

Topology Optimization and Experimental Validation of a Magnet Structure for Portable Ultra-Low-Field MRI Devices

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Abstract—Portable ultra-low-field (ULF) magnetic resonance imaging (MRI) offers advantages over conventional high-field MRI, including mobility, reduced weight, and lower cost, which make it suitable for specialized settings such as ambulances and intensive care units. To maximize its benefits, further reducing overall weight while maintaining imaging quality is a key development trend. This study applies topology optimization (TO) to the iron yoke in order to reduce its weight while achieving a stronger static magnetic field in the ULF MRI device. Unlike parametric optimization (PO), the TO method does not rely on predefined structures, enabling the discovery of novel topology designs. The optimization results demonstrate that, while maintaining an average magnetic field above 100 mT in the target region, the TO method achieves a 29.4% reduction in iron weight compared to the optimal structure obtained by the conventional PO method. The optimal structure derived from the TO method was simplified to facilitate manufacturing, and a prototype was fabricated accordingly. In this newly developed ULF MRI system, a shimming ring and passive shimming magnet blocks were incorporated, and second-order active shimming was applied, reducing the overall field inhomogeneity to 300 ppm. Water phantom imaging was successfully performed using this fully redesigned system.

Index Terms—Medical imaging, magnetic resonance imaging, optimization methods, topology optimization, permanent magnets.

I. INTRODUCTION

PORTABLE ultra-low-field (ULF) magnetic resonance imaging (MRI) devices, designed for clinical diagnostics in specialized environments such as intensive care units, ambulances, and disaster sites, have attracted significant research attention in recent years. Unlike

conventional high-field MRI, ULF MRI does not utilize superconducting magnets; instead, it employs normal-conducting electromagnets or permanent magnets (PMs) to generate the main magnetic field. In recent years, particularly the PMs-based devices have made significant strides in portability and functionality. PMs, which require no cooling and offer high stability, enable operation without shielding at magnetic fields below approximately 100 mT due to their minimal susceptibility to external interference. These characteristics contribute to reduced costs, simplified maintenance, and enhanced portability. Several prototypes of PM-based ULF MRI devices have been developed, and their improved image quality demonstrates their strong potential [1–3]. However, a major challenge in further development is finding the balance between static magnetic field (B_0) strength, homogeneity, and overall weight. Among the commonly used PM configurations, the Halbach [4–8] and bipolar [9–11] configurations are the most widely adopted. Table I presents a comparison of several representative magnet designs.

Cooley et al. [5] employed a genetic algorithm to optimize a sparse Halbach array, achieving a field strength of 64 mT with a 122 kg magnet, though the inhomogeneity reached 27,800 ppm in a 20 cm diameter spherical volume (DSV). A similar approach was taken by O'Reilly and colleagues [6], who designed a double-layered Halbach array that generated 50.4 mT with a weight of 75 kg and improved B_0 homogeneity (2500 ppm in a 20 cm DSV). Huang's team [7] developed a 151 kg Halbach structure capable of producing 101.5 mT, though it still exhibited 7500 ppm inhomogeneity within a cylindrical region of interest (ROI) with a diameter of 20 cm and a length of 12.5 cm. In another study, Patrick and his collaborators [8] designed a unilateral Halbach magnet weighing only 6.3 kg with a field strength of 63.6 mT, but the inhomogeneity was as high as 69,200 ppm over a $3 \times 8 \times 8$ cm cuboid ROI. Overall, Halbach magnet structures are lightweight, but improving their field homogeneity remains a major challenge in practical implementations.

Bipolar plate magnets, consisting of opposing PM plates with iron yokes, provide improved field homogeneity. Hyperfine [9] developed a bipolar magnet weighing 630 kg, which generated a 64 mT field for brain imaging, with no information about homogeneity provided. The University of Hong Kong [10] designed a 55 mT bipolar magnet with a total weight of 750 kg and a inhomogeneity of 250 ppm in a 24 cm DSV (after passive shimming). Chongqing University [11] built a 500 kg system that produced a 50 mT field with 100

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ppm inhomogeneity in a 20 cm spherical region (after passive shimming). Compared to Halbach configurations, bipolar magnets offer improved field homogeneity at the cost of increased overall weight.

for generating a 100 mT target field. To facilitate manufacturing, the optimized structures is regularized for practical fabrication. Based on this, the shimming ring is optimized through parameter design, working alongside

TABLE I
COMPARISON OF REPRESENTATIVE MAGNET DESIGNS FROM THE LITERATURE

Configuration	Team	Weight (kg)	ROI size (cm)	Inhomogeneity (ppm)	B_0^{ave} (mT)
Halbach	Cooley[5]	122	20 (<i>spherical</i>)	27,800	64
	O'Reilly[6]	75	20 (<i>spherical</i>)	2,500	50.4
	Huang[7]	151	20× 12.5 (<i>cylindrical</i>)	7,500	101.5
	Patrick[8]	6.3	3× 8× 8 (<i>cuboid</i>)	69,200	63.6
Bipolar	Hyperfine[9]	630	<i>Not reported</i>	<i>Not reported</i>	64
	Liu[10]	750	24 (<i>spherical</i>)	250 (<i>after passive shimming</i>)	55
	Xu[11]	500	20 (<i>spherical</i>)	100 (<i>after passive shimming</i>)	50

