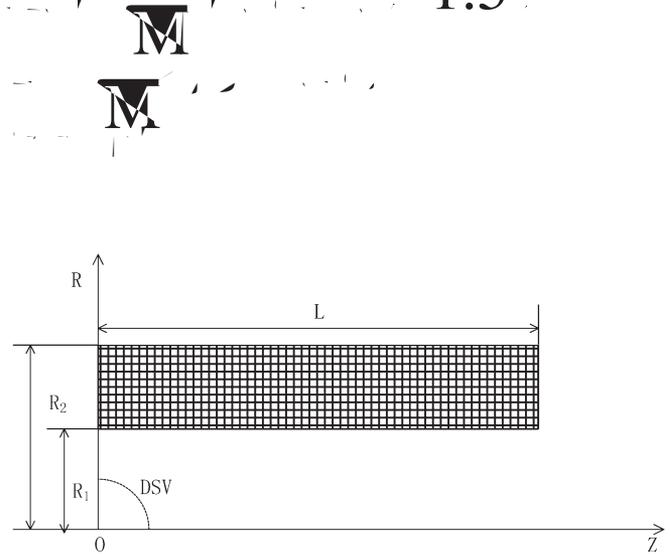


1.5



Abstract—In this paper, an effective method to design the superconducting magnet for 1.5 T dedicated extremity MRI is proposed. The feasible current carrying zones of superconducting magnet are subdivided by an array of grid elements. The size of each grid element is determined by the actual superconducting wire. The initial current distribution of superconducting magnet is optimized using 0–1 integer programming by a comprehensive consideration of superconductivity wire consumption, central magnetic field intensity, imaging region homogeneity, and the range of leakage field. The final rectangular section of magnet is obtained using the genetic algorithm optimization with artificial limitation of the coil position and section size considering the initial current distribution of superconducting magnet. The method based on the actual superconducting wire makes the MRI magnet design more feasible. A superconducting magnet for 1.5 T dedicated extremity MRI system is designed using this method. This magnet can offer 1.5 T central field with high homogeneity in diameter sphere volume (DSV), with total length of 430 mm, inner diameter of 350 mm. This method can also be used for short whole-body MRI superconducting magnet design.

Index Terms—Magnetic resonance imaging (MRI), optimization methods, superconducting magnet.

M

1. 1999 7. 0 1 1.5 M 1.5 (), 430 350.

2 6.

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17, 2013; 11, 2013. 14, 2013; 5, 2013. 100015, (: .1013). 100871, (: .). 10.1109/ .2013.2291113

Fig. 1. Schematic diagram of the superconducting magnet.

H 1999 7.

H 0 1 1.5 M 1.5 (), 430 350.

A. Grid of the Feasible Current Carrying Zone

(r, z, φ) z M R, N) 1. r_i, z

where (r_j, z_j) and (r_i, z_i) are the coordinates of the j th and i th current-carrying zones, respectively. B_{zj} and B_{rj} are the axial and radial components of the magnetic field at the target point (r_j, z_j) , respectively. B_{zi} and B_{ri} are the axial and radial components of the magnetic field at the source point (r_i, z_i) , respectively. I_i is the current in the i th zone. μ_0 is the permeability of free space.

$$B_{zj} = \frac{\mu_0 I_i}{2\pi} \frac{1}{[(r_i + r_j)^2 + (z_j - z_i)^2]^{\frac{1}{2}}} \times \left\{ K(k) - \left[\frac{r_j^2 - r_i^2 + (z_j - z_i)^2}{(r_j - r_i)^2 + (z_j - z_i)^2} \right] E(k) \right\} \quad (1)$$

$$B_{rj} = -\frac{\mu_0 I_i}{2\pi} \frac{z_j - z_i}{r_j [(r_j + r_i)^2 + (z_j - z_i)^2]^{\frac{1}{2}}} \times \left\{ K(k) - \left[\frac{r_j^2 + r_i^2 + (z_j - z_i)^2}{(r_j - r_i)^2 + (z_j - z_i)^2} \right] E(k) \right\} \quad (2)$$

$$k = \left[\frac{4r_i r_j}{(r_i + r_j)^2 + (z_j - z_i)^2} \right]^{\frac{1}{2}}. \quad (3)$$

