

OPTIMIZATION OF THE FINITE-ELEMENT MODEL OF A 1.5 T MRI SCANNER'S PASSIVE SHIMMING SYSTEM: ASSESSING THE IMPACT OF TECHNOLOGICAL TOLERANCES

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Abstract

The paper presents a method for correcting magnetic field distortions caused by technological tolerances and coil deformations using the passive shimming method for a national 1.5 T superconducting MRI scanner. Finite element modeling is used as the primary tool for calculating the magnetic field. An optimization problem is solved for placing steel pieces (shim plates) in discrete positions of the shim holders to correct the field inhomogeneity. The effectiveness of the correction is evaluated using the mean square field homogeneity metric in spherical volumes of different diameters. The validity of the dipole approximation for the shim is confirmed by comparison with its volumetric model. The paper quantifies the effect of axial and transverse displacements of the central coil on the homogeneity of the magnetic field in the volume of interest. The developed method can be used at the design stage to determine acceptable technological tolerances.

Key words

Magnetic resonance imaging, superconducting magnet, magnetic field homogeneity, passive shimming, inhomogeneity correction.

1 Introduction

Magnetic resonance imaging (MRI) plays an important role in complex diagnostic cases, for example, in surgical planning or in determining an optimal treatment strategy. The first national MRI unit was created in 1983 at the All-Russian Research Institute of Cable Industry by a group of engineers (Prof. I. B. Rubashov, V. I. Krutskikh, and E. N. Knorin). It was used to obtain an MR image of an olive, and later of a human brain [Kose,

2021]. Currently, low-field MRI systems with a maximum magnetic field strength of 0.5 T are manufactured in the Russian Federation, for example, by the scientific and production company "Az". Although the supply of MRI scanners has increased almost threefold in recent years, medical institutions still experience a shortage of this equipment. Moreover, most MRI scanners are imported and serviced remotely, which creates additional operational difficulties.

The image quality in MRI is directly determined by the degree of homogeneity of the reference static magnetic field B_0 in its operation region (OR). For modern clinical systems with a magnetic field of 1.5 T in the OR, the permissible deviations of the magnetic field strength do not exceed several parts per million (ppm). During manufacturing, assembly, cooling, and current injection into the magnetic system, inevitable distortions of its calculated "ideal" configuration arise due to electromagnetic forces. As a result, the final homogeneity of the B_0 field is typically degraded to approximately 1000 ppm. To correct such significant inhomogeneities, the passive shimming method is widely used. This method involves compensation of field distortions using local sources of secondary magnetic field — steel pieces (shim plates) magnetized to saturation [Belov et al, 1995]. Numerical modeling and optimization of magnetic systems by finite-element methods are widely used in the design of accelerator and MRI magnets [Arslanova et al, 2024].

Optimization methods for perturbed and discrete systems continue to be actively developed in computational mathematics and control theory [Ovsyannikov, 2025; Kotina et al, 2021; Kotina et al, 2018]. Such approaches can also be applied to the passive shimming problem, which can be formulated as a discrete optimization problem for the placement of ferromagnetic elements.

This work presents the development and verification of a passive shimming method for a national clinical superconducting (SC) MRI scanner with a 1.5 T magnetic field. The developed method is based on solving a discrete optimization problem for the placement of shim plates to restore the homogeneity of the magnetic field in the OR after energizing the SC magnet.

2 Assessment of the magnetic field homogeneity in the OR

The magnetic field homogeneity level is a parameter in MRI that characterizes the uniformity of the magnetic field distribution within a given OR. A spherical volume of a specified diameter containing the imaging region is typically chosen as the OR. The magnetic field homogeneity in the OR is measured in parts per million (ppm) relative to the nominal field value. To quantify the magnetic field inhomogeneity within the OR of the magnet, three metrics are commonly used.

2.1 Peak-to-Peak

The peak-to-peak (*P2P*) homogeneity characterizes the maximum deviation of the magnetic field within a given region:

$$P2P(ppm) = \left[\frac{(B_{max} - B_{min})}{B_0} \right] \times 10^6,$$

where B_0 is the nominal magnetic field value at the center of the OR.

The *P2P* metric is used for rapid assessment of the worst-case magnetic field deviation. It should be noted that the *P2P* inhomogeneity always occurs at points located on the boundary surface of the OR. The main advantage of this approach for evaluating field homogeneity is its simplicity in terms of both computation and interpretation of the results.

