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Mu-Metal Thickness Parametric Evaluation Study For Sensor Design

Zekai Uygur Zeren

Roketsan A.Ş. Turkey

[*]**Corresponding author:** Zekai Uygur Zeren, Ankara, Turkey.

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Abstract
Mu-metals are used for magnetic shielding. Sensor design is a field where mu-metals are often used so that sensors are protected from different external magnetic fields. In this study, different designs for mu-metal covers are examined parametrically in which thickness serves as the main parameter. Thickness, which is the key parameter of this study, is very important for magnetic shielding and weight considerations.

Keywords: Mu-Metal, Mu-Metal Thickness, Magnetic Permeability, Effective Shielding, Magnetic Shielding, Parametric Study, Magneto Static Analysis

Introduction

Mu-metal is frequently used in sensor designs to protect the sensor from the Earth's magnetic field and external electromagnetic fields. Magnetic fields cause a bias error in sensor measurements. Mu-metal acts as a shield against externally applied magnetic fields and bends the field through the material, thereby protecting it. Mu-metal materials are mostly effective against low-frequency AC (<20 Hz) and DC fields.

The thickness of the mu-metal shall be determined according to the expected performance of the sensor. Mu-metal shall have the minimum possible thickness as much as possible. The reason for the minimum thickness is "weight" foremost, as there is more than one sensor which is protected by a set of mu-metal cover(s) meaning more and more weight. The importance is more emphasized, especially if the sensors are used on air platforms and each gram becomes more problematic which makes redesign phase start. One other restriction to be considered when determining the thickness for mu-metal is manufacturing methods. Such materials can be shaped by sheet processing (water jet, deep drawing, etc.) and welding (laser, etc.) methods, though the latter one has some drawbacks. A very low thickness or very thick material is hard to manufacture and the thickness limits the manufacturing method.

Although there are many different designs for mu-metals, the most preferred ones are designs that overlap or are glued on top of each other. In this article, parametric studies conducted to examine the effect of the parameters in design (mu-metal thickness, overlap amount, gap in between and overlap values, slot/hole effects, magnetic field direction, etc.) are explained.

Magnetic Shielding Working Principle

- **Mu-metal working principle**

According to Maxwell's laws, magnetic flux shall necessarily complete a magnetic circuit. Therefore, it is necessary to ensure that the magnetic flux flows around the volume that needs to be shielded. For this purpose, the volume to be shielded must be wrapped with a shield material in a closed loop that allows the magnetic flux to flow around it. In order for the magnetic flux to be able to flow around the volume without leaking into it, a shield made of materials with very high magnetic permeability, such as mu-metal, is needed. In practice, since the volume to be shielded is often vacuum or air, the geometry of the shield and the magnetic permeability of the material used shall be the main determinants of the final shielding effect [1].

- **Effect of Magnetic Permeability on Shielding**

As the magnetic permeability of the shielding material used in shielding increases, a larger portion of the magnetic flux shall flow over the shield instead of flowing from the volume to be shielded. (This is similar to electrical current preferring to flow over the smaller of two parallel resistors.) Therefore, an ideal shielding material should have a very high magnetic permeability.

In practice, relatively permeable metal alloys such as mu-metal can be produced, but these materials begin to lose their shielding effects after reaching a certain magnetic flux, and magnetic saturation is observed. This saturation effect causes the mu-metal alloys commonly used for magnetic shielding to lose their shielding effects in high magnetic fields. Therefore, in magnetic shield design, the highest magnetic fields to be exposed should be taken into consideration, and whether the material shall reach saturation or not in these fields should be analyzed. The material that keeps the field away and saturates as little as possible is the right choice for this kind of application and often the materials, which reach saturation easier, have lower magnetic permeability. Once the material for shielding is chosen, which is mu-metal for this study, „„ increasing the shield thickness or the number of shield layers are common solutions [2,3] which means a trade-off here.

- Effect of Shield Geometry on Magnetic Permeability and Shielding
- For effective shielding, the magnetic flux entering the shield must completely flow around the volume and then exit the shield. Any discontinuity (such as a hole) on the shield creates a weak point where the magnetic flux can penetrate. Therefore, the ideal shield geometry is a shell that completely surrounds the volume to be shielded, without any cuts or holes. However, the production and integration of this ideal shield geometry pose significant challenges. Since access to the interior of the shield is necessary, a shield geometry consisting of multiple parts, such as a box-lid pair or layers glued on top of each other, with junction points intersecting as much as possible, is preferred over a single-piece shield with perfect continuity.

In addition to the magnetic permeability mentioned in the section B, the thickness of the shield also facilitates the flow of magnetic flux through the shield. At the same time, the magnetic saturation effect mentioned in the same section is also dependent on the thickness of the shield. Thin shields reach magnetic saturation in a lower field. Therefore, the thicker the shield, the better the shielding effect and saturation performance will be, but it is important not to use excess mu-metal material, which is both costly and relatively heavier.

Therefore, the highest magnetic field that the sensor can tolerate in the context of its use should be determined, the shielding factor that the shield needs to provide should be determined, and the minimum shield thickness which provides this factor should be selected. Besides thickness, the effective length of the shield, which is the average length of the path that the flux travels through the shield, also affect the magnetic permeability of the shield. As the path length increases, permeability decreases. Therefore, in order to keep the effective path length as short as possible, the shield should be wrapped as closely as possible around the volume to be shielded. In some cases, increasing the thickness of the shield to reduce the saturation effect can improve the saturation performance by causing a slight increase in the effective magnetic flux path length, but it can also reduce the shielding factor by reducing the magnetic permeability. Therefore, there may be a trade-off between saturation performance and magnetic permeability when calculating shield thickness.

