# Optimization of Five-Shell Axial Magnetic Shields Having Openings in the End-Caps

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***Abstract*—In this work, we have found that the key to minimizing the effect of the end-cap openings in multishell shields lies with widening the axial air-gaps between the end-caps. We have revealed that the axial air-gaps strongly influence the shielding with openings, while practically not affecting—if the gaps are not too narrow, of course—the shielding with no openings. As a result, widening the axial air-gaps can bring the axial shielding with large openings very close to that with no openings at all. To investigate as general case as possible we have described with the help of special charts the five-shell shields with typical 1.25, 1.5, and 1.75 aspect ratios for the innermost shell. The charts showed that while the shielding with no openings increases monotonically with either shortening the innermost shell or increasing the radial air-gaps, the shielding with openings reaches an extreme, which depends on the normalized permeability. Another important finding is that in contrast to small openings, the effect of large openings depends strongly on the radial air-gaps. Using the charts developed, a typical five-shell shield can be easily optimized in order to compensate for the effect of the openings and match the performance of the corresponding closed shield.**

***Index Terms*—Axial shielding factor, end-cap openings, five-shell cylindrical shield.**

## I. INTRODUCTION

MULTISHELL cylindrical shields (see Fig. 1) are a standard tool enabling the detection of extremely week magnetic fields in fundamental physics and biomedicine. In many applications, it is essential to have relatively large openings in the shield's end-caps. For example in a recently developed subfemtoteslsa multichannelatomic magnetometer [1], an access to the shield's interior should be provided for the laser beam. The access would be improved with larger end-cap openings, on the order of one-fourth of the innermost shell diameter. It is quite obvious that so large openings can dramatically reduce the axial shielding.

It is not a trivial task, however, to estimate the effect of large openings quantitatively and optimize the shield's design in order to maximize the shielding. There is no treatment of the effect of large openings in the literature.

In this work, we have found that the key to minimizing the openings effect lies with the widening of the axial air-gaps between the caps. We have revealed the following very interesting fact: the axial air-gaps strongly influence the shielding with openings, while practically not affecting—if the gaps are not too narrow, of course—the shielding with no openings. As a result, widening the axial air-gaps can bring the axial shielding with large openings very close to that with no openings at all.

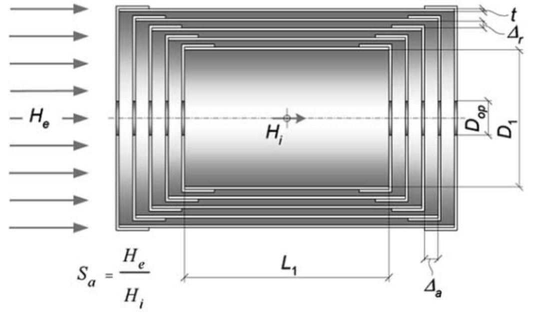

Fig. 1. Five-shell axial magnetic shield having openings in its end-caps.

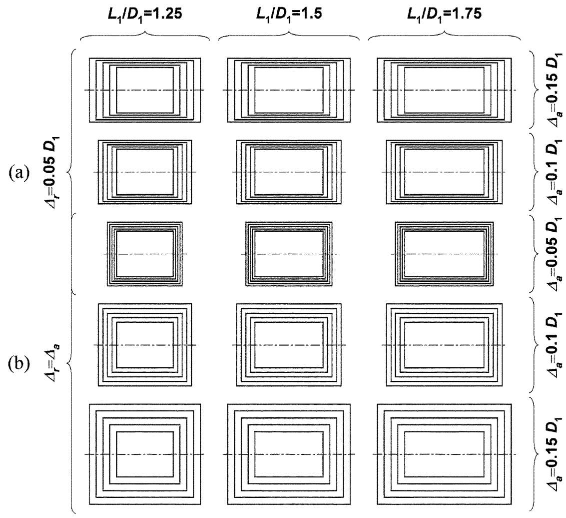

Fig. 2. Family of the shields analyzed (*to scale*). (a) The radial air-gaps are fixed, $\Delta_r = 0.05D_1$, while the axial air-gaps, $\Delta_a$, vary between $0.05D_1$ and $0.15D_1$. (b) The radial air-gaps follow the axial air-gaps variations.