2.2 Surface root mean square

The surface root mean square (*SRMS*) homogeneity characterizes the root mean square deviation of the magnetic field on the OR surface. For a continuous distribution of the magnetic field:

$$SRMS(T) = \sqrt{\frac{1}{S} \iint (B(s) - B_0)^2 ds}.$$

For a discrete set of points on the OR boundary, the root mean square inhomogeneity can be estimated as

$$SRMS(ppm) = \frac{1}{B_0} \sqrt{\frac{1}{M} \times \sum (B_j - B_0)^2} \times 10^6,$$

where B_j is the magnetic field value at the j -th point on the surface, and M is the total number of considered points.

The *SRMS* field homogeneity metric is widely used in magnet design and adjustment procedures. The absolute magnetic field deviation map on the OR boundary surface is used in the magnet shimming process.

2.3 Volume root mean square

The volume root mean square (*VRMS*) characterizes the corresponding magnetic field deviation throughout the entire OR. For a continuous magnetic field distribution:

$$VRMS(T) = \sqrt{\frac{1}{V} \iiint (B(x, y, z) - B_0)^2 dx dy dz}.$$

The *VRMS* value is the main criterion used for assessing magnetic field homogeneity in the technical documentation of MRI systems, since it provides an integral assessment of field inhomogeneities throughout the entire OR. The requirements for magnetic field homogeneity within the spherical OR are presented in Table 1 for the national serial clinical SC MRI scanner under development with a B_0 field of 1.5 T.

Table 1. Operational region field homogeneity requirements

Sphere diameter, mm	<i>VRMS</i> , ppm
500	4.4
400	1.2
300	0.2
200	0.06
100	0.02

3 Development of a computational model of the MRI scanner magnetic system

The MRI scanner magnetic system developed by JSC NIIEFA consists of five pairs of superconducting (SC) coils, where the central coil is a twin coil. Four pairs of coils (2–8, Fig. 1) are used to generate the main magnetic field in the OR, while the fifth pair (1, 9, Fig. 1) is used to reduce the stray magnetic field.

The magnet, based on a computational spatial model, is capable of providing a high level of field homogeneity in the imaging volume (Table 1).

As a basis for further analysis, a detailed finite-element (FE) model of the idealized magnet was created using nominal geometric parameters of the coils (radial and axial boundaries, number of turns, and currents). It provides a $B_0 = 1.5$ T field at the center of the OR and

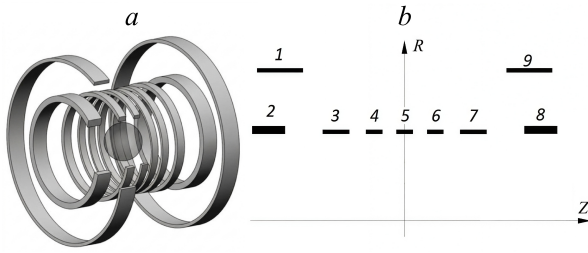


Figure 1. Geometric model of the SC coil system developed by JSC NIIEFA.

a – general view; b – cross-section.

a theoretical homogeneity ($VRMS$) on the order of 1 ppm, with $P2P \approx 3$ ppm.

The magnetic field distribution of the idealized SC magnet in the OR was calculated using COMSOL Multiphysics 6.2 software (Fig. 2) [COMSOL Multiphysics®, 2026].

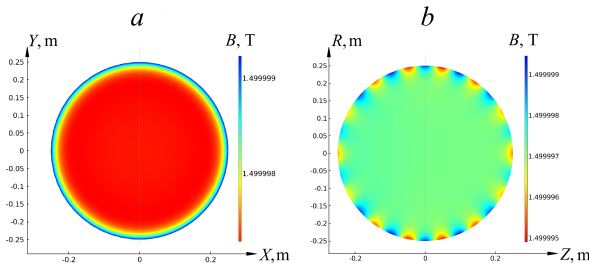


Figure 2. Magnetic field distribution inside the OR with a diameter of 500 mm for the “ideal” case.

a – XY cross-section; b – RZ cross-section.

4 Correction of magnetic field inhomogeneities in the OR using passive shimming

In practice, the magnetic field homogeneity level of a manufactured magnet turns out to be far from the ideal design specifications. The final system characteristics are influenced by a variety of factors, including manufacturing tolerances, mechanical deformations during assembly, transportation and cooling of the magnetic system, as well as the influence of external ferromagnetic objects in the scanner installation area.

