Geometrical aspects of cylindric magnetic shields in strong static fields

Zhiwei XIA (夏志伟)[1], Wei LI (李伟), Bo LI (李波) and Qingwei YANG (杨青巍)

Southwestern Institute of Physics, Chengdu 610041, People's Republic of China

E-mail: xiazw@swip.ac.cn

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Abstract
Motivated by ITER (the International Thermonuclear Experimental Reactor), research on a magnetic shield against a strong field has been carried out. In this paper, a cylindric magnetic shield is studied by using the finite element method with a nonlinear magnetization curve. The geometrical aspects of shielding performance are identified and corresponding suggestions for application are provided. Among them, the effects of the edge and cover thickness have not been mentioned elsewhere to our knowledge.

(Some figures may appear in colour only in the online journal)

1. Introduction

Magnetic shielding seems to be a very old science, with a history going back hundreds of years. The effectiveness of shielding is based on the high permeability of soft magnetic materials. Most magnetic flux is caught by the shield material, leading to a low residual field in the shield. Motivated by the engineering design of the International Thermonuclear Experimental Reactor (ITER) [1], interest has grown in magnetic shielding against a strong static field [2, 3]. For example, some susceptible components inside the gas valve box (GVB) of the gas injection system (GIS) need to be shielded against the local magnetic field of about 0.2 T [3, 4], which is a strong field, and the shield material may work near its saturation area. Nonlinear magnetic properties should be considered in this situation. In the past century, several formulas [5–12] have been developed to estimate the shielding effects of simple geometries, but unfortunately almost all of them need a constant permeability as input, which is hard to determine in the case of a strong external field because of the nonlinear properties of magnetization curves (*B–H* curves).

In this paper, the finite element method (FEM), including nonlinear material properties, is used to calculate the shielding performances of cylindric shields in an external field of about 0.2 T. A systematic study on the geometrical aspects of cylindric shields is carried out and corresponding suggestions are provided as a reference for related engineering designs.

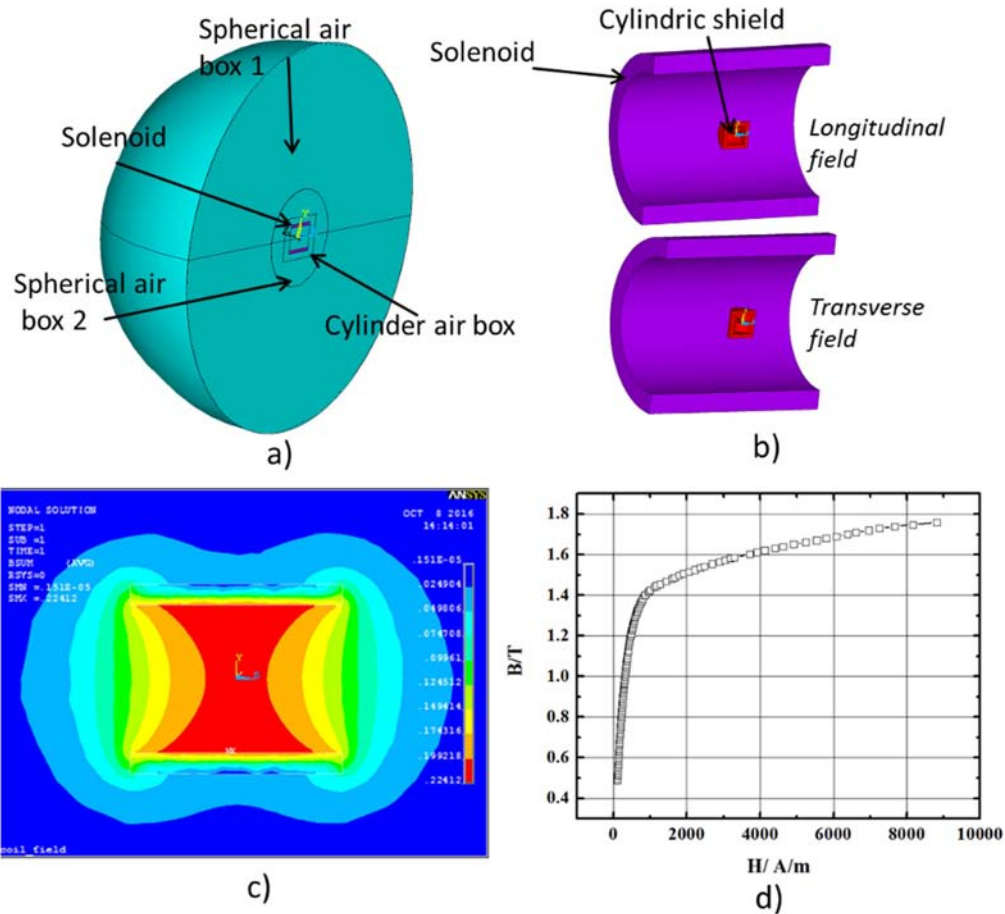[1] Author to whom any correspondence should be addressed.