Currently, these structures are primarily designed using parametric optimization (PO) and empirical methods, leading to predetermined shapes. This approach poses challenges in reducing device weight. To balance the advantages of ULF MRI with sufficient field strength, the structural design of the PM system, including the geometry of the magnets and iron yoke, is critical. Conventional designs are constrained by regular structures, which do not fully align with the naturally smooth paths of magnetic flux. Manual design approaches are unlikely to yield optimal solutions, making topology optimization (TO) [12-16] a promising method for exploring irregular structures that achieve a balance between weight reduction and field strength. TO differs from PO by enabling arbitrary shape generation within a design space, offering strong shape design capabilities. It has been applied in diverse fields, including electrical machines [15]. TO methods are mainly divided into gradient-based and stochastic types. The density-based method [12-13], a typical gradient-based approach, is computationally efficient with smooth convergence but often yields gray-scale elements requiring post-processing. Stochastic methods like the ON-OFF method [14] assign binary states (material/air) to small elements and use evolutionary algorithms, but involve many variables, making global convergence difficult. The NGnet method [15-16], based on normalized Gaussian networks, reduces variables by exploiting function smoothness and locality, leading to more manufacturable designs. TO, particularly with NGnet, has not yet been applied to MRI design, though its potential is significant for creating complex, optimized structures.

This paper proposes to use NGnet based TO method for designing the iron yoke of the ULF MRI without predefined shapes, considering the trade-off between B_0 field strength and weight. Based on this method, a novel three-dimensional (3D) topological structure for the iron yoke is proposed, significantly improving magnetic efficiency compared to conventional PO designs and reducing the weight by 29.4%

passive shimming PM blocks and active shimming coils to reduce field B_0 inhomogeneity to 300 ppm. Magnetic field measurements of the assembled system validate the consistency between the designed and experimental results. Furthermore, passive and active shimming methods are briefly introduced based on the actual system. Finally, imaging results of a water phantom using the proposed system are presented.

II. TOPOLOGY OPTIMIZATION OF ULF MRI DEVICES

A. ULF MRI devices

In the ULF MRI, the static magnetic field is generated by three primary components, as illustrated in the two-dimensional (2D) and 3D models shown in Fig. 1. A pair of bipolar PM serves as the source of the magnetic field; an iron yoke not only provides mechanical support but also forms a closed magnetic flux path, thereby enhancing the magnetic field; and a shimming ring made from iron is employed to improve B_0 homogeneity. The design objective is to maximize field strength and homogeneity in the region of interest (ROI) while minimizing total weight, particularly that of the iron yoke.

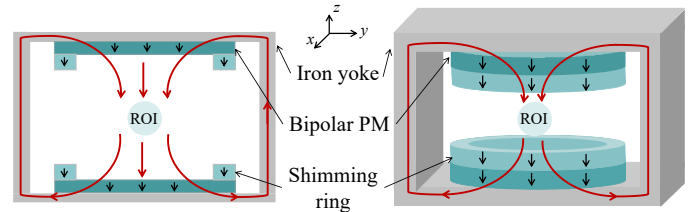


Fig. 1. Conventional structure for ULF MRI devices.

In this work, the target B_0 is assumed to be aligned along the z -direction. Therefore, the magnetic field component B_z is evaluated, and the average value B_z^{ave} is used as the reference for field homogeneity. The B_0 inhomogeneity is defined as the peak-to-peak deviation within the ROI with a diameter of 200 mm, normalized by B_z^{ave} , and expressed in parts per million (ppm):

$$\text{Inhomogeneity} = \frac{(B_z^{\max} - B_z^{\min})}{B_z^{\text{ave}}} \times 10^6. \quad (1)$$

Among the three structures mentioned above, the planar circular bipolar PMs already provides a well-optimized configuration for generating a uniform field. Additionally, PMs are difficult to manufacture in complex, irregular shapes, making the conventional bipolar plate magnet structure a practical choice. Therefore, we fix the structure of the bipolar magnet and consider the iron yoke and shimming ring as optimization variables. In our design, the iron yoke and the shimming ring were optimized sequentially in two stages. This approach was chosen because our preliminary study showed that sequential optimization reduces computation time and helps avoid local optima. In Stage 1, the iron yoke was optimized using topology optimization to achieve a required average field flux density in the ROI with minimal weight. In Stage 2, the annular shimming ring was optimized using traditional parameter optimization to improve the field homogeneity.

B. NGnet-based TO method for iron yoke design

Traditional ON-OFF TO design methods discretize the design domain into multiple elementary units, where each unit is assigned a binary variable (0/1) to determine its presence. However, as the number of units increases, the optimization space grows exponentially, leading to high computational complexity and difficulties in achieving smooth topologies. This study employs the NGnet-based TO method [15], introducing a layer of normalized Gaussian basis functions (NGs) above the elementary unit level. These NGs govern the shape function over local regions, transforming discrete unit-based optimization into a global, smooth parameterized process. This approach significantly reduces computational complexity, improves convergence, and enables the generation of smoother topological structure.

In the NGnet-based TO method, the shape function representing the topological structure is formulated as

$$y(\mathbf{x}, \mathbf{w}) = \sum_{i=1}^N w_i b_i(\mathbf{x}), \quad (2)$$

where $w_i \in [-1, 1]$ denotes the weighting coefficient, N represents for the number of NGs. and $\mathbf{x}$ is the position vector, respectively. $\mathbf{w}$ is weighting coefficient vector and $\mathbf{w} = [w_1, w_2, \dots, w_N]$. In other words, the shape function $y(\mathbf{x}, \mathbf{w})$ is obtained by superimposing N basis functions $b_i(\mathbf{x})$, each weighted by its corresponding coefficient w_i . The basis function $b_i(\mathbf{x})$ is the NG function, and it is defined as

$$b_i(\mathbf{x}) = G_i(\mathbf{x}) / \sum_{j=1}^N G_j(\mathbf{x}), \quad (3)$$

$$G_i(\mathbf{x}) = \frac{1}{(2\pi)^{d/2} \sigma^d} \exp\left\{-\frac{1}{2\sigma^2} |\mathbf{x} - \mathbf{x}_i|^2\right\}, \quad (4)$$

where $G_i(\mathbf{x})$ is a classical Gaussian function in a d -dimensional space. Here, $d=3$ to represent 3D space, and σ and $\mathbf{x}_i$ denote the standard deviation and center of the Gaussian base function, respectively. Equation (3) normalizes

the classical Gaussian function over the design domain to ensure that the shape function varies within a defined range.