The passive shimming method is used to correct distortions of the main magnetic field. This procedure is an essential step in the tuning of MRI systems, regardless of the initial magnet quality. The passive shimming method involves placing steel plates in special non-magnetic cassettes (shim holders) located along the circumference of the cylindrical volume surrounding the magnet’s working region (Fig. 3).

All steel plates (shims) inside the magnet are uniformly magnetized in the axial direction to the saturation mag-

netization M_{sat} and act as sources of a secondary magnetic field. By selecting the shim thicknesses and fixing their positions, local deviations of the reference magnetic field in the OR can be compensated.

The magnetic field generated by a single shim can be approximated by its equivalent dipole magnetic moment m_z , which can be calculated using the following formula:

$$m_z = M_{sat}V, \quad (1)$$

where M_{sat} is the saturation magnetization (A/m), and V is the volume of shim (m^3).

To verify the implemented dipole approximation, two independent finite-element (FE) models were developed and analyzed. The first model contained a point magnetic dipole, while the second model included a volumetric element corresponding to a filled shim-holder pocket made of material magnetized to saturation. The results of magnetic field calculations at the OR boundary for both models demonstrated the required agreement, confirming the validity of the dipole approximation for shims.

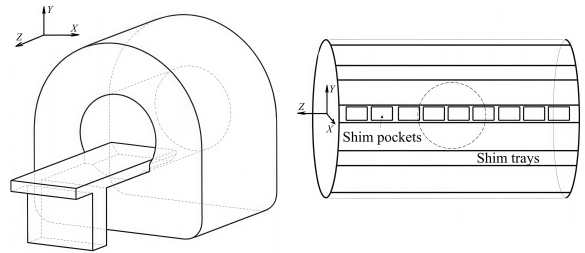


Figure 3. Passive shimming system diagram in a tunnel-type magnet.

In the most common design of superconducting MRI scanners, 12 to 24 symmetrically arranged cassettes are placed inside the magnet (Fig. 3). Each cassette contains pockets that hold stacks of plates of the required thickness.

The number of cassettes, the number of pockets in each cassette, and the pocket sizes are determined at the design stage. The number of steel plates filling each pocket of a specific cassette is calculated using specialized software based on a field map obtained from physical measurements of the magnetic field at the OR boundary.

After installing the shimming plates, field mapping is repeated and, if necessary, the number of plates (package thickness) is adjusted. This process may require several iterations to achieve the desired homogeneity. Field correction in the OR using passive shimming is performed in the absence of the patient. When a patient is placed inside the MRI scanner, additional field distortions may occur, for example, due to the presence of magnetic and

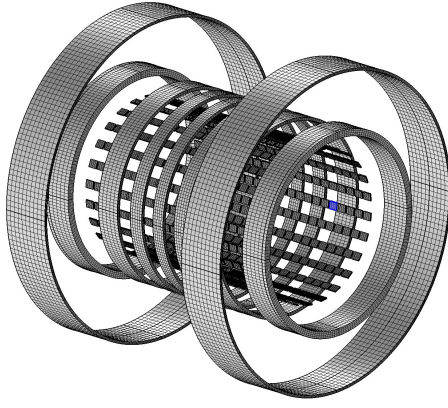


Figure 4. Layout of coils and passive shimming system in the FE-model

conductive materials in the patient's body. Such distortions are corrected using dynamic shimming.

JSC NIEFA has developed a passive shimming system for a 1.5 T MRI scanner. The system design consists of 24 cassettes (shim holders), which are evenly spaced around a circle enclosing the OR of the system with an angular pitch of 15° .

Each shim holder contains 21 pockets for placement of corrective steel plates. The pockets are arranged along the longitudinal axis of the magnet with a constant pitch of 60 mm between their centers. Such a geometric configuration creates a regular correction grid consisting of 504 discrete positions and enables accurate control of the spatial distribution of the magnetic field (Fig. 4).