Analysis Setup Details

In "Comsol" program [4], magneto static analyses are conducted for the external magnetic field affecting a coil protected by mu-metal covers. The coil, which has the rectangular cross section, is the point of interest for this sensor; the mu metal covers are the parts, which overlap onto each other and within a distance in-between, protect the coil from the external magnetic field. (Fig. 1) Analyses are run for DC frequency, and there is no study based on AC (variable) frequency. The aim is to see the cases in which the thickness can be minimized, so the design shall be optimized [3].

To shorten solution times, mainly "coarse mesh" option is used. It is certain that more accurate results can be obtained with finer mesh option, but significant differences are not observed in the analyses conducted with both coarse and fine meshes at the beginning of the study. Due to the lack of significant differences in the results, analyses continued with the coarse mesh to complete the numerous analyses here.

Analyses can be performed in 2D or 3D. 2D analyses (axisymmetric) shorten the solution time. However, in this study, 3D modeling (derived from a 2D sketch) is utilized to see the change in magnetic flux density across all sections. It is important to provide constraints within the sketch because structure can be distorted due to changes in parameters during analysis.

A larger spherical volume covering all parts is determined for the analysis, and all empty regions are assumed to be filled with air. For analyses conducted at room temperature, temperature changes and therefore dimensional changes in the parts or changes in material properties due to temperature are neglected.

The input value for magnetic flux density is determined as 10 mT (0.01 T). This value is accepted to be due to external influences and is much larger than another effect, which is the Earth's magnetic field. It is generally expected that the input magnetic flux value shall decrease to the order of 1/100-1/1000 on the coil in these analyses. DC magnetic permeability value is accepted to be 140,000 as a characteristic of mu-metal.

Although this value is higher in various sources (up to 400,000-500,000), a lower value has been taken from the literature for the desire to remain on the safe side due to the change in the permeability property of mu-metal over time. In addition, this value has been obtained by conducting various tests on the shield at hand.

In nested mu-metal cover designs, there is a clearance gap due to the tolerance of the productions. (The inner part diameter is larger than the outer part diameter, and an interference fit is generally preferred.) To fill this clearance gap, Kapton tape is often wound around the inner cover external side. Another function of the tape is to hold the covers together against external factors (vibration, etc.). In addition, these covers are screwed onto the bodies to which the coil is connected.

The thickness of the inner and outer covers is assumed to be the same along the section. Having the same thickness along the section also facilitates manufacturing in bringing the parts to their final dimensions.

In the analyses, parameters are increased by the same amount of increment, and the start and end values are based on experience. Thickness analyses, which started at 0.6 mm, are parametrized by increasing 0.1 mm in all parts and ending at 1.5 mm. Thickness is increased for all parameters at the same time; for example, a thickness of 0.6 mm is kept constant as a parameter, and any other thickness is not modeled as 0.8 mm; all thicknesses are increased gradually the same way. The reason for this is that having numerous analyses in this way and the processes taking too long. Additionally, such designs are not very practical in practice. In addition, the amount of overlap is simultaneously changed with the shield thickness. (i.e. as the thickness of the covers is increased 0.1 mm in each step, the overlap is increased 1 mm at the same time and this is achieved by parametric sketch design in the simulation environment).

In real situations, there are radii on the inner and outer corners of sheet metal parts due to bending. These radii vary depending on the thickness of the material during mold production. During (parametrically defined) analyses, radius information for the inner or outer cover has not been specified. Although the absence of radii results in increased flux density at sharp corners, this situation has not been considered as it does not reflect reality. (reality. (Fig. 3).

The volumetric average magnetic flux of mu-metal covers is being considered as the important result, while the local flux density should be neglected. There is no total weight limit specified for the covers, and as mentioned, preferred one is to go with the lightest possible design.

The characteristics of the coil that the shield needs to cover, as well as the distances to the inner and outer mu-metal covers, are determined based on a specific design in the initial analysis, and as the parameters change, the distances also change. (The distances between the coil and mu-metal cover are not constant, meaning a volume limit has not been set.)

Analysis Cases

In this section, the analysis cases are named and described. (see Fig. 2)

Case 1 (V1): In the first case, parameters such as the amount of overlap, outer mu-metal side thickness, outer mu-metal top thickness, inner mu-metal side thickness, and inner mu-metal top thickness are determined as the main parameters. Parametric analysis has been run to see how the magnetic field density changes for varying thicknesses. It should be noted again that the parameters are increased/decreased simultaneously.

Case 2 (V2): In the second case, the first case is conducted again this time to see the effect of parameters individually by increasing each single parameter step by step while keeping the others constant. In the analyses of the first and second cases, since the covers are brought into contact with each other, the gap is negligible.

Case 3 (V3): In the third case, a different study is done to see the effect of the gap between covers, the gap begins from 0 and ends at 1 mm. The gap can be imagined as the interference between covers.

Case 4 (V4): In the fourth case, effects are observed by changing the flux direction. (direction x and 45˚ vectored combination of x and z directions(inclined)). The combined magnitude is the same for all subcases.

Case 5 (V5): In the fifth case, a slot is added to one of the covers, and the effect of the slot was observed for direction x, direction z and again 45˚ vectored combination of x and z directions(inclined) magnetic flux.

Case 6 (V6): In the sixth case, 3 screw holes were added to the cover without a slot, and analyses were run for the worst-case scenario, which is an inclined magnetic flux.