Accordingly, the material property M_e of each element in the design region is determined by the following equation.

$$M_e = \begin{cases} \text{material 1} & (y(\mathbf{x}_e) \geq 0) \\ \text{material 2} & (y(\mathbf{x}_e) < 0) \end{cases} \quad (5)$$

where $\mathbf{x}_e$ denotes the centroid of element e . The NG basis functions are uniformly distributed across the design region. The variance σ^2 , which controls their spread, is typically chosen so that the circles (or spheres) of radius σ are arranged to just touch one another. For instance, in optimizing the iron yoke in the ULF MRI devices, material 1 represents the iron and material 2 corresponds to the air.

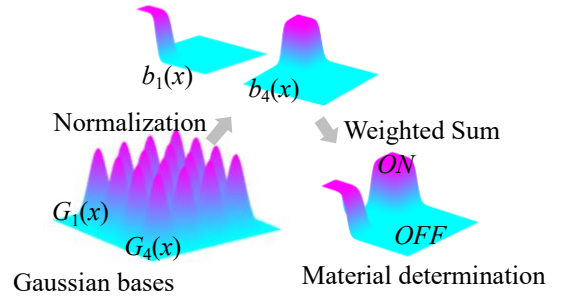


Fig. 2. Material determination based on the NGnet method.

To provide a more intuitive illustration, Fig. 2 presents the material determination process based on the NGnet method, corresponding to Equations (2) to (5). The Gaussian bases $G_i(\mathbf{x})$ are first normalized to ensure consistency. A weighted sum of basis functions $b_i(\mathbf{x})$ is then computed to generate a continuous material distribution. Finally, based on a threshold, the material is assigned as either material 1 or material 2, resulting in a certain topology. In TO, the set of weighting coefficients $\mathbf{w} = [w_1, w_2, \dots, w_N]$ is optimized by stochastic approaches such as CMA-ES (Covariance Matrix Adaptation Evolution Strategy, for single-objective optimization) or NSGA-II (Non-dominated Sorting Genetic Algorithm II, for multi-objective optimization) to minimize the fitness value. Essentially, TO is transformed into a PO problem with significantly fewer variables.

Fig. 3 illustrates the workflow of the TO approach. For our current single-objective optimization function, CMA-ES is used as the optimization tool to adjust the populations (weighting coefficients of NG basic functions). The fitness value of each candidate solution is evaluated through the finite element method (FEM), and the material distribution is iteratively refined to achieve the optimal structure.

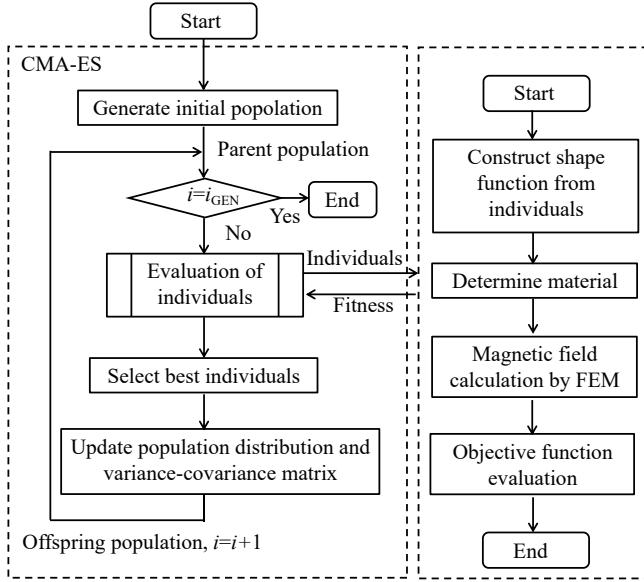


Fig. 3. Flowchart of NGnet TO method.

III. TOPOLOGY OPTIMIZATION RESULTS

A. Topology design setting for the iron yoke

The iron yoke is designed by the NGnet based TO method. As illustrated by the Fig. 4, the design region for the iron yoke is covered by circles representing the influence region of the NG bases. The structure is a mirror symmetric, allowing us to focus only on the 1/8 model during the design process. The standard deviation σ of the NG basis functions is set to 100 mm, with a total of 48 basis functions used in the 1/8 model.

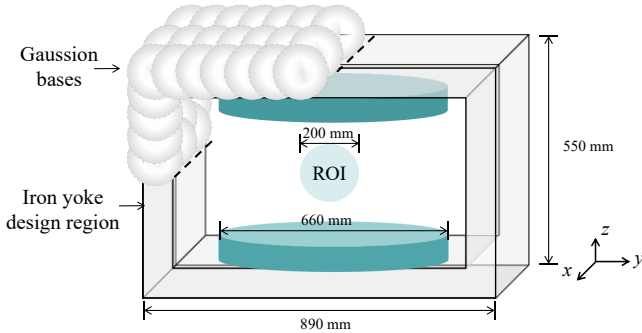


Fig. 4. TO region definition in 3D space ($\sigma = 100$ mm, 48 NG bases in 1/8 model).