5 Mathematical model of the shimming system

Magnetostatic fields in the working region of an MRI scanner satisfy Laplace's equation ($\nabla^2 V = 0$, where V is the scalar magnetic potential). The solutions of this equation in spherical coordinates are spherical harmonics. This allows the representation of an arbitrary static magnetic field $\mathbf{B}$ as an expansion in orthogonal basis functions [Griffiths, 2023]:

$$B(r, \theta, \varphi) = B_0 + \sum_{n=1}^{\infty} \left(\frac{r}{R} \right)^n \sum_{m=0}^n P_n^m(\cos \theta) \times (C_{n,m}^R \cos(m\varphi) + S_{n,m}^R \sin(m\varphi)),$$

where n and m are the degree and order of the spherical harmonic, $P_n^m(\cos \theta)$ are the associated Legendre polynomials, and $C_{n,m}^R$ and $S_{n,m}^R$ are the expansion coefficients (harmonic amplitudes) obtained by integrating the measured field over the surface of a sphere of radius R .

For the axisymmetric component ($m = 0$) and the constant field term $\mathbf{B}_0$:

$$\begin{cases} C_{n,0}^R = \frac{2n+1}{4\pi} \int_0^\pi \left[\int_0^{2\pi} B(R, \theta, \varphi) d\varphi \right] \times P_n(\cos \theta) \sin \theta d\theta, \\ S_{n,0}^R = 0, \\ C_{0,0}^R = B_0 \end{cases}$$

For harmonics with azimuthal dependence ($m \geq 1$):

$$\begin{cases} C_{n,m}^R = \frac{2n+1}{2\pi} \frac{(n-m)!}{(n+m)!} \int_0^\pi P_n^m(\cos \theta) \sin \theta \times \left(\int_0^{2\pi} B(R, \theta, \varphi) \cos(m\varphi) d\varphi \right) d\theta, \\ S_{n,m}^R = \frac{2n+1}{2\pi} \frac{(n-m)!}{(n+m)!} \int_0^\pi P_n^m(\cos \theta) \sin \theta \times \left(\int_0^{2\pi} B(R, \theta, \varphi) \sin(m\varphi) d\varphi \right) d\theta \end{cases}$$

The shim plates are made of electrical silicon steel with a saturation flux density of

$$B_{sat} = \mu_0 M_{sat} = 2.15 \text{ T}.$$

The saturation magnetization M_{sat} is achieved in an external magnetic field exceeding 40–50 A/m (approximately 50–60 mT). The plates are manufactured in two thicknesses: 0.05 mm and 0.3 mm. Shims are placed into cassette pockets with a depth of 6 mm at the corresponding Q_k positions. Each stack of plates has a magnetic moment proportional to its thickness δ_k .

Since the magnetization of thin steel plates can be considered approximately uniform, the magnetic field they produce can be described using the analytical expression for a point magnetic dipole with moment $\mathbf{m}$, whose magnitude is given by Eq. (1). The magnetic field of a dipole is given by [Tamm, 1979]:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left[\frac{3(\mathbf{m} \cdot \mathbf{r})\mathbf{r}}{r^5} - \frac{\mathbf{m}}{r^3} \right].$$

The magnetic moment component m_z of a plate magnetized along the z axis can be estimated as

$$m_z = M_{sat} dV,$$

where $dV = a_x a_y a_z$, and a_x, a_y, a_z are the geometric dimensions of the plate.

Then the z -component of the magnetic field at point $P(x, y, z)$ produced by a plate located at $Q(x_{sh}, y_{sh}, z_{sh})$ and oriented along the z axis is given by:

$$B_z(P, Q) = \frac{\delta_k B_{sat}}{4\pi} \times \frac{-(x - x_{sh})^2 - (y - y_{sh})^2 + 2(z - z_{sh})^2}{[(x - x_{sh})^2 + (y - y_{sh})^2 + (z - z_{sh})^2]^{5/2}}. \quad (2)$$

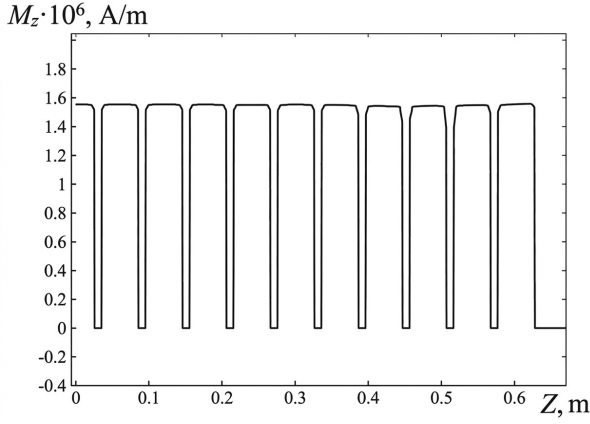


Figure 6. Magnetization of fully loaded shim pockets along Z -axis passing through the centers of the pockets.