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{d\alpha}{\sqrt{1 - k^2 \sin^2 \alpha}} \quad (4)$$

$$E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1 - k^2 \sin^2 \alpha} d\alpha. \quad (5)$$

B. Magnetic Field at Target Point

$$B_{zj} = \sum_{i=1}^N e_i a_{ij} I_i \quad (6)$$

$$B_{rj} = \sum_{i=1}^N e_i b_{ij} I_i \quad (7)$$

$$a_{ij} = \frac{\mu_0}{2\pi} \frac{1}{[(r_i + r_j)^2 + (z_j - z_i)^2]^{\frac{1}{2}}} \times \left\{ K(k) - \left[\frac{r_j^2 - r_i^2 + (z_j - z_i)^2}{(r_j - r_i)^2 + (z_j - z_i)^2} \right] E(k) \right\} \quad (8)$$

$$b_{ij} = -\frac{\mu_0}{2\pi} \frac{z_j - z_i}{r_j [(r_j + r_i)^2 + (z_j - z_i)^2]^{\frac{1}{2}}} \times \left\{ K(k) - \left[\frac{r_j^2 + r_i^2 + (z_j - z_i)^2}{(r_j - r_i)^2 + (z_j - z_i)^2} \right] E(k) \right\}. \quad (9)$$

where $e_i = 0$ or 1 , and \mathbf{M} is the magnetization vector.

C. 0-1 Integer Programming

The optimization problem can be formulated as a 0-1 integer programming problem. The objective function is to minimize the total length of the magnet, L , subject to the constraints that the axial magnetic field at the target point, B_{zj} , must be within a specified range, and the radial magnetic field at the target point, B_{rj} , must be within a specified range. The constraints are given by

$$L = 2\pi \sum_{i=1}^N e_i r_i. \quad (10)$$

where B_{zj} and B_{rj} are the axial and radial components of the magnetic field at the target point (r_j, z_j) , respectively. B_0 is the nominal axial magnetic field at the target point. ε is the tolerance factor.

$$\mathbf{M} : \sum_{i=1}^N e_i r_i \quad (11)$$

$$: |B_{zj} - B_0| \leq \varepsilon B_0 \quad (12)$$

where B_{zj} and B_{rj} are the axial and radial components of the magnetic field at the target point (r_j, z_j) , respectively. B_0 is the nominal axial magnetic field at the target point. ε is the tolerance factor.

$$: \begin{cases} |B_{zj} - B_0| \leq \varepsilon B_0 \\ |B_{zj}| \leq B_{z,shield} \\ |B_{rj}| \leq B_{r,shield} \end{cases} \quad (13)$$

where $B_{z,shield}$ and $B_{r,shield}$ are the axial and radial shield magnetic fields at the target point (r_j, z_j) , respectively. B_0 is the nominal axial magnetic field at the target point. ε is the tolerance factor.

D. Rectangularity of Current Carrying Zones

The current-carrying zones are assumed to be rectangular. The length of the i th zone is $2r_i$ and the height is $2z_i$. The current density in the i th zone is J_i . The total current in the i th zone is $I_i = 2r_i 2z_i J_i$.

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A. Requirement of Superconducting Magnet

The current-carrying zones are assumed to be rectangular. The length of the i th zone is $2r_i$ and the height is $2z_i$. The current density in the i th zone is J_i . The total current in the i th zone is $I_i = 2r_i 2z_i J_i$.