2. Method

The ANSYS® APDL software package is used in our study. The tetrahedral element SOLID237 is adopted and it has ten nodes, with one degree of freedom (DOF) of edge-flux Az on each of six mid-side nodes and no DOF on four corner nodes. It also has the capability to deal with nonlinear properties of magnetic materials. Moreover, the edge-based magnetic vector potential element could provide more accurate solutions than magnetic vector potential elements (SOLID96, 98 etc.) for iron problems [13, 14].

In our study, the external field is generated by a solenoid with a dimensions of $\phi_{in} = 700$ mm and length 1000 mm. The field distribution inside the solenoid is calculated and shown in figure 1(c). The cylindric shield is placed in the central area, where a quasi-uniform field reaches about 0.2 T with an unevenness of 2.3% along the axis and 1.1% along the diameter within a dimension of 250 mm. A surrounding spherical air box of radius 6 m is defined by a convergence study. $Az = 0$ is set for all nodes on the external surface of the air box to simulate the infinite boundary. In addition, only half of the whole model is built for symmetric structures (see figures 1(a) and (b)).

Soft iron of grade DT4C is selected as the shield material and its *B–H* curve is an important input for the FEM calculation. In order to obtain a *B–H* curve that is close to the realistic material properties, the tested *B–H* curve has been smoothed and then calibrated by a series of experiments [3] (figure 1(d)).

Figure 1. FE model and related properties. (a) The FE model includes solenoid, cylindric shield and three levels of surrounding air; (b) the cylindric shield is placed in the central part inside the solenoid, and it is rotated to simulate different field directions; (c) the external field distribution along the length of the solenoid is calculated with only the solenoid and surrounding air; (d) the *B–H* curve of soft iron of grade DT4C is calibrated by experiment.

Table 1. Accuracy study with different mesh sizes for the central part.

No. of step	Mesh size/mm			Total mesh number/million	Residual field at the center in shield/G	Deviation between adjacent steps
	Air inside the coil	Shield material	Air inside the shield			
1	12	10	10	0.591	80.52	N.A.
2	10	10	10	0.657	84.06	4.4%
3	10	8	8	0.661	83.70	0.4%
4	8	8	8	0.798	84.85	1.4%
5	8	6	6	0.808	86.52	2.0%
6	6	6	6	1.102	88.04	1.7%
7	5	5	5	1.445	88.65	0.7%

The single-factor method is employed, whereby one parameter varies while other parameters are fixed. The default dimensions of the cylindric shield concerned are assumed to be $\phi_{in} \times H_{in} = 100\,mm \times 100\,mm$ and 20 mm thickness. External fields with different directions will be applied by rotating the cylindric shields. The 0.2 T field parallel to the cylinder axis is called the 'longitudinal field', while that perpendicular to the axis is called the 'transverse field' (figure 1(b)).

The accuracy is studied based on a shield with default dimensions in a longitudinal field. Different mesh sizes are applied for the central part, which includes air inside the coil,

the shield material and air inside the shield. The mesh sizes are decreased step by step and the deviation between adjacent steps is calculated. As shown in table 1, the accuracy is better than 3% when the total mesh number is over 0.661 million. The typical mesh settings are shown in figure 2.