Practical experience has shown that the primary function of the yoke is to create a magnetic loop to increase the field strength, while the shimming ring is responsible for reducing inhomogeneity. We can design the iron yoke and the shimming ring in sequence. For the TO problem, our objective is to achieve an average magnetic flux density in the z -direction (B_z^{ave}) greater than 100 mT within the ROI, while minimizing the weight of the iron yoke (W). We define the objective function as:

$$F(\mathbf{w}) = \frac{W(\mathbf{w})}{W_{\text{ref}}} \rightarrow \min., \quad (6)$$

$$\text{sub. to } B_z^{\text{ave}} \geq B_z^{\text{ref}},$$

where W is the weight of the iron yoke in the full 3D model, with $B_z^{\text{ref}} = 0.1$ T, and $W_{\text{ref}} = 216$ kg. In this formulation, the optimization variables are the weighting coefficients of the NG basis contained in the vector $\mathbf{w}$, which are initialized as random numbers ranging from -1 to 1. These weights are optimized using CMA-ES, a stochastic single-objective optimization algorithm. The optimization hyper-parameter settings for CMA-ES are given in TABLE II.

TABLE II
HYPER-PARAMETERS FOR CMA-ES

Number of variables	48
Number of generations	200
Population size	16

The performance of each individual in the optimization process is evaluated through 3D FEM calculations. The nonlinear B - H curve of Q235 steel is used to model its magnetic behavior. This material property is implemented in the FEM calculations, as illustrated in Fig. 5. We employed Samarium Cobalt (SmCo) PMs, modeled with a constant remanent flux density ($B_r = 1.094$ T), and a fixed relative permeability (1.063). A linear magnetization model for PMs was assumed in the FEM calculations to simplify the field computation. Since the bipolar PM are uniformly magnetized in the same direction, the effect of demagnetization can be neglected.

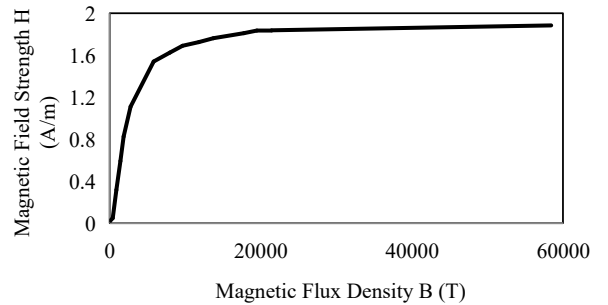


Fig. 5. B - H curve of the Q235 steel used for the iron yoke.

Although in 2D optimization it is common to assign material properties directly to the FEM mesh elements, in our approach the 3D design domain is discretized into predefined cubic units with an edge length of 5 mm, which serve as the material design units. FEM adaptive remeshing is applied after each material update. This strategy decouples the material assignment from the FEM mesh and alleviates the meshing difficulty in 3D optimization. An adaptive meshing strategy was employed, with initial mesh sizes of 20 mm for the magnets and iron, 10 mm for the ROI, and 100 mm for the air region. Refinement was performed until the relative change in magnetic energy fell below 0.5%. The total number of mesh

elements varied with the model geometry, typically ranging from 70,000 to 100,000 elements. In the iron yoke optimization stage, this level of precision was sufficient because field inhomogeneity was not considered at this stage. In the actual optimization process, three simulations were run in three parallel processes, effectively reducing the computation time to one-third. Based on an optimization setting of 200 generations with 16 individuals per generation, the total number of simulations is 3200. Therefore, the total computation time is approximately 71.1 hours.

B. Topology design result for the iron yoke

Fig. 6 illustrates the evolution history of the fitness value F , which exhibit periodic fluctuations and gradually stabilizes after approximately 200 generations. This behavior arises from the trade-off relationship between field strength B_z^{ave} and weight W , as they are iteratively adjusted during the evolutionary process to minimize the objective function F .

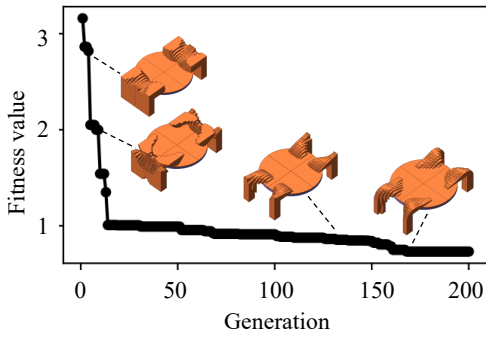


Fig. 6. Convergence history of fitness value for the TO.

Fig. 7 presents several representative structures throughout the TO process. As the optimization advances, the total weight of the iron yoke W progressively decreases while ensuring B_z^{ave} consistently remains above 100 mT. In this study, we use the NGnet-based method with smooth Gaussian basis functions, which naturally leads to continuous structures. Since the optimization target is the iron yoke for guiding magnetic flux, structures with holes are not favorable and thus are avoided during the optimization process. As a result, the optimal structure obtained is excessively smooth and free of holes, which facilitates fabrication and manufacturing. To further facilitate manufacturing and reduce costs, we manually regularized the optimized structure from Fig. 8 (a), resulting in the structure shown in Fig. 8 (b), which facilitates manufacturing without significantly compromising magnetic performance. Fig. 9 illustrates the magnetic flux distributions of the initial, optimized, and regularized structures. It can be observed that the optimized structure better aligns with the natural path of the magnetic flux lines, preserving the key flux pathways to the greatest extent.

