Influence of Magnetic Property of Ferromagnetic Shield on High Field Magnet Analysis

Keisuke Yoshizawa, So Noguchi, and Hajime Igarashi

***Abstract*—In this paper, an influence of a magnetic property of a ferromagnetic shield on design of a high field magnet, which generates high magnetic field with high homogeneity, such as NMR and MRI, is described. The NMR and MRI magnets often need the magnetic shield to protect an environment and to reduce a stray magnetic field. An iron shield used as a general magnetic shield typically has a nonlinear magnetic property. In magnetic analysis for the magnet design, we have to take into account the nonlinearity of the magnetic property of iron to compute the accurate magnetic field, since the ferromagnetic shield is exposed to so high magnetic field. That is, the iron is saturated in high magnetic field. So far the design of the high field magnets with the ferromagnetic shield exposed to over 2 T has been less reported. Recently, it was reported that the nonlinear magnetic properties of iron were measured at high magnetic fields over 2 T. The difference among the magnetic fields of the high field magnets with the ferromagnetic shield, computed by the finite element method with a few magnetization curves, is investigated.**

***Index Terms*—High-temperature superconductors, magnetic field analysis, magnetic shielding, NMR, MRI.**

I. Introduction

A superconducting magnet system, such as NMR and MRI, is required to generate a high magnetic field with high homogeneity. At design stage of the NMR magnet configuration, magnetic field analysis is required. In the NMR magnet system, a magnetic shielding (e.g. iron shield, active shield and room shielding) is often installed to avoid exposing the environment to the strong stray field. Especially, the iron shield is commonly employed as a typical magnetic shielding. Therefore, the nonlinearity of the magnetic property of the iron shield has to be taken into account on the analysis of the NMR magnet design.

Recent years, the higher magnetic fields can be realized by the superconducting magnets wound with high temperature superconducting (HTS) tapes [1]–[5]. The iron shield installed to these magnet systems is exposed to the higher magnetic field. Therefore, on the analysis of the NMR magnet systems, we have to take into account the nonlinear magnetization curve (B-H curves) in the range of the significantly high magnetic field over the saturation magnetic field (over 2 T).

The relative magnetic permeability of the iron is expected to be 1.0 over the magnetic field where the ferromagnetic materials are completely saturated. However, the experimental nonlinear magnetization curve of the ferromagnetic materials in such high magnetic field has not been reported until recent years. On the common magnetic field analysis, the magnetization curves in the range of the significantly high magnetic field (over 2 T) are extrapolated from the measured data at the low magnetic fields (below 2 T). However, the extrapolated relative magnetic permeability doesn't become 1.0 in the range of the significantly high magnetic field. Therefore, the computed results with the extrapolated magnetization curves may cause a difference from the result with the accurate magnetization curve.

In this study, the magnetic field generated by the NMR magnet with the magnetic shielding is investigated using a few magnetization curves. The magnet configurations designed in [6] and [7] to generate the highly homogeneous and high magnetic field are employed. To these magnet configurations, the magnetization curves to be compared are the curve based on the experimental data over 2 T [8], the extrapolated curve used in a commercial software, and the curve referred from [9]. The result using the magnetization curve based on the experiment is compared with the results using the other curves. The magnetic field around the center and the homogeneity are investigated, they are important for the design of the NMR magnet systems.

II. Analysis Model

A. Magnetization Curves (BH curves)

To investigate the influence of the magnetic property on the computation accuracy, the three magnetization curves called BH1, BH2, and BH3, as shown in Fig. 1 (a) and (b), are employed. Fig. 1 (a) shows the enlarged view of the BH curves in the range of the relatively low magnetic field, and Fig. 1 (b) shows the BH curves in the range including the significantly high magnetic field. The BH1 curve is the experimentally obtained curve, where the relative permeability (μ_r) equals to 1.0 on the significantly high magnetic field over 2 T. The magnetic property in the range from 0 to 5.5 T was reported in [8], where the sample material is a magnetic steel sheet (Fe with 3wt% Si). The BH2 curve is used in a commercial magnetic field analysis software. The BH2 curve in the range from 0 to 0.10 MA/m is almost the same as the BH1 curve since the BH2 curve in the range of the low magnetic field is also obtained from the experiments. However, the BH2 curve over the significantly high magnetic field is extrapolated from the measurement data in the low magnetic fields, and the relative permeability on the saturation field is approximately 1.035. The