3. Results and discussion

3.1. Effects of the edge

In a strong external field, edge effects near the interior surface of the shield should be noted. The magnetized iron generates
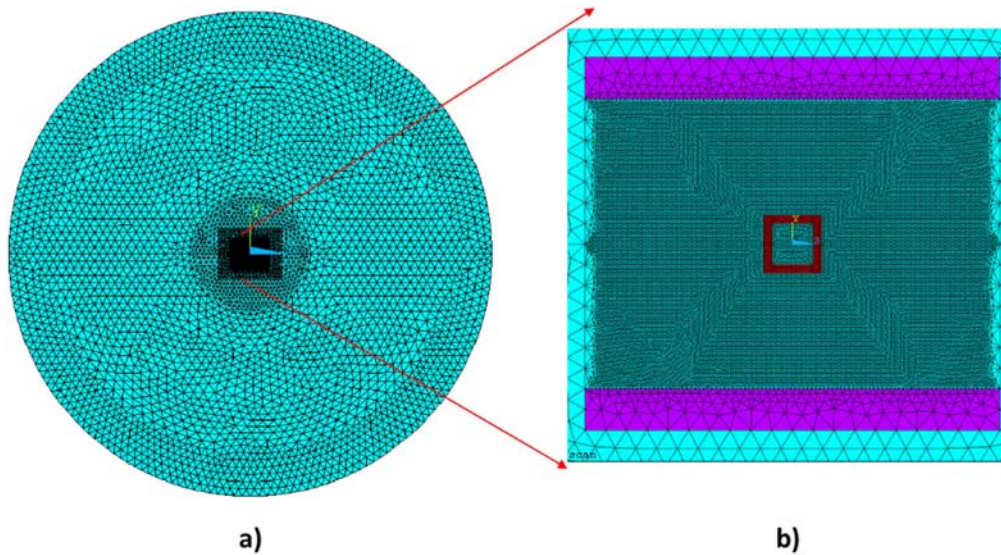
Figure 2. Typical mesh settings. (a) Mesh overview; (b) mesh of the central part: purple is the coil and red is the shield.
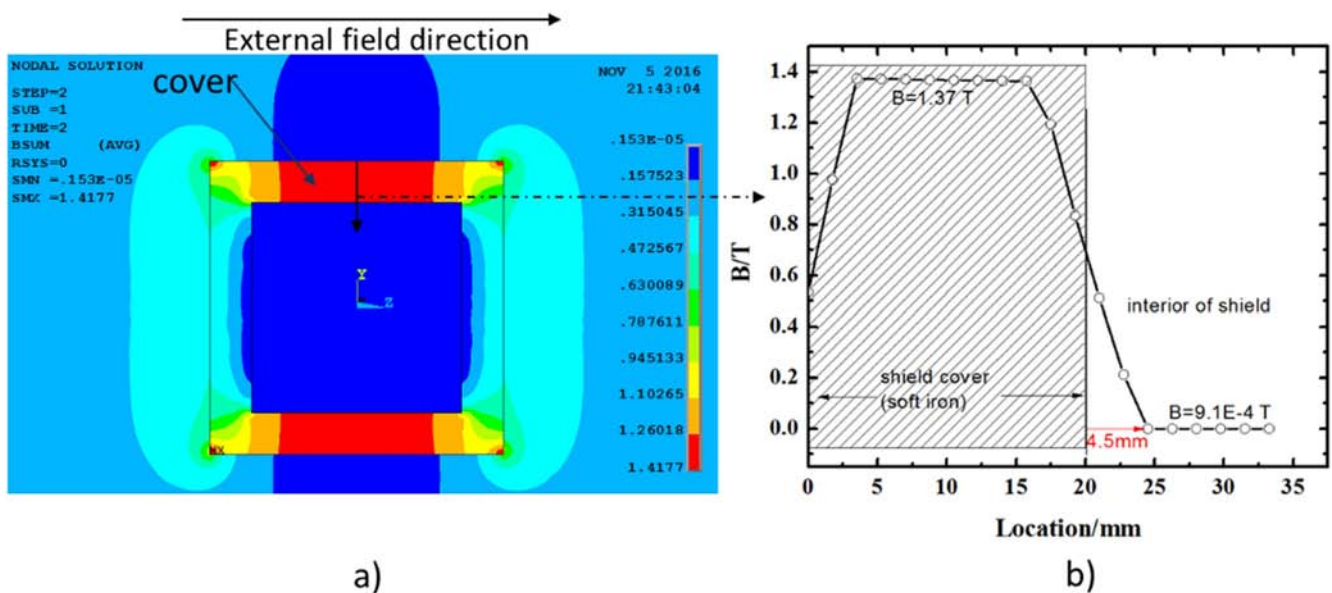

Figure 3. Edge effects in a transverse field. (a) Magnetic field distribution in a cylindric shield with default dimensions; (b) magnetic field distribution along a specified path through the shield cover.

a stray field in its surroundings, which is similar to what a permanent magnet does. Taking the cylindric shield with default dimensions as an example, the maximum magnetic field in the shield material reaches 1.4 T in a transverse field. As shown in figure 3, the magnetic flux concentrates in the central parts of the covers and the field decreases quasi-linearly within a distance of about 5 mm from the internal surface towards the interior of the shield. As a result, the residual field even reaches above 0.2 T at a location 2 mm from the interior surface of the shield. In application, it is suggested that the susceptible parts of components should not be placed within 10 mm from the shield cover/wall. It should be noted that the field distribution near the edges will be neglected in the following studies as defaults.

3.2. Effects of the cover

For a cylindric shield, covers on each end are always recommended [3] whenever feasible. As a further study, the impact of cover thickness is calculated and interpreted preliminarily.