Case 7 (V7): In the final part, in the 7th case, the effect of mu-metal plates adhered to a closed mu-metal volume is examined step by step, first plate put above the cover and then to both above and below of the cover.

The "_" sign shows the subcase of the main case. The coordinate system is shown on the results. The direction is also implied in Fig. 2.

Conclusion

The following points are important as they shall be considered during design period. The results are also given here in this chapter. (examine the figures in RESULTS page) The magnetic flux input and direction should be known and/or measured accurately. Even if the weight/volume requirement (or maximum limit) is not given to the designer, it should be expected as the most important parameter in such designs.

The permeability of mu-metal should be checked not only through the raw material datasheet but also through measurement. The permeability of mu-metal changes over time and is related to aging and can also be affected by handling during transportation. Additionally, mechanical production processes to obtain the final part can cause changes in permeability. (It is known that there is a change in permeability with heat input.) Therefore, measuring the permeability on the final part manufactured is beneficial.

There is no gap between the sheets except the V3 case. Difference in results can be observed by adding an air gap to the cover parts at the same time with the parameters changed. This study is a future work as the previous subject discussed.

The results indicate that the direction of the magnetic field affects the flux generated in the parts.

The slot is both important as a single parameter and considering the direction of the external field also has a major role for the results.

All cases show that the corners and areas close to corners on the coil are, not always but, often show high magnetic flux density compared to the other areas. This is due to numerical errors of coarse meshing and to the fact that these areas are close to both ends of the overlap.

Even the thinnest design decreases the magnetic flux density on the coil to 1/100th of the original flux. This is valid for completely enclosed volume simulations such as V1 and V2.

The first case (V1) implies that as the thickness increases, the flux density decreases. Though this being a very anticipated result, the overlapping is highly effective to function as a barrier and to decrease the overall average flux values on the coil.

The second case (V2) shows that the external cover's side thickness's change alone has more impact on the decrease in the flux density on the coil compared to other parameters. It should be kept in mind that if the requirements are tight and the designer is allowed to do little change on the parameters, this thickness shall be the one to be considered first.

In the third case (V3), the gap between the covers seems to be remarkably effective on the flux density inside the closed volume. As the gap increases, it is sure that the flux is allowed inside directly onto the coil. Though this is not a real case, the designer should be aware of this situation and close the gap with proper material while using necessary tolerances for the fit between covers.

The fourth case (V4) shows that the though the volume is an again enclosed one, the direction of the external magnetic field has a major effect on the results.

Both the flux density distribution and magnitude on the coil are very dependent on the input, i.e. the direction and magnitude of the field applied, as shown in the figures. These are again important parameters to consider in the early stages of design.
Though the total flux density is close in terms of magnitude for both cases (i.e., V4_1 and V4_2), the results are more emphasized on yz plane rather than on xz plane when the field is in direction x.

Another conclusion is that increasing the thickness (side thicknesses of the covers) in V4_1 is more effective on decreasing the flux density.

In the fifth case (V5), the slot seems to drive the results for all subcases. Though the scenario is not a real one, in the sense that the holes are closed with some proper material in design, the designer again should be careful about this point. Parametric analyses should be run for the hole with the smallest possible dimensions.

If a hole like a slot is available on the cover, then increasing the thickness does not seem to lower the flux density as much as it does in other cases if the field is not perpendicular to the slot. As in case V5_3, increasing the thickness of the material is effective when the field is perpendicular to the slot.

If the magnetic field direction is exactly known, then the slot should not be imposed to the field directly, better be on the other side of the cross section if possible. This not only decreases the flux density results, but also lets the designer be effective in increasing or decreasing the right thickness of the covers accordingly.

The sixth case (V6) shows similar results with case 5. The screws are close to the coil, so the distribution is very much affected from the design particularly.

In the seventh case (V7), though different cases are considered, the results show that even a slight increase in the new plate cover thickness (glued on top the old cover), there is an improvement to decrease the density. The direction is not effective for cases V7_1 and V7_2, which are the initial trials for this case.

It is worthy to note that, compared to all other cases, V7_3 shows that even for the least thickness (0.5 mm), the results are greatly improved considering the magnitude of the density on the coil. (the results are 1/200th of 10 mT at most) However, the results seem to change not so effectively as the thickness is increased for the case V7_2, as the results are already improved as a sheet of mu metal is put to the other side.

Cross checking all parameters at the same time is recommended as an additional part for this work. To clarify, for instance simulations are run while all thicknesses are 0.9 mm, except that one of the cover's top thickness ranges from 0.5 to 1.5 mm. If all these thickness trials are done, this means a very big set of data and seem to be very time consuming. The simulations in this study are simplified, but this kind of intricate study is the best way to achieve the minimum material usage. Manufacturing constraints are important for all cases even this study is further done (let us say irrespective of which parameter it is, all thicknesses are 0.6 mm, while one of them is 1.5 mm, it would be better to think whether it is feasible to manufacture or not).

It would be better to say that this study shall be referred to as a guide for the designers working on this kind of application rather than say that the best case is determined as a result of this study. Given all constraints, the designer shall go with the lightest possible design, as mentioned throughout the study, which means that these parametric analyses shall be conducted.

Besides all, it should be kept in mind that these results are all simulation based and the real cases for a determined thickness is planned ahead of this study, which will give the test and analysis comparison.