Central magnetic field (T)	1.5
DSV (mm)	160
Inner diameter of Dewar (mm)	>280
Outer diameter of Dewar (mm)	<600
Total length of Dewar (mm)	<520
Inner diameter of coils (mm)	>350
Outer diameter of coils (mm)	<450
Total length of coils (mm)	<430

Cu/Sc ratio	Bare size (mm)	Ins size (mm)	RRR	Ic@4.2K,5T
1.3:1	0.5*0.8	0.55*0.85	>100	>335A

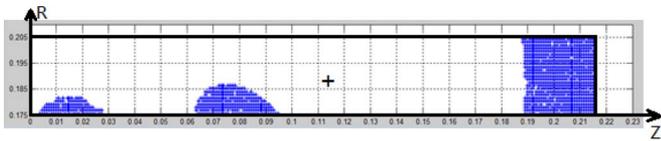


Fig. 2. Cross-sectional view of the coil assembly.

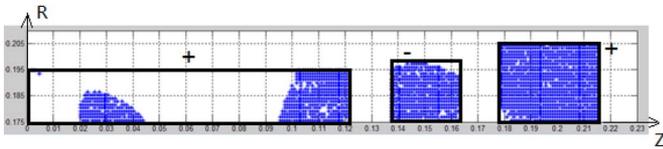


Fig. 3. Cross-sectional view of the coil assembly.

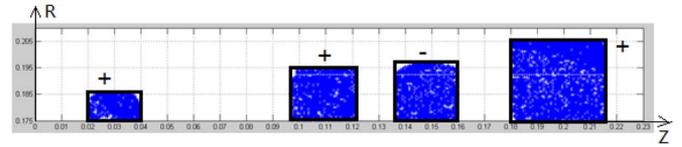


Fig. 4. Cross-sectional view of the coil assembly with current directions.

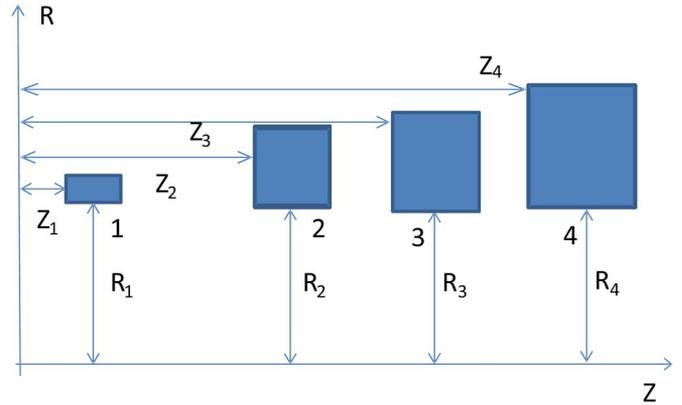
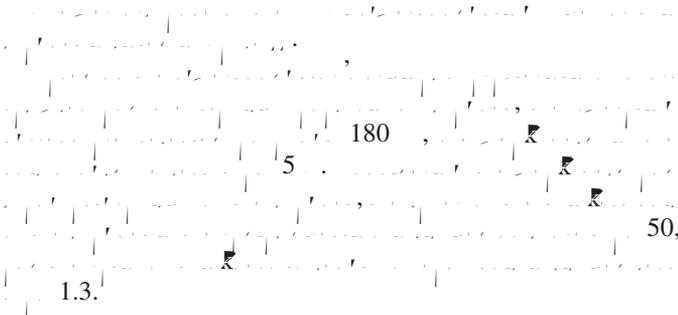


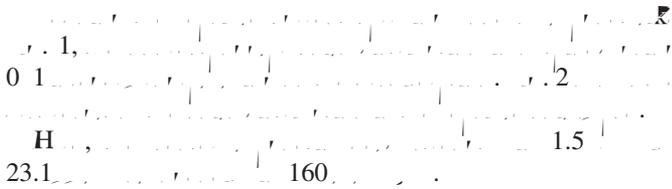
Fig. 5. Schematic diagram of the four coils.

Coil no.	Inner radius(m)	Layers in the radial direction	Zmin(m)	Turns in the axial direction	current direction
1	0.176	17	0.0187	23	+I
2	0.175	31	0.093	27	+I
3	0.1755	33	0.1348	25	-I
4	0.1765	50	0.1796	41	+I

B. Performance of Superconducting Wire



C. Result of the First Iteration



D. Creation of the Negative Current Zone



Fig. 6. H versus R plot.