Figure 4 shows the effects of the cover in a longitudinal field. Adding covers greatly reduces the residual field and makes the field distribution flatter. With increasing cover thickness, the residual field at the shielded center decreases fast and then increases slowly, so the optimal cover thickness is about 5–8 mm in our study. Our calculated results indicate that the covers could share the total magnetic flux load but meanwhile they lead more flux into the shield. The two opposing effects result in an optimum value of cover
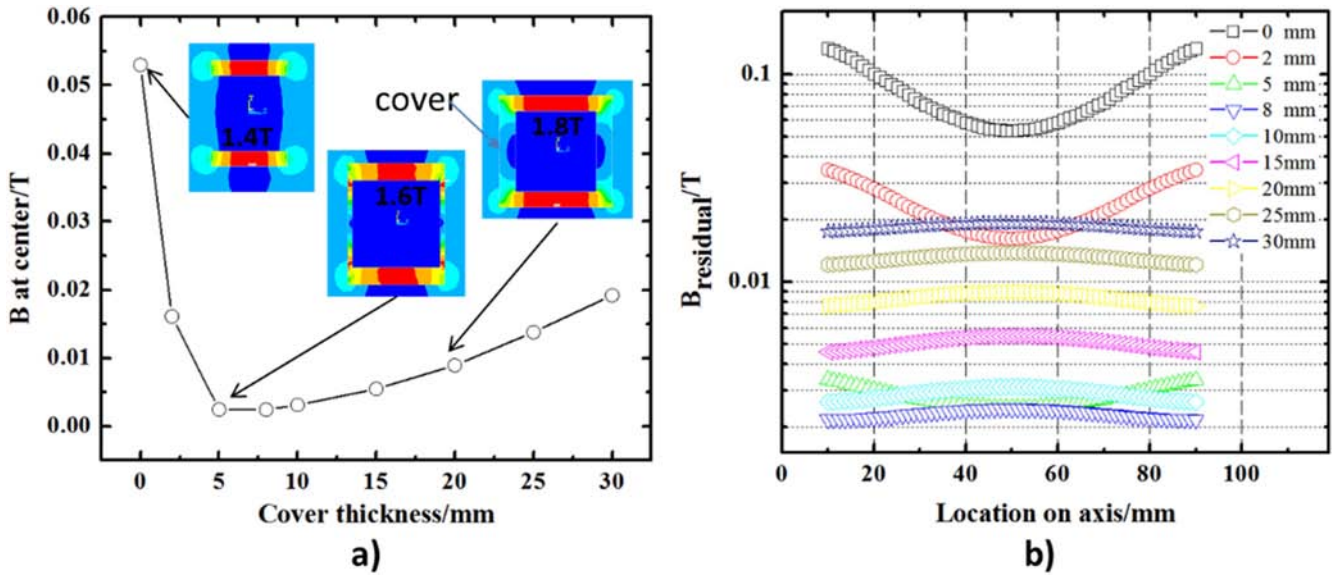
Figure 4. Effects of the cover in a longitudinal field. The cylindric shield has the default dimensions with a 20 mm side wall. (a) Residual fields at the shielded center, with a typical field distribution in the shield material; (b) residual field distribution along the axis of the cylinder.
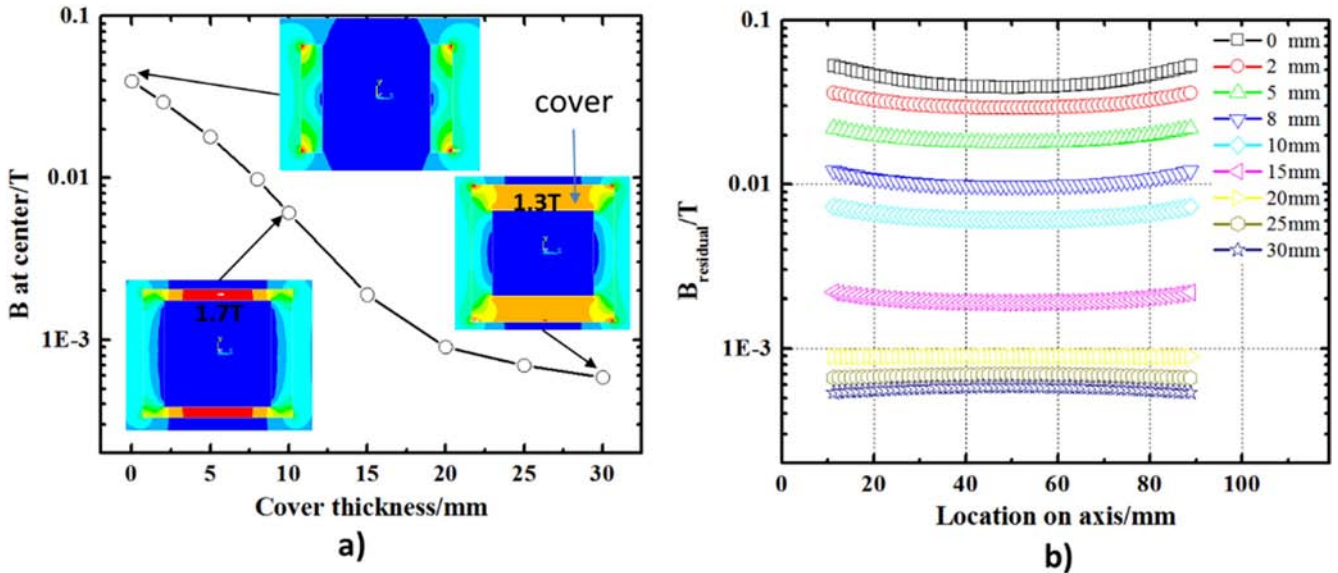
Figure 5. Cover effects in a transverse field. The cylindric shield has dimensions of $\phi_{in} \times H_{in} = 100 \, \text{mm} \times 100 \, \text{mm}$ and the side wall is 20 mm thick. (a) Residual fields at the shielded center, with a typical field distribution in the shield material; (b) residual field distribution along the axis of the cylinder.

thickness. As is well known, for a cylindric shield, a longitudinal field is much more difficult to shield than a transverse field due to the flux concentration effect [8]. Benefiting from our study, one could obtain a better performance in a longitudinal field by simply adjusting the cover thickness.