The ratio $\gamma = B_z(P, Q)/dV$ is referred to as the sensitivity coefficient.

In the MRI shimming system, it is convenient to define the position of the shim pocket Q in cylindrical coordinates $(\rho_{sh}, \varphi_{sh}, z_{sh})$:

$$\begin{cases} x_{sh} = \rho_{sh} \cos \varphi_{sh}, \\ y_{sh} = \rho_{sh} \sin \varphi_{sh}, \\ z_{sh} = z_{sh}, \end{cases}$$

where ρ_{sh} is the radial position, φ_{sh} is the azimuthal angle, and z_{sh} is the axial coordinate along the scanner axis (Fig. 5).

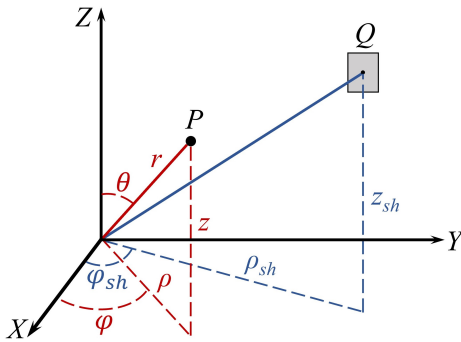


Figure 5. Coordinate system used to describe the position of a steel plate (Q) and a probe point (P).

To describe the field evaluation point (P) on the OR boundary, a spherical coordinate system (r, θ, φ) is used, naturally associated with the geometry:

$$\begin{cases} x = r \sin \theta \cos \varphi, \\ y = r \sin \theta \sin \varphi, \\ z = r \cos \theta, \end{cases}$$

where r is the radius vector magnitude from the scanner center to the measurement point, θ is the polar angle measured from the z axis, and φ is the azimuthal angle measured from the x axis.

To analyze allowable deformations of the magnet geometry, a finite-element model of the magnet and shimming system was developed. To eliminate discretization errors associated with extremely thin plates, all shims were modeled with a uniform thickness of 6 mm (fully filled cassette). The effective magnetic moment was scaled proportionally to the actual thickness of the steel-plate bundle.

A finite-element analysis of the magnet with fully filled shim holders was performed. The results confirmed that all shims are uniformly magnetized to saturation M_{sat} and act as sources of a secondary magnetic field with a vector aligned with the z -axis (Fig. 6).

6 Mathematical formulation of the field correction problem

The shimming problem is formulated as the minimization of deviations of the magnetic field ΔB_i from the nominal value B_0 at the center of the OR (1.5 T), evaluated at the i -th point on the spherical surface. Let δ_k denote the thickness of the shimming plates in the k -th pocket.

In this case, the goal is to minimize the residuals at all measurement points between the initially measured field deviation and the field contribution produced by the shims. Taking into account (2), this can be written as follows:

$$\sum_i \left[\Delta B_i + \sum_{k=1}^{k_{max}} \delta_k \gamma_{i,k} \right]^2 \rightarrow \min,$$

where i is the index of the measurement point, and k is the index of the shim pocket. The solution is sought under the constraint that the plate thicknesses δ_k do not exceed the height of the shim-holder pocket.

The main quality criterion of the correction is the root-mean-square deviation of the field (VRMS) within a spherical volume with a diameter of 500 mm. Additionally, homogeneity is evaluated for spherical volumes with diameters of 400 mm, 300 mm, 200 mm, and 100 mm, as well as for an ellipsoidal volume of dimensions 500 mm $\times$ 500 mm $\times$ 450 mm (flattened along the Z -axis). The specification typically defines acceptable values of this metric for the corresponding volumes (Table 1).