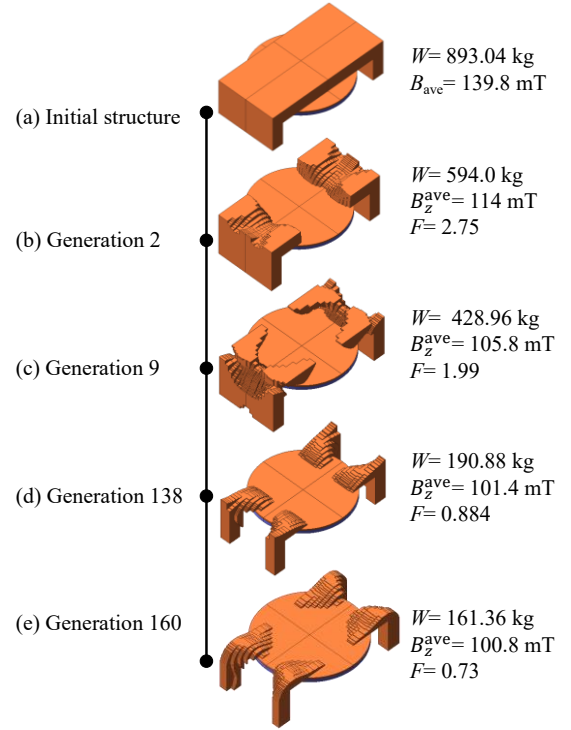


Fig. 7. Evolution of the iron yoke topology (vertically symmetric half model) during optimization, where W represents the weight of the iron yoke in the full model.

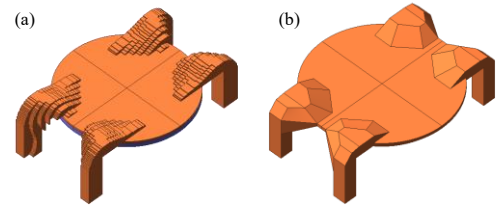


Fig. 8. Topologies of the iron yoke (vertically symmetric half model): (a) optimized structure; (b) regularized structure derived from the optimized design.

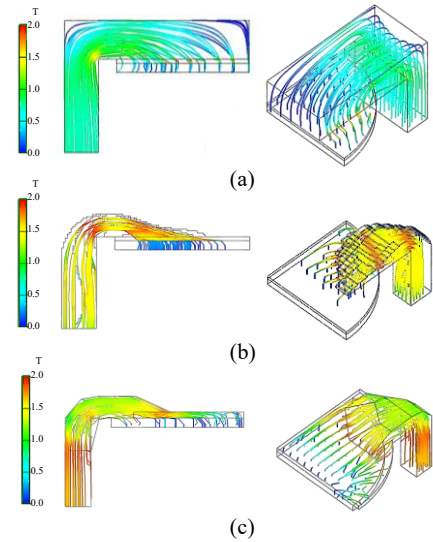


Fig. 9. Magnetic flux comparison (1/8 model), between (a) conventional, (b) optimized, and (c) regularized structure.

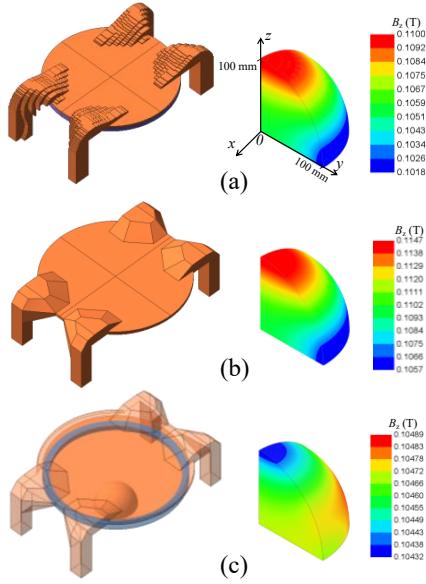


Fig. 10. Magnetic field comparison, among (a) the optimized structure, (b) the regularized structure, and (c) the regularized structure with the shimming ring.

Fig. 10 presents the magnetic flux distributions of the optimized structure, the regularized structure, and the regularized structure with a shimming ring. The regularization has a minimal impact on the field distribution while significantly reducing manufacturing costs and installation complexity. However, if manufacturing constraints are not a concern, retaining the optimized structure remains the preferred choice. After adding a shimming ring made of iron, the magnetic field inhomogeneity in the target region was reduced to approximately 4000 ppm.

IV. PARAMETRIC OPTIMIZATION RESULTS

For comparison with TO, the same design problem for the iron yoke was also solved using conventional PO method. The design space and parameter settings for the PO are shown in Fig. 11. The optimization variables are the overall width (L_x) and height of the yoke (L_y), as well as the thickness (t_x) and height of the yoke walls (t_y). The optimization objective is the same as that of the TO, as defined in equation (5) in the previous section.

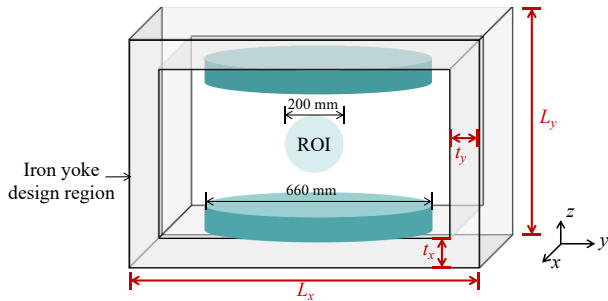


Fig. 11. Definition of the design region for PO in 3D space.