In order to optimize the shields with different lengths, we have investigated the influence of the innermost shell aspect ratio on the axial shielding with and with no openings.

Finally, we took into account the effect of the radial air-gaps and have developed a set of charts that help optimize typical five-shell axial shields having different dimensions, permeability and either having or not having relatively large openings in their end-caps.

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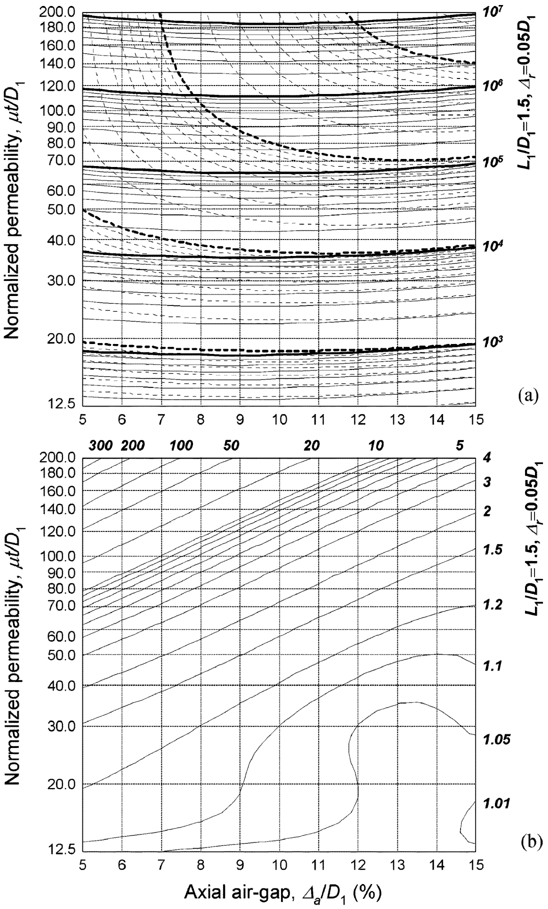

Fig. 3. Axial shielding with an $L_1/D_1 = 1.5$ five-shell shield as function of the axial air-gaps, $\Delta_a$, and normalized relative permeability, $\mu t/D_1$. The radial air-gaps are a fixed parameter, $\Delta_r = 0.05 \cdot D_1$. (a) Axial shielding factor, $S_a$, calculated for the shield with (dashed lines) and with no openings (solid lines). (b) Reduction of the$S_a$ due to the openings. $D_{\rm op} = 0.25 \cdot D_1, t = 0.01 \cdot D_1$.

## II. METHOD

To come to the above results, we assumed first that both the radial, $\Delta_r$, and axial, $\Delta_a$, air-gaps in a typical five-shell shield (see Fig. 1) should be relatively narrow, say 5% to 15%, compared to the innermost shell diameter, $D_1$. For wider gaps, the shield will simply be too bulky (see Fig. 2). Then, we analyzed the behavior of a double-shell shield described in [2] and have noticed that 5% to 15% axial air-gaps between the shells have a small effect on the axial shielding.

It means that the axial air-gaps can be widened without sacrificing the axial efficiency. Assuming that multiple-shell shields should behave in a similar manner, we decided to investigate whether widening axial gaps from 5% to 15% could compensate for the effect of the openings.

In order to investigate as general case as possible we used the methodic developed in [3], where the shields are described with the help of special charts. To be focused on a practical case, we consider only shields with a 1.25, 1.5, and 1.75 aspect ratios, $L_1/D_1$, for the innermost shell. We also assume that all the shells are of the same small thickness $t = 0.01 \cdot D_1$ and they are equally spaced in the radial and axial directions, correspondingly. For the sake of generalization, we also do not consider the nonlinearity of the shielding material.