To compute these metrics, the field measured on a sphere with a diameter of 500 mm is expanded into a spherical harmonic series. This representation enables analytical evaluation of the field at any point within the

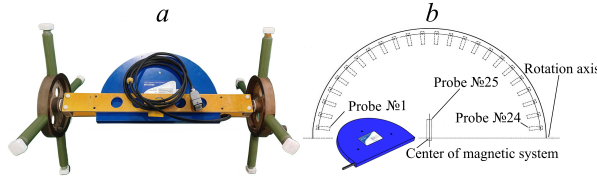


Figure 7. NMR teslameter.

a – NMR measurement frame; b – sensor layout.

sphere, and the root-mean-square deviation in a sphere of radius R can be calculated using the formula [Havens et al, 2002]:

$$VRMS = \left[\frac{3}{2} \sum_{n=1}^{\infty} \sum_{m=0}^n \frac{(n+m)!}{(n-m)!} \times \frac{1}{(2n+1)(2n+3)} \left(\frac{r}{R} \right)^{2n} [\varepsilon_m C_{n,m}^2 + S_{n,m}^2] \right]^{\frac{1}{2}}.$$

$$\text{where } \varepsilon_m = \begin{cases} 2, & m = 0, \\ 1, & m \geq 1. \end{cases}$$

The use of analytical expressions significantly accelerates the computation of homogeneity metrics. The homogeneity assessment for the ellipsoidal region is performed using numerical integration. The computational cost of the proposed workflow is dominated by the finite-element analysis, where an appropriate balance between mesh density and solution accuracy should be achieved. Once the magnetic field map has been obtained, the evaluation of homogeneity metrics and the optimization of shim thicknesses are performed using analytical expressions and require less than 5 minutes on a standard engineering workstation.

A teslameter (e.g., Metrolab MFC2046 NMR) is used to map the magnetic field. The measurement system consists of 24 sensors evenly distributed along an arc (Fig. 7). The sensor frame rotates around the central axis of the magnet, recording field values at 24 angular positions, resulting in a total of 576 control points on the spherical surface of the OR with a diameter of 500 mm.

To correct field distortions in the MRI scanner, dedicated software was developed for shim selection. This software uses measured field data on the spherical boundary of the OR to determine the optimal distribution of shim thicknesses in the cassette pockets.

To verify the software algorithms, finite-element (FE) simulations of a magnet with imposed deformations were performed on a geometrically idealized model. The distorted field map obtained from the FE simulation was used as input data for the software.

After the computation, the shim thicknesses were updated in the FE model of the magnet. As a result, the field homogeneity at the OR boundary was restored to a level comparable to that specified in the technical requirements.

The considered perturbations were selected to represent typical classes of manufacturing and assembly imperfections encountered in superconducting MRI magnets, including positioning errors, mechanical deformations, and winding inaccuracies. The selected values should therefore be regarded as representative engineering test cases illustrating the capabilities of the proposed shimming methodology rather than as strict manufacturing tolerance limits. The shimming algorithm for the SC magnet of a 1.5 T MRI scanner was tested on the following FE models with imposed perturbations:

1. Displacement of the central coil along the z -axis ($\Delta Z = 2$ mm);
2. Displacement of the central coil along the x -axis ($\Delta X = 2$ mm);
3. Radial deformation of the central coil cross-section (4 mm);
4. Deviations in the number of turns in the coils.

For each perturbation, the field map in the OR and the corresponding homogeneity metrics were evaluated.

7 Displacement of the central coil position

The central coil is the closest coil to the magnet's OR; therefore, even minor deviations in its position lead to a significant impact on the magnetic field distribution. Two displacement scenarios were simulated in the FE model of the magnet: a 2 mm displacement along the longitudinal Z -axis and a 2 mm displacement along the horizontal X -axis. All other system parameters (positions of the remaining coils, currents, and material properties) were kept unchanged and corresponded to the design values.

After performing a magnetostatic FE analysis of the perturbed configurations, the magnetic field distribution in the OR was obtained (Fig. 8a, Fig. 9a). After applying passive shimming, the field homogeneity improved from 460 ppm to 4 ppm for the axial displacement case and from 234 ppm to 4 ppm for the lateral displacement case. The magnetic field distributions after shimming are shown in Fig. 8b and Fig. 9b.

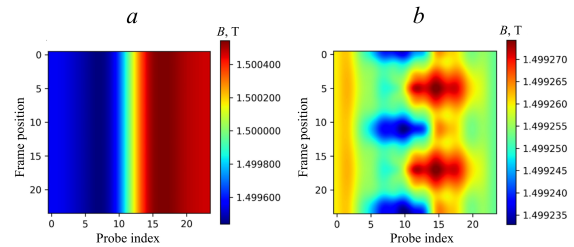


Figure 8. Magnetic field distribution on the OR surface with a diameter of 500 mm; central coil shifted by $\Delta Z = 2$ mm.

a – before passive shimming; b – after passive shimming.