Acknowledgment

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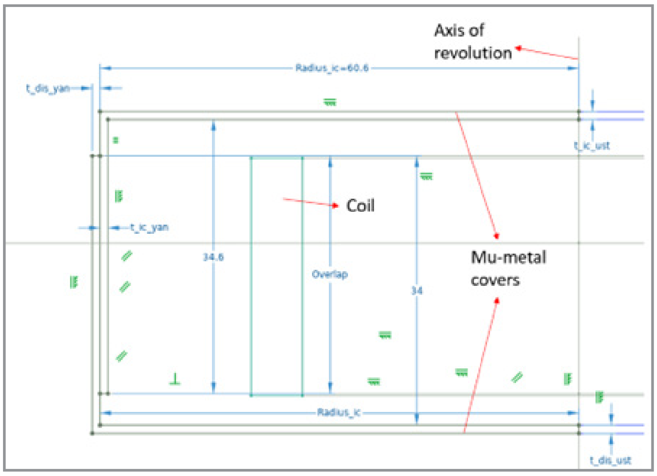


Figure 1: 2D sketch in Comsol (cross section is revolved around the axis denoted)

Configuration	Parameter name	Range as specified in Comsol (mm)*	Magnitude (Tesla)	Direction
V1	Overlap	range(23,1,32)	0.01	+z
	t_dis_ust	range(0.6,0.1,1.5)		
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V2_1	Overlap	range(22,1,32)	0.01	+z
V2_2	tdis_ust	range(0.6,0.1,1.6)	0.01	+z
V2_3	tdis_yan	range(0.6,0.1,1.6)	0.01	+z
V2_4	t_ic_ust	range(0.6,0.1,1.6)	0.01	+z
V2_5	t_ic_yan	range(0.6,0.1,1.6)	0.01	+z
V3	gap	range(0,0.1,1)	0.01	+z
V4_1	Overlap	range(23,1,32)	0.01	+x
	t_dis_ust	range(0.6,0.1,1.5)		
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V4_2	Overlap	range(23,1,32)	0.007	+x
	t_dis_ust	range(0.6,0.1,1.5)	0.007	+z
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V5_1	Overlap	range(23,1,32)	0.007	+x
	t_dis_ust	range(0.6,0.1,1.5)	0.007	+z
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V5_2	Overlap	range(23,1,32)	0.01	+x
	t_dis_ust	range(0.6,0.1,1.5)		
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V5_3	Overlap	range(23,1,32)	0.01	+z
	t_dis_ust	range(0.6,0.1,1.5)		
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V6	Overlap	range(23,1,32)	0.007	+x
	t_dis_ust	range(0.6,0.1,1.5)	0.007	+z
	t_dis_yan	range(0.6,0.1,1.5)		
	t_ic_ust	range(0.6,0.1,1.5)		
	t_ic_yan	range(0.6,0.1,1.5)		
V7_1_1	t_icust	range(1,0.1,1.1)	0.01	+z
	t_icalt	range(1,0.1,1.1)		
	t_ustparca	range(1,0.1,1.1)		
V7_1_2	t_icust	range(1,0.1,1.1)	0.01	-z
	t_icalt	range(1,0.1,1.1)		
	t_ustparca	range(1,0.1,1.1)		
V7_1_3	t_icust	range(0.5,0.1,1.6)	0.01	-z
	t_icalt	range(0.5,0.1,1.6)		
	t_ustparca	range(0.5,0.1,1.6)		
V7_2	t_icust	range(1,0.1,1.6)	0.01	+z
	t_icalt	range(1,0.1,1.6)		
	t_ustparca	range(1,0.1,1.6)		
	t_altparca	range(1,0.1,1.6)		

Figure 2: Parameters table for the cases mentioned (*the middle value denotes the increment)

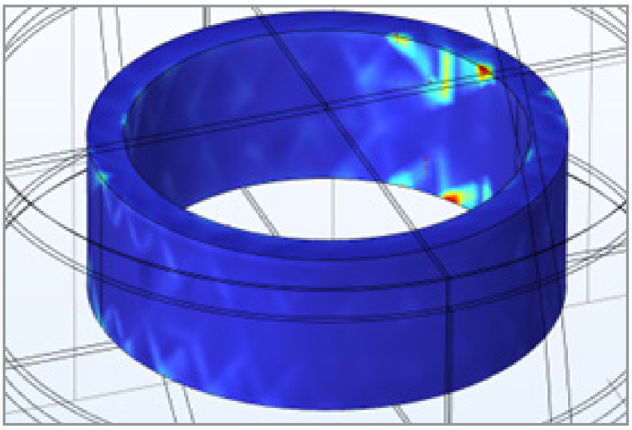
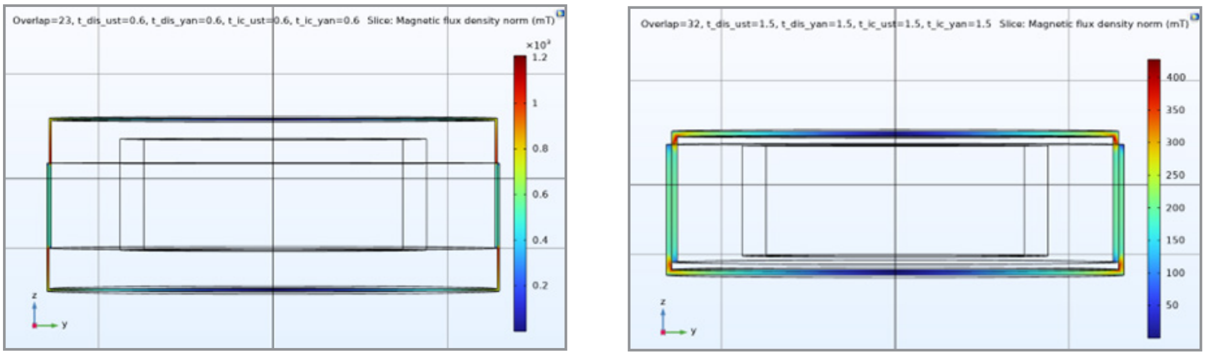
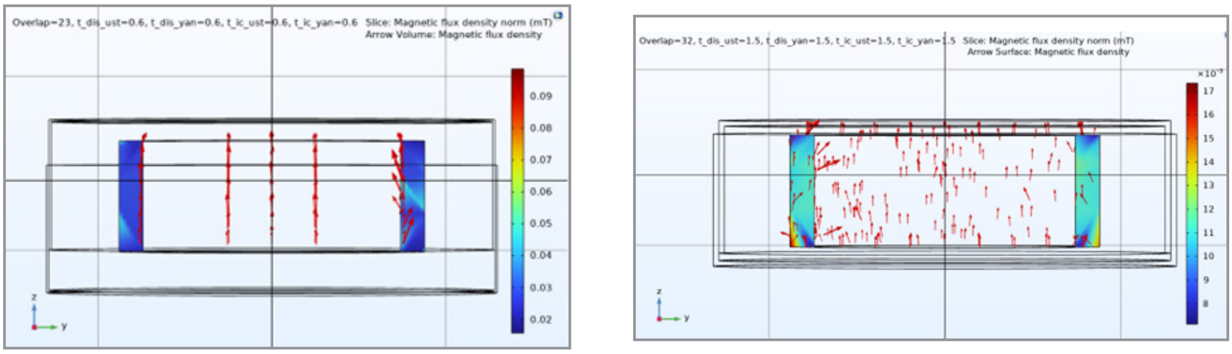