As shown in figure 5, the residual field decreases with increasing cover thickness in a transverse field. This can be interpreted by using magnetic circuit theory. The magnetic flux concentrates in covers, so they are the major magnetic circuits. Assuming the magnetic flux $\Phi = B \cdot S$ to be constant, the magnetic induction (B) inside the covers decreases with increasing section area (S), which is in direct proportion to the cover thickness.

The above results indicate that the covers play an important role in the cylindric shield. When using covers, their thickness should be optimized considering the direction of the external field.

3.3. Effects of the thickness

It is well known that good shielding performance can be obtained in a thick shield since its material works with high permeability and low magnetic induction. However, a thick shield design usually means a heavy weight and high cost in practice, especially in a strong field. A good engineering design should be a balance of performance and cost.
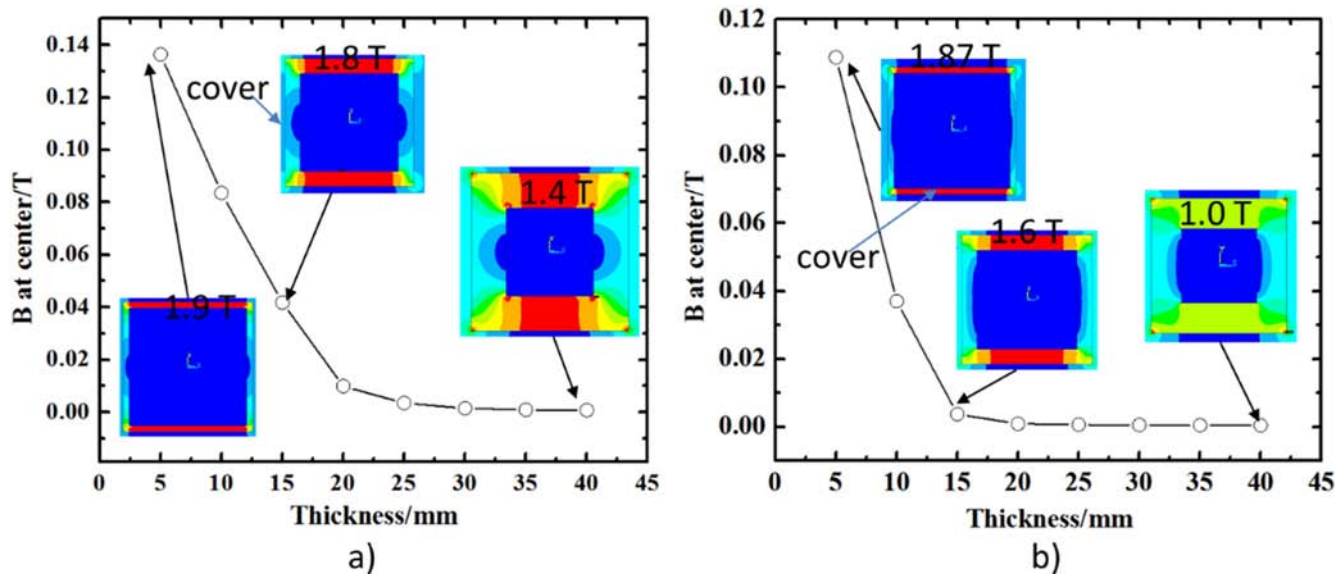
Figure 6. Residual field at the center of the shield for different thicknesses. (a) In a longitudinal field; (b) in a transverse field.
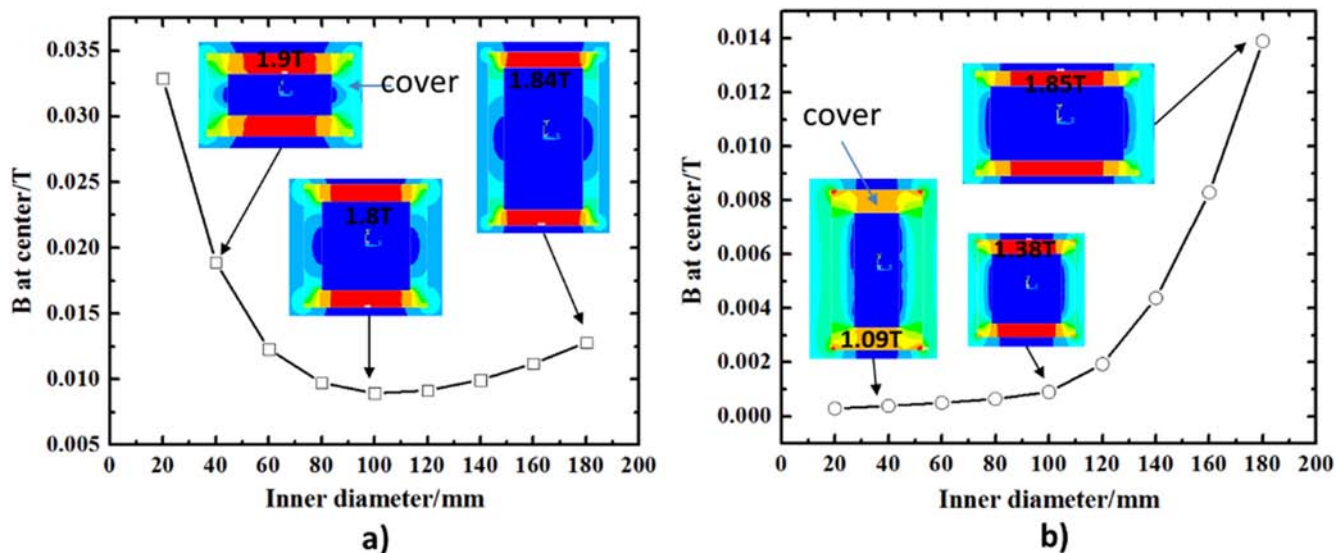