8 Deformation of the central coil shape

In addition to axial displacements, deformation of the circular coil cross-section into an elliptical shape significantly degrades the magnetic field homogeneity. Such deformation may occur during mechanical fixation of superconducting coils in the cryostat.

This study considers deformation of the central coil cross-section, where the difference between the major and minor axes of the ellipse is 4 mm, corresponding to a relative deformation of 0.38%. The initial field inhomogeneity in this case was characterized by a VRMS deviation of 52 ppm. After two shimming iterations, the residual field inhomogeneity was reduced to VRMS = 0.5 ppm. The total mass of the shims was 5.36 kg.

9 Deviations from the optimal number of turns in the coils

During coil winding, deviations from the calculated number of turns may occur. As an example, a local deviation in the number of turns (1%) in the shielding coil (No. 9, Fig. 1) is considered, which leads to a deterioration of the field homogeneity (up to 318 ppm). Direct shimming of this local defect requires 16.2 kg of shims. However, this configuration cannot be realized due to overflow of several pockets in the shim holders within the considered shimming system.

A random deviation of the number of turns in the coils from the nominal value of approximately 0.001% leads to field distortion up to 15 ppm. After shimming, the homogeneity level reaches 1 ppm with a shim mass of 0.46 kg.

The magnetic field distribution on the spherical surface before and after shimming is shown in Fig. 10. The effects of manufacturing deviations are summarized in Table 2.

10 Conclusion

The finite-element (FE) modeling of representative manufacturing defects made it possible to quantify their influence on magnetic field homogeneity and on the effectiveness of passive shimming. Based on these results,

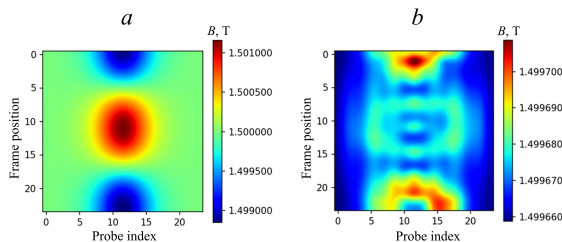


Figure 9. Magnetic field distribution on the OR surface with a diameter of 500 mm; central coil radial deformation (4 mm).

a – before passive shimming; *b* – after passive shimming.

requirements for the manufacturing accuracy of magnet components can be formulated.

The paper presents and validates a passive shimming method for a 1.5 T superconducting MRI magnet. The correction problem is formulated as minimization of the residuals between the measured field deviations and the field generated by the shims, subject to constraints on the maximum plate thickness in each pocket.

The developed shimming software was shown to be effective for representative manufacturing imperfections, including mechanical displacements, coil deformations, and winding errors. In all investigated cases, the required magnetic field homogeneity specified in the technical requirements was achieved.

Although the present study focuses on a 1.5 T whole-body MRI magnet, the proposed methodology can be readily adapted to superconducting MRI magnets with different field strengths and geometrical configurations by updating the corresponding magnet model and shimming system parameters.

The proposed approach can also support manufacturing quality control and commissioning by enabling quantitative assessment of manufacturing deviations, definition of acceptable production tolerances, and evaluation of whether the required field homogeneity can be achieved by passive shimming. The developed method is therefore recommended for the design, manufacturing support, and commissioning of superconducting MRI systems.

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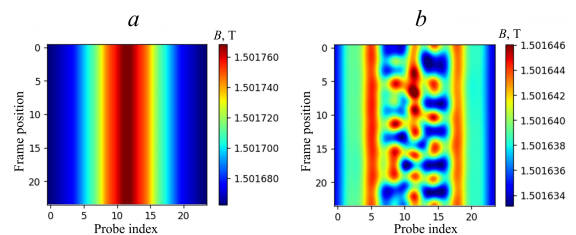


Figure 10. Magnetic field distribution on the OR surface with a diameter of 500 mm; uniform coil turn deviation.

a – before passive shimming; *b* – after passive shimming.

Table 2. Summary of the effect of manufacturing deviations on magnetic field homogeneity before and after passive shimming

Type of deviation	Value of deviation	VRMS, ppm before	VRMS, ppm after	Mass of steel plates, kg
ΔZ	2 mm	459	4.0	19.36
ΔX	2 mm	234	4.0	11.15
Radial coil deformation	4 mm	52	0.5	6.00
Local (Coil 9)	1%	318	1.7	16.20
Uniform (coil turns)	$\pm 0.001\%$	15	1.0	0.46

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