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BH3 curve is calculated by the fitting curve equations given as [9]

$$\nu = 191.3033 + 8.69673\,(B^2) \qquad (0 \le B^2 \le 1) \quad (1)$$
$$\frac{\partial \nu}{\partial B^2} = 8.69673$$

$$\nu = 199 + (B^2)^{8.69673} \qquad (1 \le B^2 \le 2.56) \quad (2)$$
$$\frac{\partial \nu}{\partial B^2} = 8.69673\,(B^2)^{7.69673}$$

$$\nu = 12063.37(B^2) - 27132.22 \qquad (2.56 \le B^2) \quad (3)$$
$$\frac{\partial \nu}{\partial B^2} = 12063.37$$

where ν is the reluctivity and B is the magnetic flux density, respectively. The material is also the magnetic steel. These equations are convenient to be used in the finite element method with the Newton-Raphson method [9].

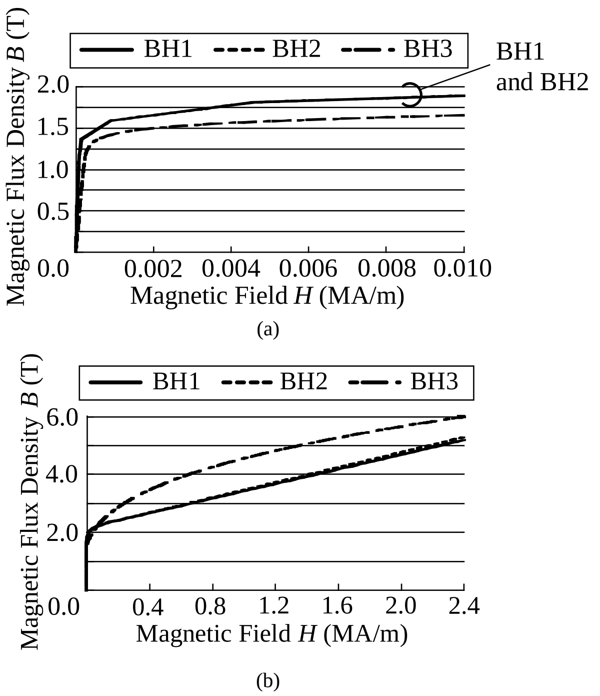


Fig. 1. The magnetization characteristic curves (BH curves) used as the characteristic of the iron shield. The BH1 is the experimentally obtained curve. The BH2 is the extrapolated curve from the measurement data, used in a software. The BH3 is calculated from the fitting curve equations. (a) BH curves of relatively low magnetic field. (b) BH curves with high magnetic field

B. *Magnet Configurations*

In the paper, two MRI magnet systems designed in the previous papers [6], [7] are employed. The first magnet has an iron shield and an active shield as shown in Fig. 2 (a), and the other magnet has only an iron shield as shown in Fig. 2 (b), where j is the current density of coils. These magnet configurations were designed to generate 1.5 T magnetic field with high homogeneity.

In addition, the analysis results with two times current density are also investigated, because to generate the higher magnetic field (approximately 3.0 T) is targeted, such as NMR. The high magnetic field causes the magnetic saturation of the iron shield. In this paper, the analysis results of the former current density (to generate 1.5 T) are called Case 1-L and Case 2-L in order, and the analysis results of the two times current density (approximately 3.0 T) are called Case 1-H and Case 2-H, respectively.