Figure 3: Corner flux density details

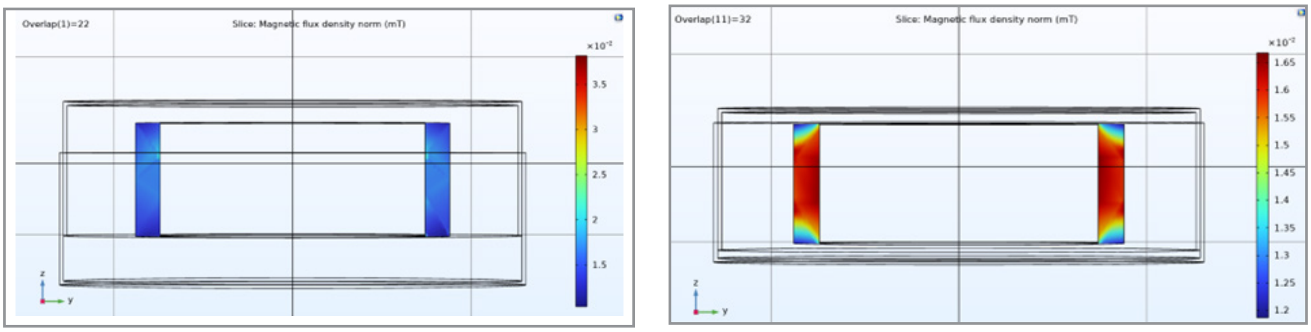
Results



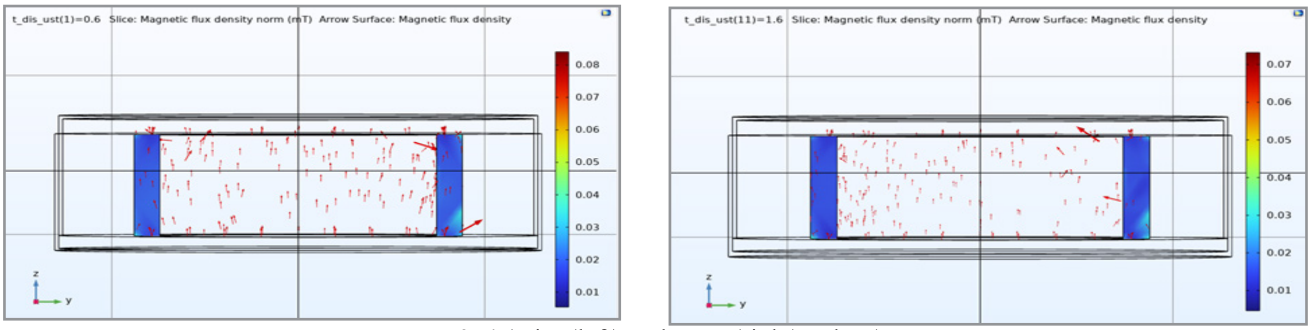
V1 (min. (left) and max. (right) values)



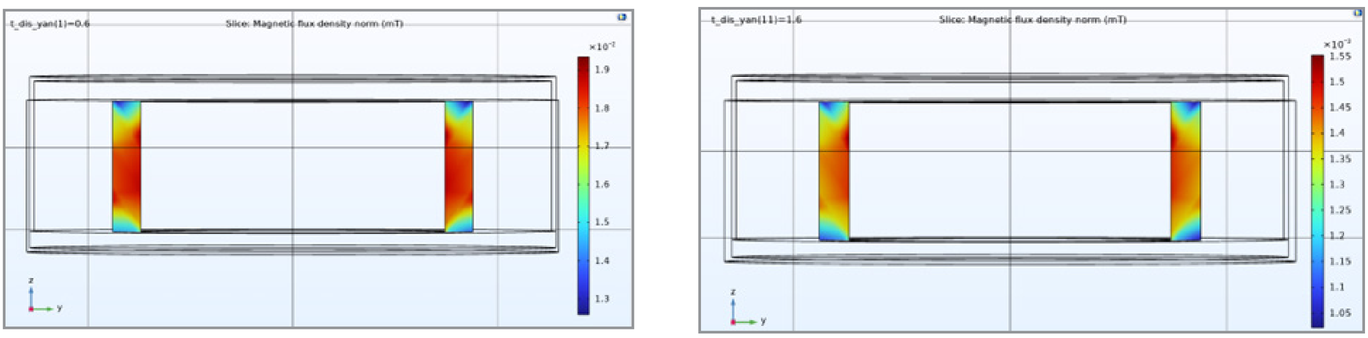
V2_1(min. (left) and max. (right) values)