Fig. 12 presents the optimal structures (vertically symmetric

half model) obtained through TO and PO. The PO structure achieves an B_z^{ave} of 100.8 mT in the target region, comparable to that obtained with the TO method, but its iron weight increases to 208.79 kg, representing a 29.40% increase compared to the TO-derived structure. This indicates that TO provides a more efficient design than conventional PO. Fig. 12 also compares the magnetic flux distributions of the optimal structures obtained from TO and PO. It can be observed that certain low-utilization regions of the yoke remain in the parameter-optimized structure, whereas these regions are effectively eliminated through the evolutionary process of TO.

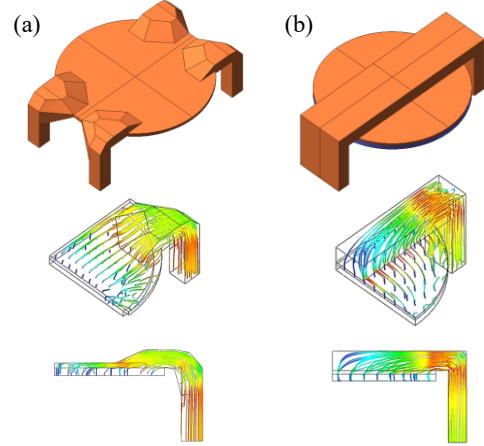


Fig. 12. Optimal structure and their corresponding magnetic flux distributions, obtained through (a) TO and (b) PO method.

V. MEASUREMENT AND IMAGING RESULTS

A. Fabricated low-field MRI device

As shown in Fig. 13, the iron yoke was fabricated according to the optimized and regularized shape using steel Q235. The bipolar PM is assembled from multiple cubic NdFeB PM blocks, while the shimming ring is also made of steel Q235. In addition to the weight of the iron yoke discussed above, this system's total weight including the magnets, shimming rings, anti-eddy plates, and all associated components is approximately 500 kg.

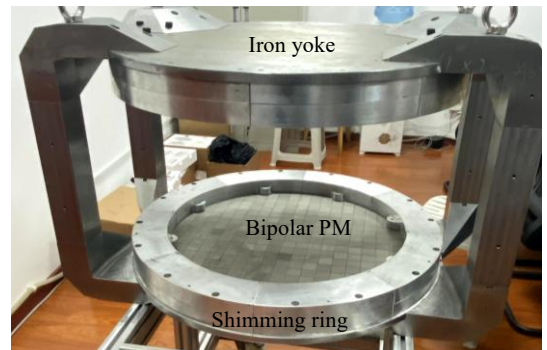


Fig. 13. Fabricated structure.

The B_z component within ROI was measured using the stepper platform illustrated in Fig. 14, which presents a

conceptual diagram of the field measurement setup. The stepper platform has three axes and is equipped with a mounted probe, enabling 3D magnetic field measurements within the ROI. Fig. 14(b) presents a corresponding photograph of the actual setup. Magnetic field measurements were carried out with a Metrolab Precision NMR Teslometer (PT2026), which offers a resolution of 0.01 ppm in a uniform 3 T field and an accuracy of ± 5 ppm of the field strength.

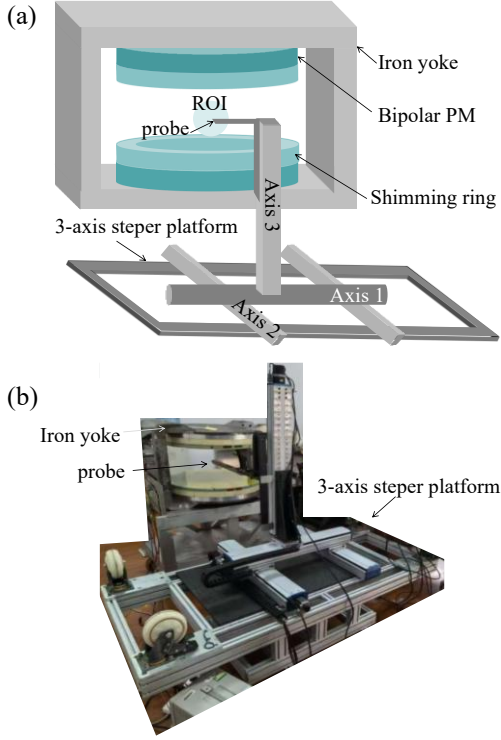


Fig. 14. Measurement platform of magnetic field in ROI, (a) conceptual diagram, and (b) actual setup.

Fig. 15 presents the measured field deviation and magnetic field B_z in the ROI before passive shimming, where the maximum field inhomogeneity is approximately 7000 ppm. Here, the field deviation at each point within the ROI is defined as the difference between the local magnetic field and the average field. This signed deviation reflects spatial variations in the field, allowing both positive and negative differences to be visualized relative to the center.

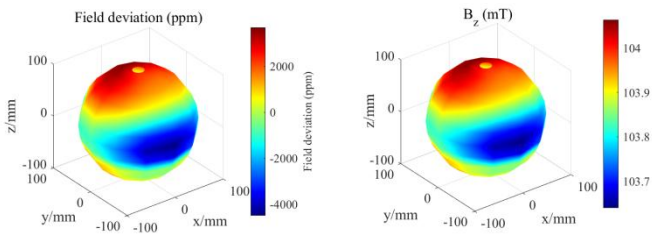


Fig. 15. Measured field in the ROI.