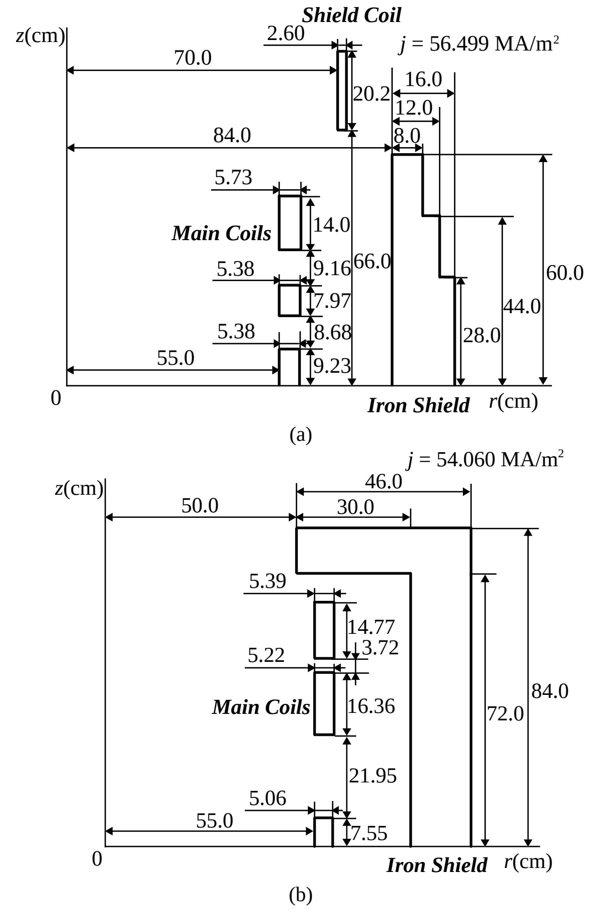


Fig. 2. The high field magnet configurations. (a) The active shield and iron shield are installed as the magnetic shielding (Configuration 1). (b)Only iron shield is installed (Configuration 2).

III. Results and Discussion

A. *Evaluation Method*

In the paper, the magnetic field generated by the magnets mentioned above is computed by the finite element method using the nonlinear magnetization curves, BH1, BH2 and BH3. To evaluate the influence of the magnetic property on the magnetic field around the center and the homogeneity, the magnetic fields B_i (i=0,…,31), as shown in Fig. 3, are computed and compared each other.

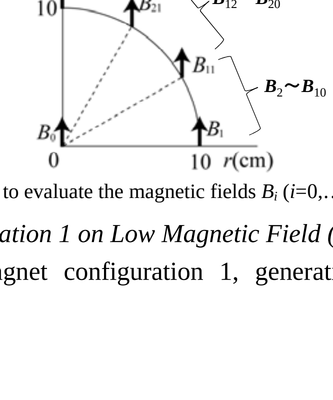
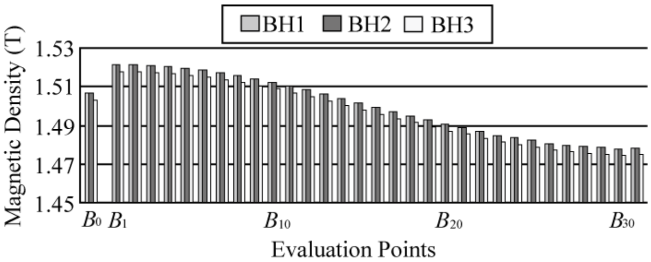


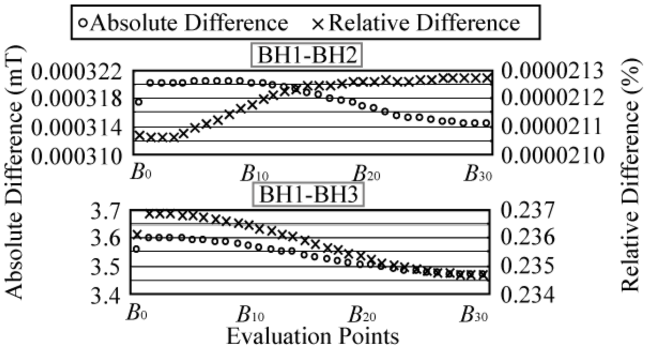
Fig. 3. The points to evaluate the magnetic fields B_i (i=0,…,31).

B. *Configuration 1 on Low Magnetic Field (Case 1-L)*

For the magnet configuration 1, generating 1.5 T, the magnetic fields computed using the BH1, BH2 and BH3 curves are shown in Fig. 4 (a), the absolute and relative differences are also shown in Fig. 4 (b). As seen in Figs. 4 (a) and (b), the BH1–BH3 differences are much larger than the BH1–BH2 at all points. It shows that the difference of analysis result strongly depends on the difference of the magnetization curves. That is, the BH3 curves differ from the actual data even in the range of the low magnetic field (below 2 T), as seen in Fig. 1 (a). In Fig. 4 (b), the BH1–BH2 difference is nearly 0. The reason is that both the BH1 and BH2 curves are obtained from the experiments below 2 T.



(a)



(b)

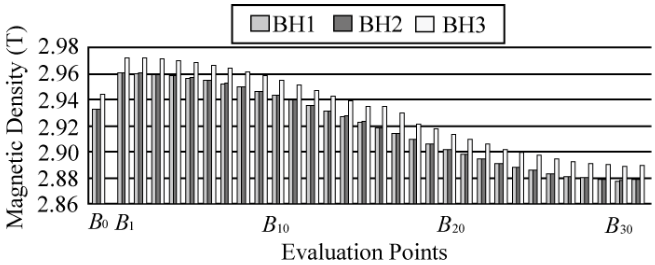
Fig. 4. Result on Case 1-L (1.5 T). (a) Magnet flux density B_i (i=0,…,31). (b) The differences between the BH1 curves and the others. The upper graph shows the BH1–BH2, and the lower graph shows the BH1–BH3.