Figure 7. Effects of inner diameter. (a) Residual field at the shielded center in a longitudinal field; (b) residual field at the shielded center in a transverse field.

Cylindric shields with the default dimensions are studied with different thicknesses of side wall (equal to cover thickness). As shown in figure 6, increasing thicknesses cause a reduction in the residual field in both longitudinal and transverse fields. However, this decrease is first rapid and then very slow, which means that increasing the thickness gains little beyond a certain value. It can be seen in figure 6 that the critical value is about 25 mm for a longitudinal field and 20 mm for a transverse field. It is suggested that the critical thickness be used in application in order to get a high ratio of performance to cost.

3.4. Effects of the inner diameter and height

A piece of iron placed in a magnetic field will catch magnetic flux, and the total flux caught is related to the demagnetizing factor, N, which depends on the shape of the iron, i.e., its aspect ratio. This ratio is determined by the inner diameter and height for cylindric shields with constant thickness. The effects of inner diameter and height are studied based on the cylindric shield with a thickness of 20 mm.

The effects of inner diameter are shown in figure 7. In a longitudinal field, the residual field at the center of the shielded volume decreases fast and then increases slowly with increasing diameter and a fixed inner height of 100 mm (see figure 7(a)). At first, the shield is long and thin, when its longer side is along the field direction, and hence a strong residual field