B. Passive shimming using PM blocks

Building upon the structure in Fig. 13, discrete shimming

PM blocks will be attached to the surface of the bipolar PM to compensate for magnetic field deviations caused by manufacturing and assembly, thereby improving field homogeneity in ROI. This process is referred to as passive shimming. As shown in the Fig.16, discrete PM shimming blocks are placed on the surface of the bipolar PMs. In practice, these blocks are significantly smaller than depicted, typically with a maximum diameter of 15 mm and a height of up to 10 mm. The primary purpose of passive shimming is to compensate for inevitable field inhomogeneities caused by machining tolerances, and it is a widely adopted technique in practical fabrication. Fig. 17 shows the field deviation and B_z field distribution after passive shimming, reducing the maximum field inhomogeneity to approximately 600 ppm.

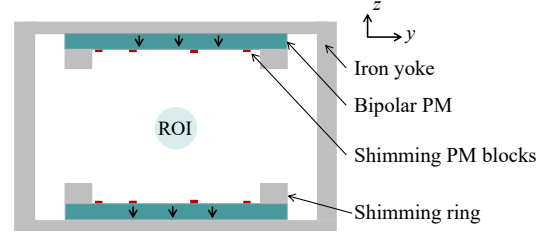


Fig. 16. Layout of the permanent magnet blocks.

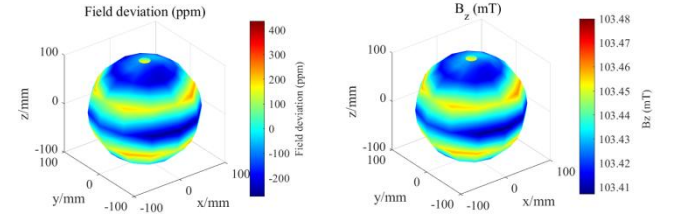


Fig. 17. Measured field in the ROI, after passive shimming with small PM blocks.

C. Active shimming using compensation coils

Active shimming [18] involves the use of specially designed compensation coils to correct magnetic field inhomogeneity by generating predefined spatial field components. First-order shimming compensates for linear deviations along the X , Y , and Z axes, while second-order shimming targets more complex nonlinear distortions using higher-order spherical harmonic components. The first-order shimming coils have a structure identical to that of the gradient coils [2], whereas the second-order shimming coils are shown in the Fig. 18. The first and second rows of Fig. 18 show the wiring paths and the fabricated models of the shimming coils, respectively, while the third row presents the corresponding magnetic field patterns generated by them. The zx and zy shimming coils typically share the same structure, with the difference arising from a 90-degree horizontal rotation during installation. By applying adjustable currents to these coils, the non-uniform components of the magnetic field can be effectively canceled.

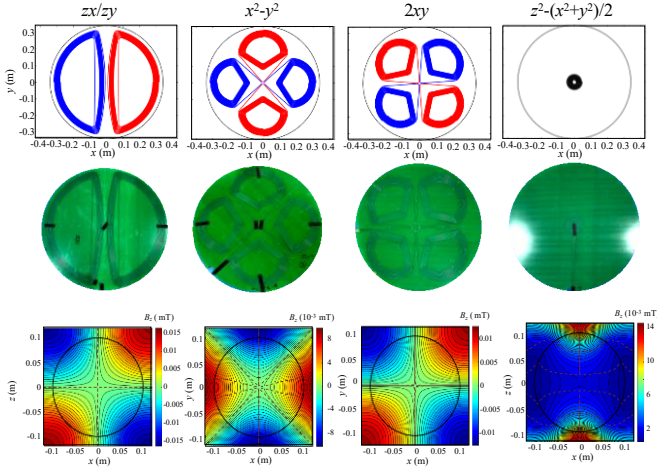


Fig. 18. Second-order shimming coils: coil paths and field.

The shimming process dynamically adjusts the currents in the shim coils in real time based on system feedback to optimize magnetic field homogeneity. Due to differences in the structures of the shimming coils, the efficiency of magnetic field generation also varies. The absolute value of the currents applied to the first-order shimming coils (gradient coils) and second-order shimming coils are shown in TABLE III. A self-developed multi-channel constant current source shown in Fig. 19 was employed, offering a maximum output current of ± 1000 mA with a current accuracy of ± 3 mA.

TABLE III
CURRENTS APPLIED TO THE FIRST- AND SECOND-ORDER SHIMMING COILS

1 st -order	x		y	z	
current (mA)	56		81	480	
2 nd -order	zx	zy	x^2-y^2	$2xy$	$z^2-(x^2+y^2)/2$
current (mA)	12	300	16	63	74



Fig. 19. Self-developed multi-channel constant current source.

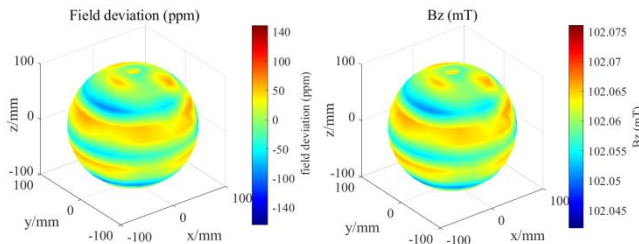


Fig. 20. Measured field in the ROI, after active shimming.

Fig. 20 shows the measured magnetic field and its field deviation in ROI after the active shimming, and the maximum inhomogeneity was reduced to approximately 300 ppm.

In this section, the RF transmit and receive coils used in the experiment are the same as those described in our previously published paper [11]. Both the transmit and receive coils are solenoidal in design. The receive coil is shaped as an elliptical cylinder with a short axis of 19 cm, a long axis of 23 cm, and a height of approximately 15 cm. The placement of the RF coils is illustrated in Fig. 21. The water phantom used for testing was a cylinder with a base radius of 7.5 cm and a height of 12 cm. To minimize RF induced eddy current, the RF transmit coil is shielded with a copper mesh, and to suppress gradient-induced eddy currents in the bulk iron, a laminated anti-eddy plate is employed. The gradient design explicitly accounts for the high-permeability distortion using an image-based modeling approach in Ref. [3].