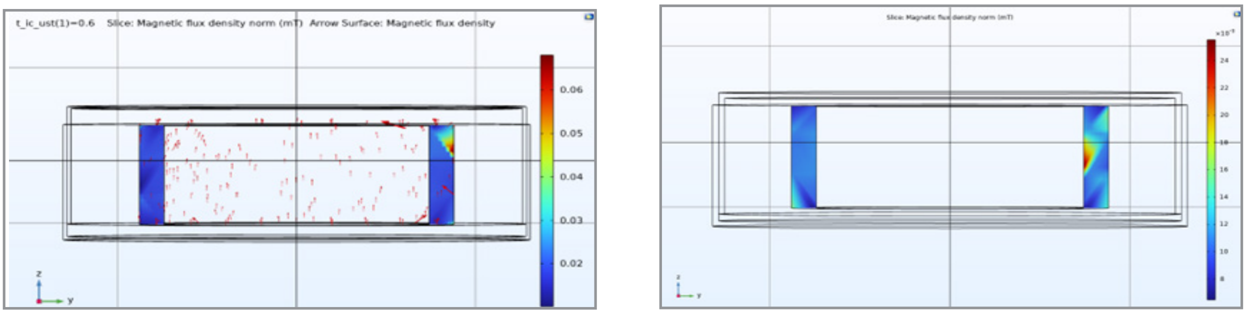
V2_3 (min. (left) and max. (right) values)



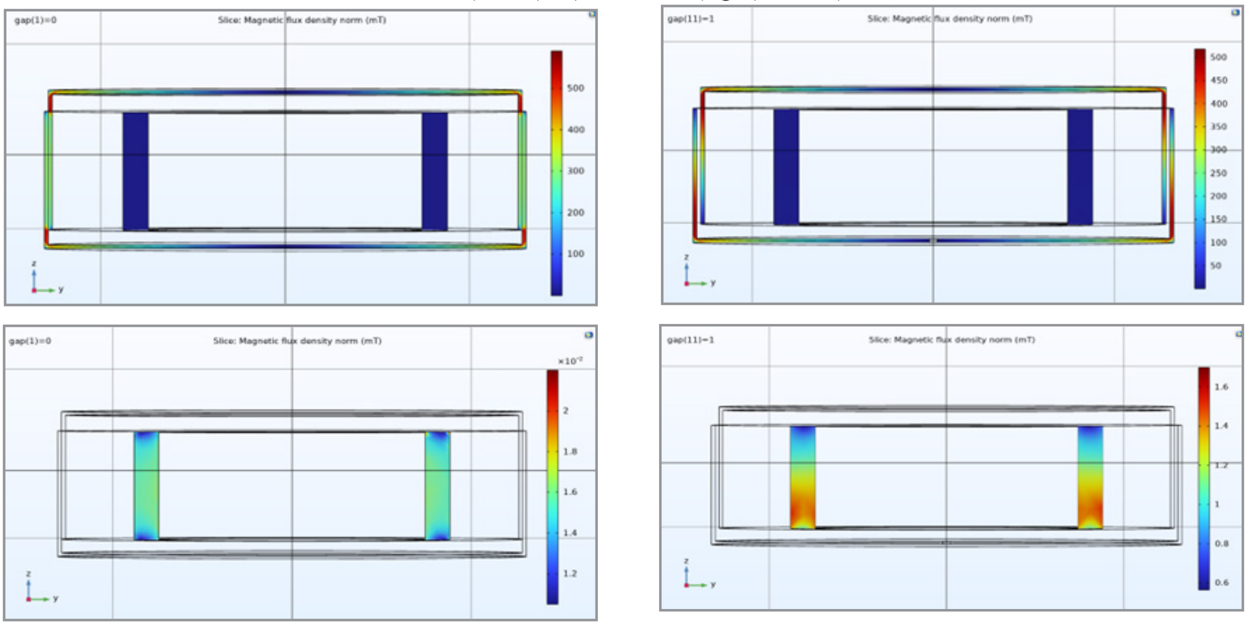
V2_4 (min. (left) and max. (right) values)