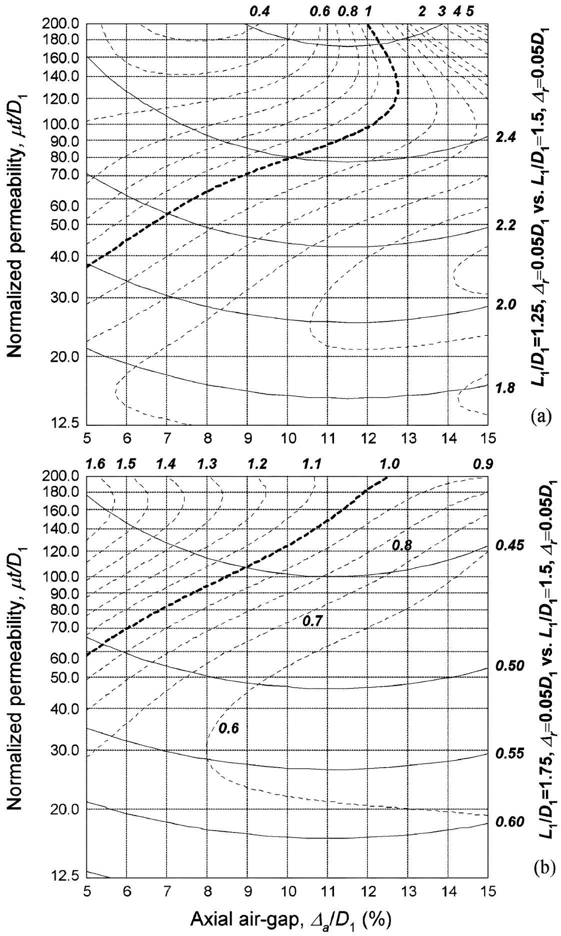

Fig. 4. A comparison between the shields with an (a) $L_1/D_1 = 1.25$ and (b) $L_1/D_1 = 1.75$ [see Fig. 2(a)] and the reference shield (see Fig. 3). The dashed lines and gray digits represent the shielding with openings, and the solid lines and black digits represent the shielding with no openings. The radial air-gaps are a fixed parameter, $\Delta_r = 0.05 \cdot D_1 . D_{\rm op} = 0.25 \cdot D_1, t = 0.01 \cdot D_1$.

We analyzed both the shielding with no openings and the shielding with relatively large, $D_{\rm op} = 0.25 \cdot D_1$, openings in the end-caps. We suppose that there is no need in fact for larger openings and, therefore, consider the worst case.

Fig. 2 shows the family of the shields analyzed. As seen from this figure, the shields are divided into two main groups: (a) and (b). In group (a), the radial air-gaps are fixed, $\Delta_r = 0.05 \cdot D_1$, while the axial air-gaps, $\Delta_a$, vary between $0.05 \cdot D_1$ and $0.15 \cdot D_1$. In group (b), the radial air-gaps follow the axial air-gaps variations: $\Delta_r = \Delta_a$.

## III. NUMERICAL STUDY

We chose the shield with an $L_1/D_1 = 1.5$ from group (a) in Fig. 2 as the reference and compared to it all the other shields. The axial shielding factor, defined in Fig. 1 as the ratio of the external uniform field and the field at the shield's center: $S_a = H_e/H_i$, was calculated numerically with the help of Maxwell® 2D software, manufactured by Ansoft.

The $S_a$ for the reference shield is given in Fig. 3(a) as a function of the axial air-gaps, $\Delta_a$, and normalized relative permeability, $\mu t/D_1$. The shielding reduction due to the openings is shown in Fig. 3(b).