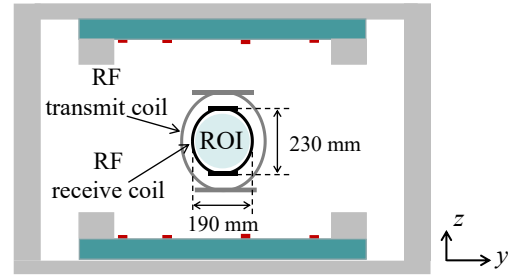


Fig. 21. Placement of the RF transmit and receive coils.

In the MRI system, the free induction decay (FID) signal is also used as an indicator of field inhomogeneity [19]. A slower decay of the FID signal indicates better magnetic field homogeneity. Fig. 22 presents the FID amplitude before active shimming, after first-order active shimming, and after second-order active shimming. The FID signal decay is significantly slowed after second-order shimming, indicating improved field homogeneity. Fig. 23 shows the FID spectrum measured using the cylindrical water phantom after second-order shimming. The FWHM of the peak corresponds to a field inhomogeneity of approximately 35 ppm within the ROI. The inhomogeneity estimated from the FID is lower than the measured field inhomogeneity because the water phantom used for testing was smaller and did not fill the full 20 cm-diameter spherical ROI, resulting in better homogeneity within the smaller region.

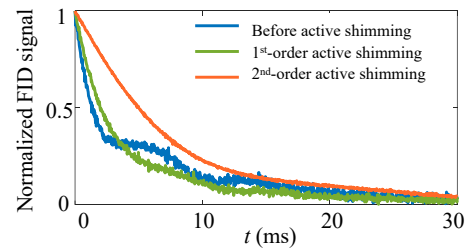


Fig. 22. Normalized FID signal amplitude.

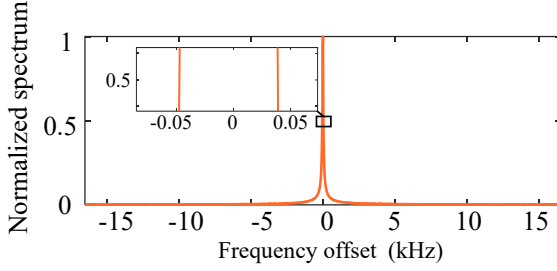


Fig. 23. Frequency spectrum of FID after second-order shimming.

Fig. 24 shows the overall structure of the ULF MRI system designed in this study, incorporating all necessary components, including gradient and active shimming coils, RF transmit and receive coils, as well as other essential electronic subsystems. Fig. 25 presents T2-weighted images of a water phantom acquired under three conditions: before shimming, after first-order active shimming, and after second-order active shimming. The application of second-order shimming significantly reduces distortions caused by magnetic field inhomogeneity, leading to improved image quality.

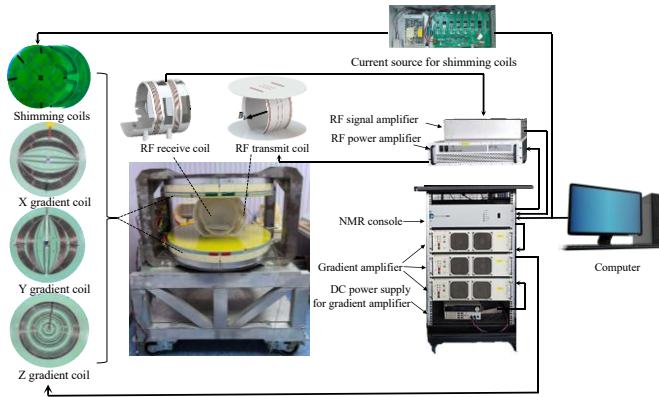


Fig. 24. Overall structure of the ULF MRI system designed in this study.

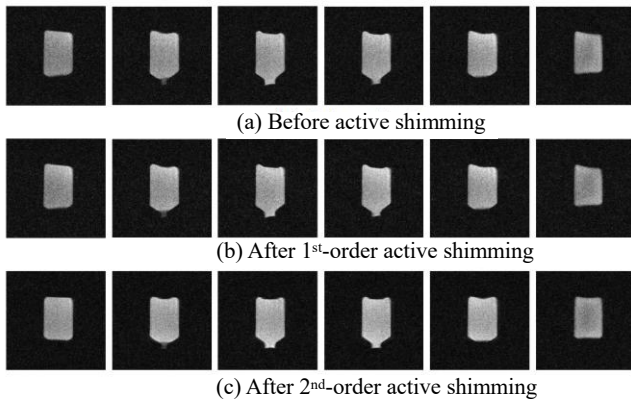


Fig. 25. T2-weighted imaging results of the water phantom, (a) before active shimming, (b) after first-order active shimming, and (c) after second-order active shimming.

VI. CONCLUSION

This study innovatively applies TO methods to the design of ULF MRI systems, resulting in a novel and irregularly shaped iron yoke structure. Compared to conventional PO methods, the TO-based design significantly reduces the total weight of the iron yoke. The results highlight the potential of TO in this domain, paving the way for more refined and high-performance designs in future applications. Future work may consider both the structural configuration and magnetization orientation of the PMs, enabling the creation of a new architecture that combines the advantages of Halbach arrays and bipolar PM configurations, while also ensuring ease of fabrication.

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