is observed due to the magnetic flux collective effect [8]. When the inner diameter increases to above 100 mm (aspect ratio > 1), the shield becomes stumpy and hence the flux collective effect is weak, but meanwhile the large cover leads extra flux into the shield, so the residual
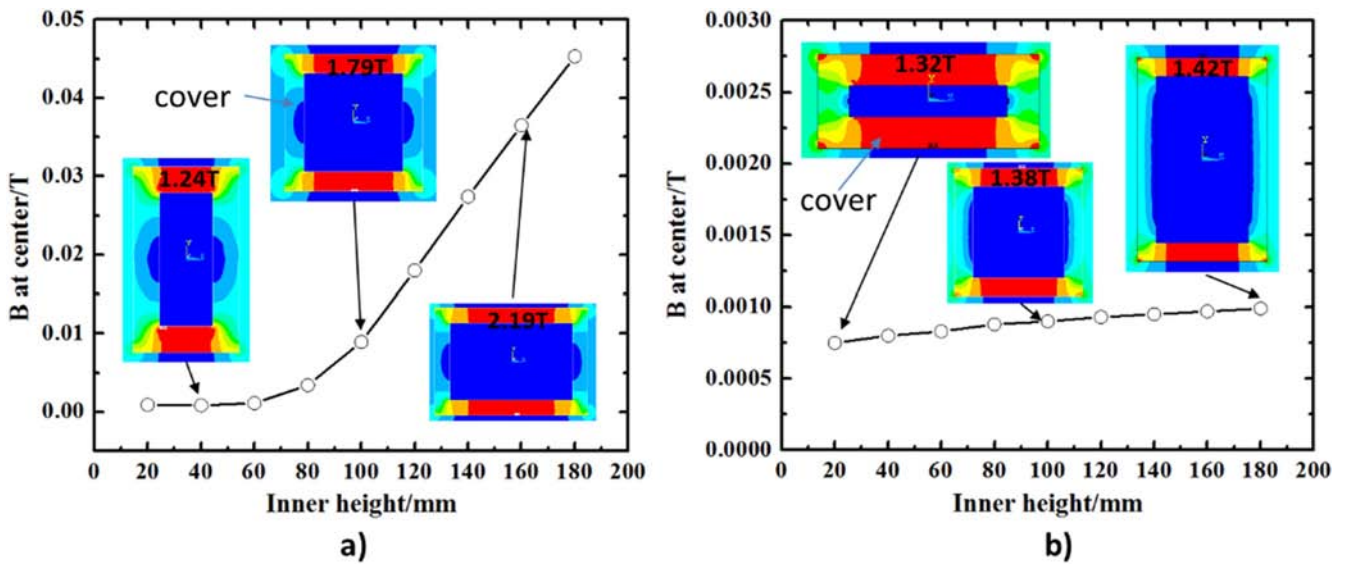
Figure 8. Effects of inner height. (a) Residual field at the shielded center in a longitudinal field; (b) residual field at the shielded center in a transverse field.
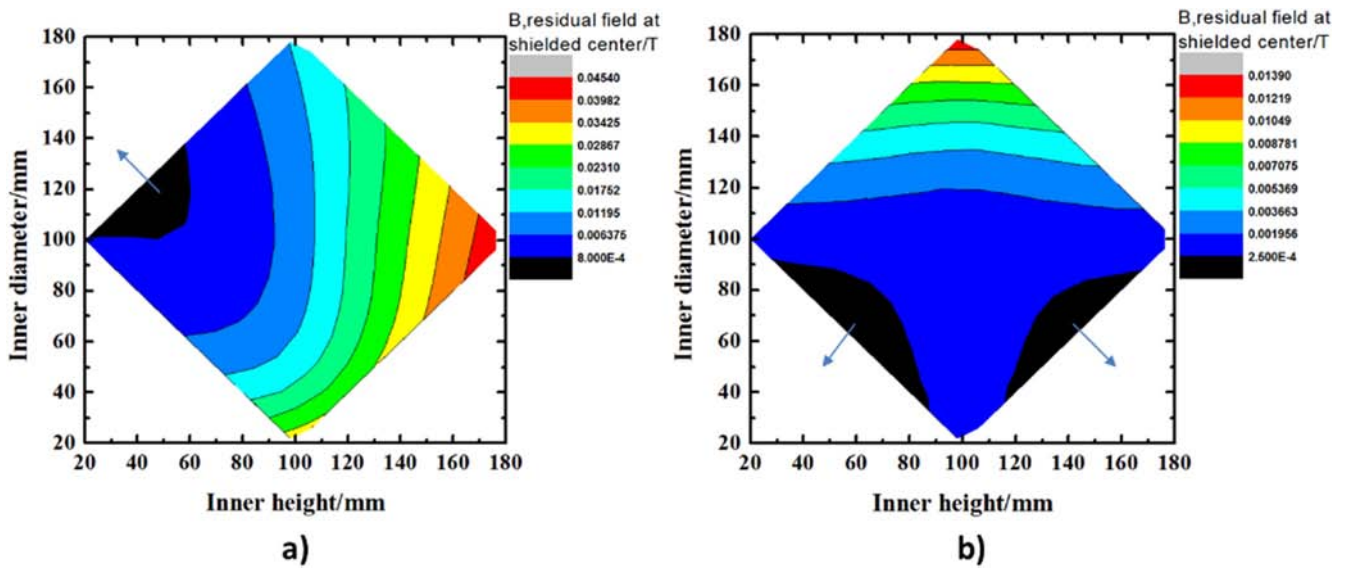

Figure 9. Contours of residual field on the diameter–height plane. (a) In a longitudinal field; (b) in a transverse field.

field increases slowly. For a transverse field (see figure 7(b)), the residual field increases slowly with diameter (<100 mm), and then fast for inner diameters larger than 100 mm.

As shown in figure 8(a), the residual field increases with the inner height in the longitudinal field. The longer the side along the field direction, the more flux enters the shield. As a result, the side wall is near saturation and the residual field rises very fast. On the other hand, the inner height has very little impact on the performance in a transverse field (see figure 8(b)).

All the above trends are consistent with that predicted by the formulas [8], but more complex in details since nonlinear permeability has been included in our study. As a summary of this section, the contours of residual fields on the diameter–height

plane are shown in figure 9. The contours show that a short cylindric shield is recommended in the longitudinal field, while a thin one is preferred in the transverse field.