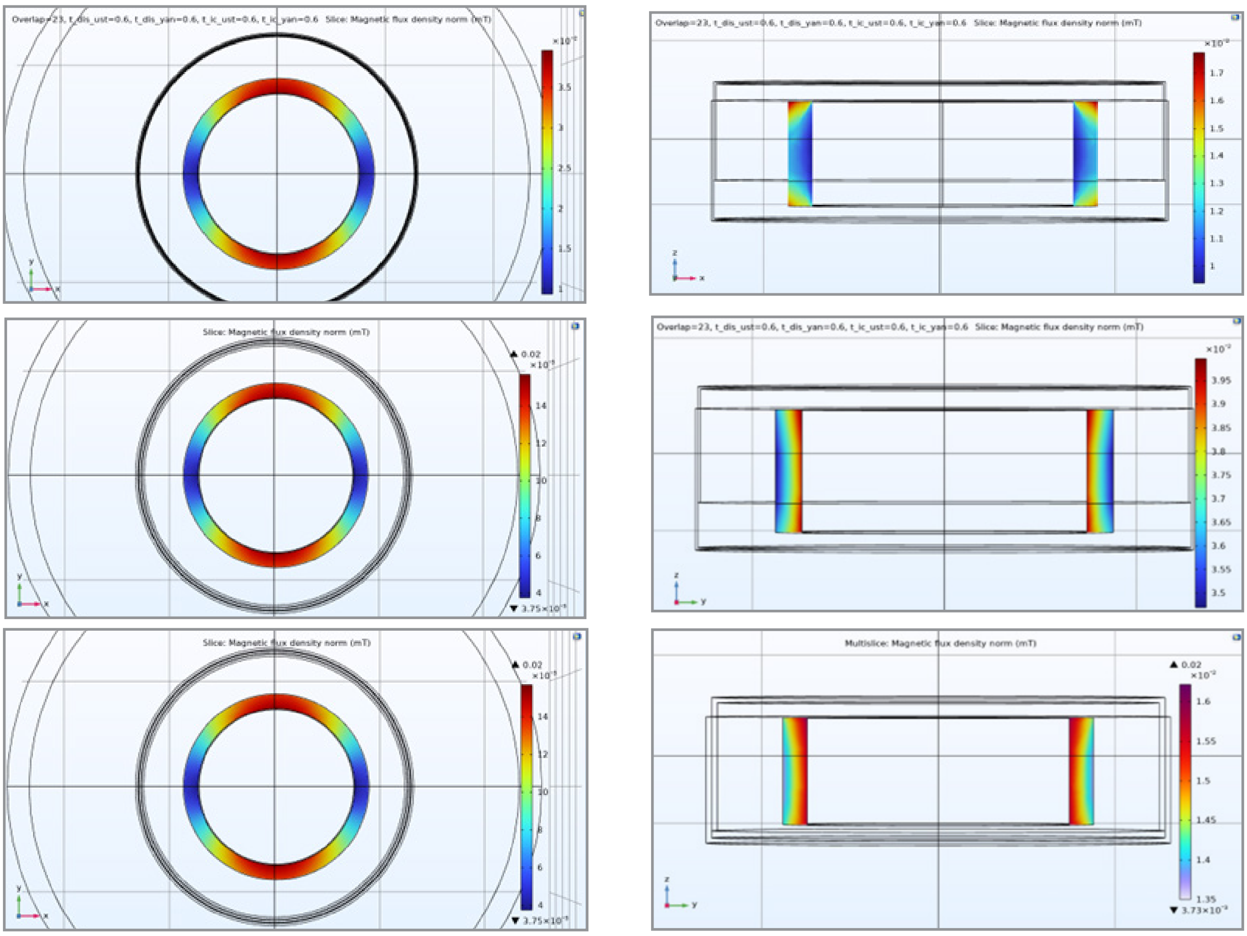
V2_5 (min. (left) and max. (right) values)



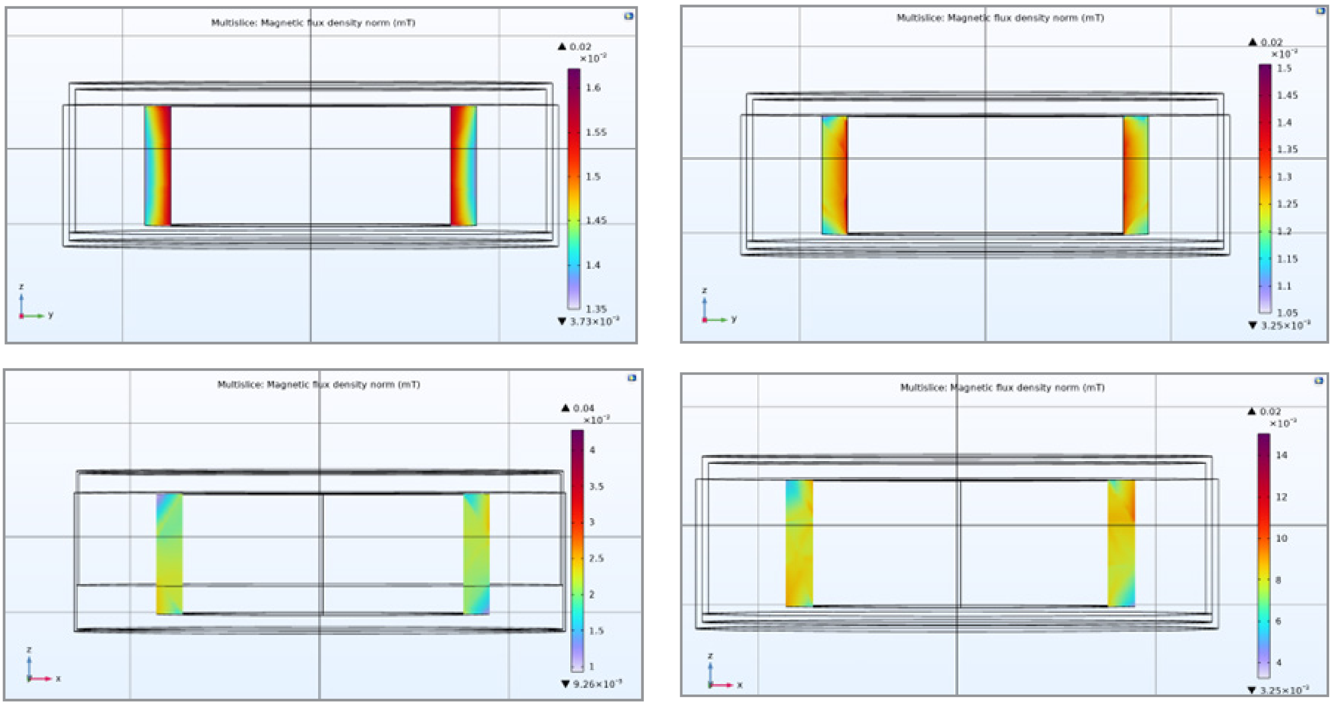
V3 (min. (left) and max. (right) values)



