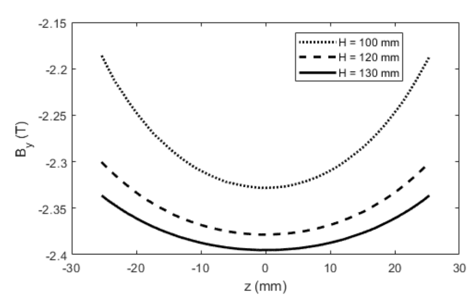

Figure 3: Cross section along the bore axis of B_y component for various layer thickness H of a single layer Halbach cylinder assembly.

While the visual representation of heatmaps (Fig. 2) or field strength (Fig. 3) is useful for qualitative analysis, the single value metrics for homogeneity have been tested to quantitatively compare design geometries. Although the minimum field strength is a convenient metric, the overall

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change in the field strength throughout the bore is also important to consider, as a larger range of magnetic field within the region of interest may make it more difficult to shim the entire field to a narrow range of magnetic field. Therefore, the range of magnetic field within a design is useful to assess how easy the assembly will be to shim. The multiple layer Halbach cylinder design (default design has been suggested by Yu et al. [13]) is particularly effective at flattening the field magnitude distribution along the bore as shown in Fig. 4.

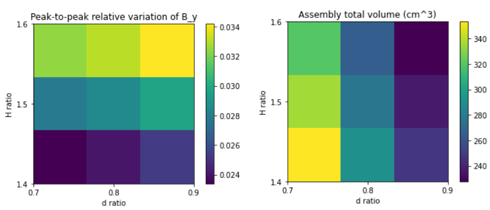

Figure 4: Effect of multiple layer Halbach parameters on magnetic field flatness calculated as range over mean and corresponding total assembly volume shown on the right.

Similarly, homogeneity heatmaps can be compared by reducing map to the range of voxel uniformities. Minimum and maximum voxel uniformity plotted against assembly thickness for a single layer Halbach (see Fig. 5(a)) shows the range of uniformity values is inversely proportional to the assembly thickness which also agrees with the line plots in Fig. 3 for field strength. Figure 5(b) shows that for H dipole design adding iron sheet has similar effect.

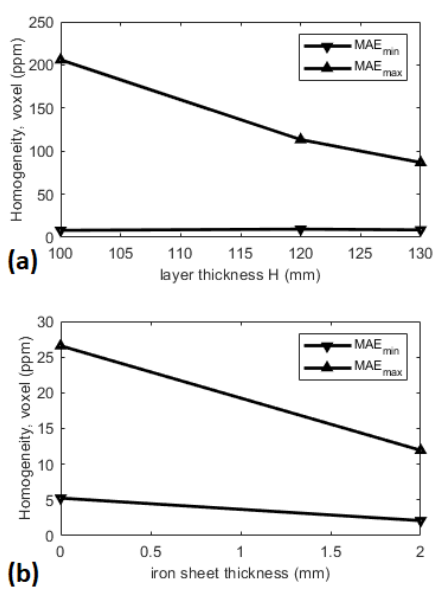

Figure 5: Uniformity range dependence on: a) single layer thickness for Halbach assembly, b) iron sheet thickness for H-type assembly.

CONCLUSION AND FUTURE DEVELOPMENTS

Although the primary motivation for this work is developing compact in-vivo NMR diagnostic diagnostic devices, the design principles we present such as the optimization of permanent magnet configurations for high field homogeneity in small volumes are broadly relevant to accelerator science. Hence we hope the methodologies demonstrated here can therefore inform not only biomedical instrumentation but also will be considered for future compact beam diagnostics the development of beam diagnostic systems for accelerator applications.

We have proposed a number of metrics of comparison, namely field strength distribution and bore and voxel uniformity of 3D magnetic fields. The developed approach which connected simulation and analysis into a single script made it easy to apply new 3D geometries for permanent magnets assemblies and compare them for magnetic field strength and uniformity. Future work could extend parameter sweep to genetic algorithms to have an automated parameter optimization to find the most efficient assembly designs which could also include passive shims.

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