C. Configuration 1 on High Magnetic Field (Case 1-H)

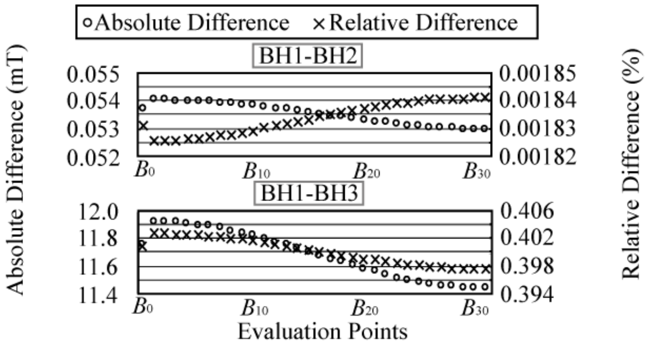
For the configuration 1 generating the higher magnetic field, the magnetic fields computed using the BH1, BH2 and BH3 curves are shown in Fig. 5 (a), the absolute and relative differences are also shown in 5 (b). As seen in Figs. 5 (a) and (b), the BH1–BH3 differences are also much larger than the BH1–BH2 at all points. However, in Fig. 5 (b), the result of the BH2 is slightly different from that of the BH1. The reason is that the magnetic permeability of the BH2 over the saturation field is 1.035, not equal to that of the BH1.

D. Configuration 2 on Low Magnetic Field (Case 2-L)

For the configuration 2 generating the low magnetic field, the magnetic fields computed using the BH1, BH2 and BH3 curves are shown in Fig. 6 (a), the absolute and relative differences are also shown in 6 (b). As seen in Fig. 6, even the result of the BH2 doesn't correspond with that of the BH1. The reason is that a little difference of the magnetic property causes a large difference of the magnetic fields since a lot of iron is used. Even when the iron is exposed to the low magnetic field, we have to pay attention to choosing the magnetic property curve.

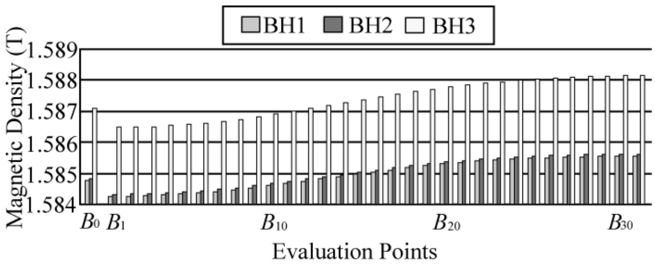


(a)

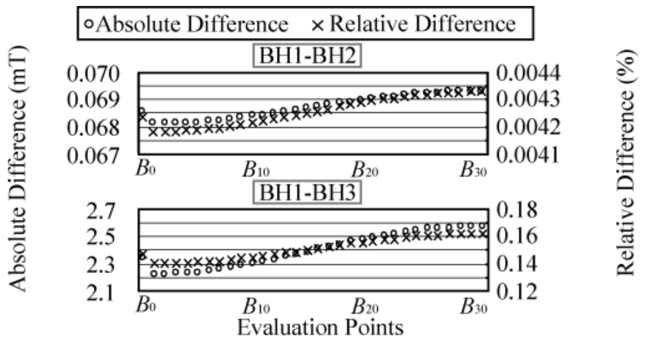


(b)

Fig. 5. Result on Case1-H (3.0 T). (a) Magnet flux density B_i (i=0,…,31). (b) The differences between the BH1 curve and the others. The upper graph shows the BH1–BH2, and the lower graph shows the BH1–BH3.