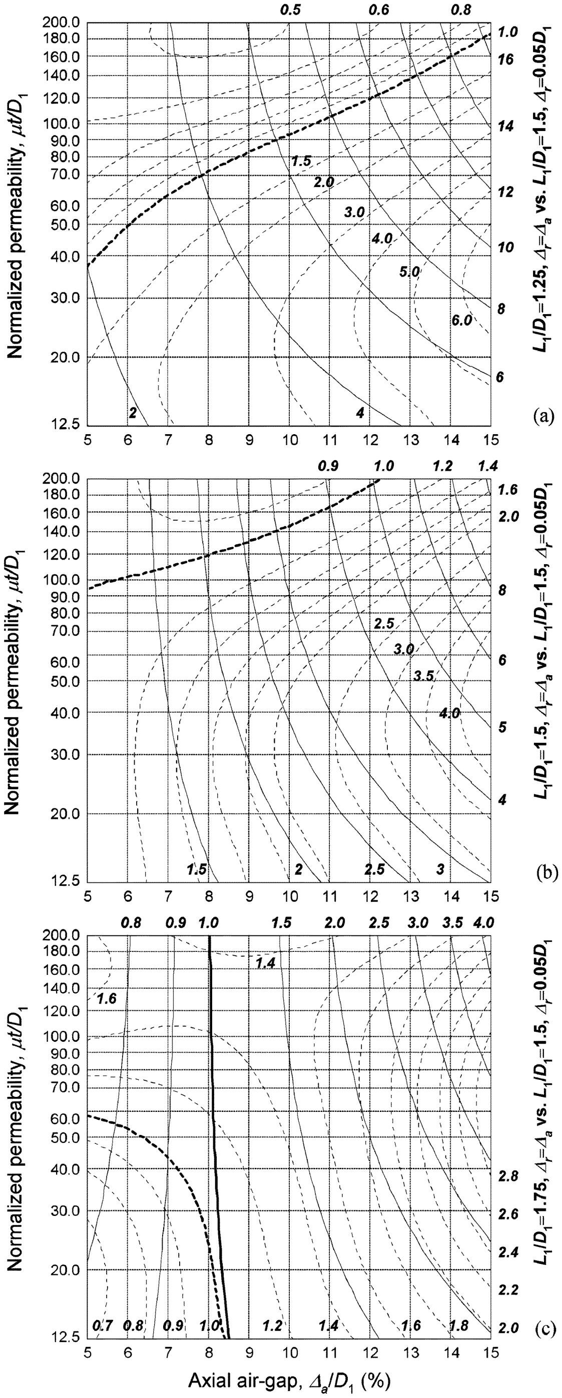

Fig. 5. Comparison between the shields with variable radial air-gaps, $\Delta_r = \Delta_a$, and an (a) $L_1/D_1 = 1.25$, (b) $L1/D1 = 1.5$, (c) $L_1/D_1 = 1.75$ [see Fig. 2(b)] and the reference shield (see Fig. 3). The dashed lines and gray digits represent the shielding with openings, and the solid lines and black digits represent the shielding with no openings. $D_{\mathrm{op}} = 0.25 \cdot D_1$ and $t = 0.01 \cdot D_1$.

The results of Fig. 3 support our initial assumption that the shielding with no openings should not be affected too much by the 5% to 15% width axial air-gaps. Fig. 3 also reveals another very interesting and important fact: widening the axial-air gaps from 5% to 15% brings the axial shielding with openings very close to that with the completely closed shield.

Fig. 4 shows the axial shielding factor for either a shorter, $L_1/D_1 = 1.25$, or longer, $L_1/D_1 = 1.75$, shields, belonging to the same group (a) in Fig. 2, divided by that for the reference shield. Fig. 5 compares in the same manner all the shields from group (b) in Fig. 2 against the reference shield.

Figs. 4 and 5 reveal a principal difference in the behavior of the shields with and with no openings. While the shielding with no openings increases monotonically with either increasing the radial air-gaps or shortening the innermost shell; the shielding with openings reaches an extreme, which depends on the normalized permeability $\mu t/D_1$.

The bold dashed lines in Figs. 4 and 5 represent the boundary case, where the shielding with openings is identical for the shields compared.

Fig. 5(b) also shows that, in contrast to small openings [4], the effect of large openings depends strongly on the radial air-gaps.

## IV. CONCLUSION

Using the charts developed, a typical five-shell shield can be easily optimized in order to compensate for the effects of the openings and match the performance of the corresponding closed shield. It is interesting that the above compensation can bring the axial shielding with large openings very close to that with no openings at all.

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