3.5. Effects of an opening in the cover

Technical application frequently requires some openings in the cylindric shield for a pipe/tube, wire and other connections. The openings usually have a negative effect on the magnetic shielding due to the loss of shielding material and higher magnetic resistance. The effects of circular openings in the cover are studied based on a cylindric shield with the default dimensions.
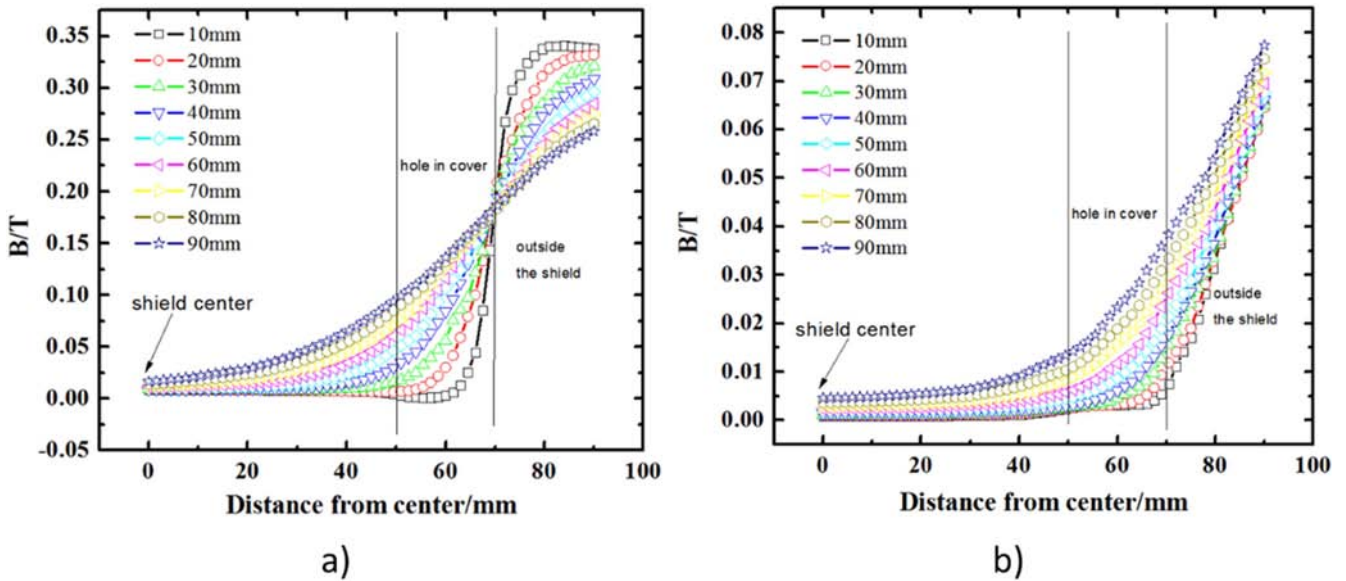
Figure 10. Residual field distribution in a cylindric shield with circular openings of different diameters. (a) In a longitudinal field; (b) in a transverse field.

The circular openings are located at the center of one cover and their diameters are in the range from 10 mm to 90 mm. As shown in figure 10(a), in a longitudinal field, the residual field inside the hole is even lower than that in the interior of the shield for a hole diameter of 10 mm. The residual field at the center of the shield for a 90 mm hole is 85% larger than that for a 10 mm hole. Furthermore, the fields enter the shield with an exponential slope, $\exp(k_0 x) \exp\left(-\frac{k_L}{r}x\right)$, where r is the radius of the hole, $k_0 = 0.039\,57$ and $k_L = 2.36$. But this formula is not applicable for extremely small or large openings, e.g., 10 mm and 90 mm.

The results for a transverse field are given in figure 10(b). The residual field at the center of the shield for a 90 mm hole is four times (394%) that for a 10 mm hole. The field decreases with an exponential slope, $\exp\left(-\frac{k_T}{r}x\right)$, where $k_T = 2.54$, which is not applicable for the case of the 10 mm hole.

The impact of openings in covers is more severe in a transverse field since the covers are the major magnetic circuit in this situation. In applications, it is suggested that openings should not be on the major magnetic circuit, e.g., covers in a transverse field, or the side wall in a longitudinal field.

4. Summary

The geometrical aspects of a cylindric magnetic shield have been systematically studied with the aid of FEM calculations with nonlinear magnetic properties. The results indicate that the thickness, aspect ratio and opening have a major impact on the shielding performance. Moreover, one should also note the effects of the edge and cover thickness, which are mentioned for the first time to our knowledge. Based on these results, the corresponding suggestions for practical application would greatly benefit the engineering design of the magnetic shielding against strong static fields.

References

[1] Ikeda K 2007 *Nucl. Fusion* **47** E01
[2] Xia Z W *et al* 2009 *Nucl. Fusion Plasma Phys.* **29** 353 (in Chinese)
[3] Xia Z W *et al* 2014 *Plasma Sci. Technol.* **16** 629
[4] Li W 2008 *Fusion Eng. Des.* **87** 813
[5] Rucker A W 1894 *Phil. Mag.* **37** 95
[6] Wills A P 1899 *Phys. Rev.* **9** 193
[7] Sterne T E 1935 *Rev. Sci. Instrum.* **6** 324
[8] Mager A 1970 *IEEE Trans. Magn.* **6** 67
[9] Dubbers D 1986 *Nucl. Instrum. Methods Phys. Res.* A **243** 511
[10] Freake S M and Thorp T L 1971 *Rev. Sci. Instrum.* **42** 1411
[11] Gubser D U, Wolf S A and Cox J E 1979 *Rev. Sci. Instrum.* **50** 751
[12] Mager A 1968 *J. Appl. Phys.* **39** 1914
[13] Preis K *et al* 1991 *IEEE Trans. Magn.* **27** 3798
[14] Preis K *et al* 1992 *IEEE Trans. Magn.* **28** 1056