(a)

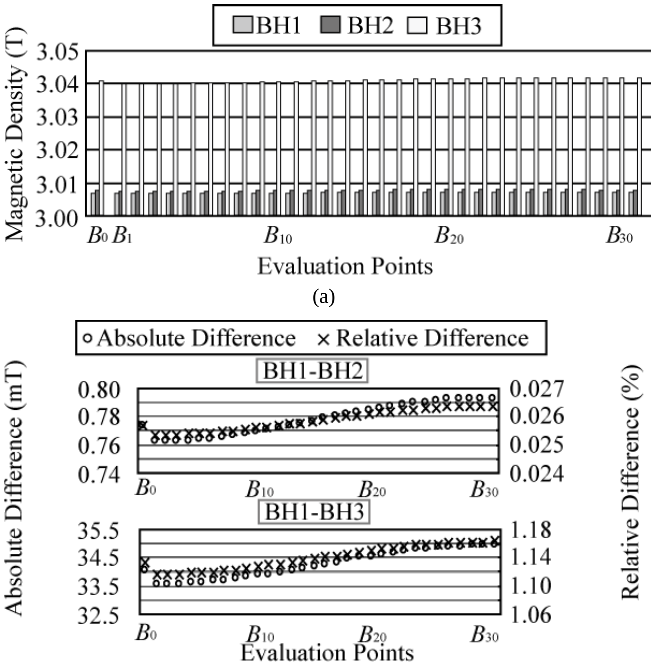


(b)

Fig. 6. Result on Case2-L (1.5 T). (a) Magnet flux density of B_i (i=0,…,31). (b)The differences between the BH1 curve and the others. The upper graph shows the BH1–BH2, and the lower graph shows the BH1–BH3.

E. Configuration 2 on High Magnetic Field (Case 2-H)

For the configuration 2 generating the higher magnetic field, the magnetic fields computed using the BH1, BH2 and BH3 curves are shown in Fig. 7 (a), the absolute and relative differences are also shown in 7 (b). As seen in Fig. 7, the tendency mentioned above is clearly observed. The result of the BH3 is especially awful.



(b)

Fig. 7. Result on Case2-H (3.0 T). (a) Magnet flux density B_i (i=0,…,31). (b) The differences between the BH1 curve and the others. The upper graph shows the BH1–BH2, and the lower graph shows the BH1–BH3.

F. Field Homogeneity

The magnetic field homogeneity on each case is shown in Table I, where the function F of the magnetic field homogeneity is defined as

$$F = \frac{B_{\max} - B_{\min}}{B_0} \tag{4}$$

where $B_{\max}$ and $B_{\min}$ are the maximum and the minimum values among B_i (i=0,…,31), respectively. As seen in Table I, the computed magnetic field homogeneity is also affected by the used BH curve. The field homogeneity of the NMR and MRI magnets is one of the most important factors. It is, therefore, necessary to use the correct BH curve obtained from the experiments in the high magnetic field. Comparing the BH1 with the BH2 in Table I, a little difference of the curves influences the field homogeneity.

TABLE I MAGNETIC FIELD HOMOGENEITY

Case	Magnetic Field Homogeneity Function F		
	BH1	BH2	BH3
Case1-L	0.0289	0.0289	0.0288
Case1-H	0.0286	0.0286	0.0286
Case2-L	0.000820	0.000822	0.00105
Case2-H	0.000160	0.000169	0.000586

G. Discussion

The BH3 curve is useless since it differs from the experiments in the region of not only the high magnetic field but also the low magnetic field. When the BH2 curve is employed, it is necessary to take care of the strength of the magnetic field applying to the iron shield. The differences of the magnetic fields in the cases of the Configuration 2 are larger than that in the cases of the Configuration 1. The reason is the placement and amount of the iron shield. The iron shield of the Configration2 is put on near the main coils to reduce the stray magnetic field, and it is exposed to the high magnetic field. Therefore, the difference of the BH curves appears slightly. Such a difference shouldn't be disregarded, because the NMR magnet systems require the magnetic field homogeneity in ppm order.

The obtained tendencies are summarized as follows.

1. The higher the magnetic field is, the larger the difference between the BH1 results and the others is, because the difference among the magnetization (BH) curves are larger in the high magnetic field (over 2 T).
2. Putting on the iron shield near the main coils, the difference becomes large, because the iron shield is exposed to the high magnetic field.
3. The magnetic field homogeneity is also affected by the difference of magnetization curves.

Recent years, it is possible to measure the magnetization data of ferromagnets, and a lot of experiment data will be reported. When the analysis of the highly homogeneous and high-field superconducting magnet with iron shield, such as NMR, is performed for the design, we should pay more attention to the magnetic property of the iron.

IV. CONCLUSION

In the paper, the magnetic fields generated by the superconducting magnets with different configurations were computed by using three magnetization curves of the iron. From the results, the higher the magnetic field is, the larger the difference between the computed magnetic fields using the magnetic property based on the experiment data and the others, even if the curve prepared in a commercial software was used. These differences can't be disregarded at the design stage of NMR magnets. Therefore, we should pay attention to the magnetic property of the iron when the analysis is performed.

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