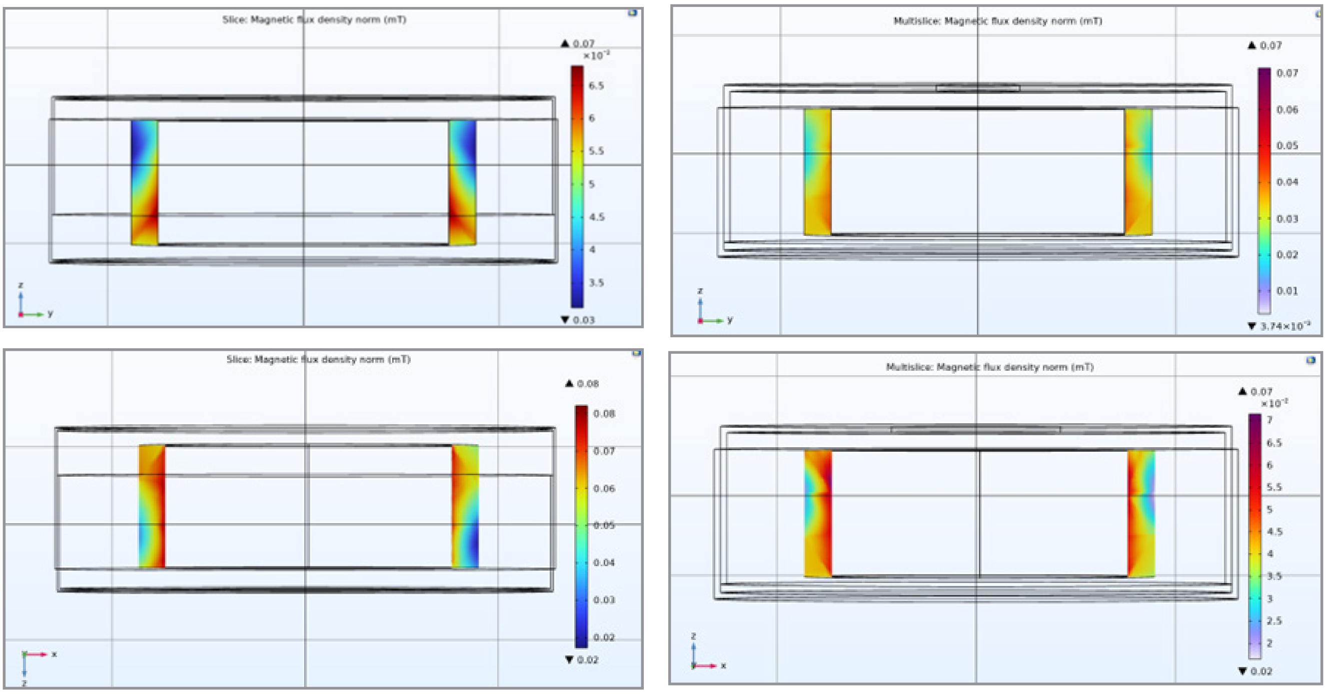
V4_1 (min. (above three figures) and max. (below three figures) values)



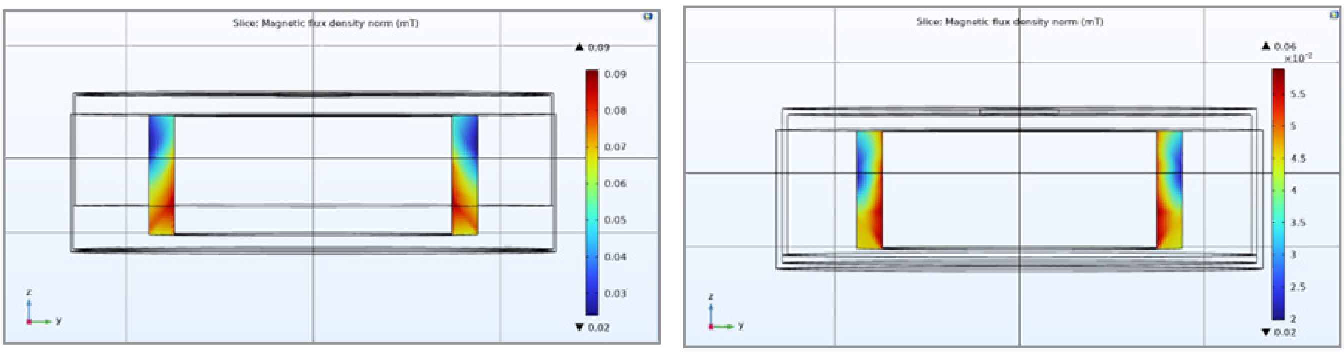
V4_2 (min. (left) and max. (right) values)

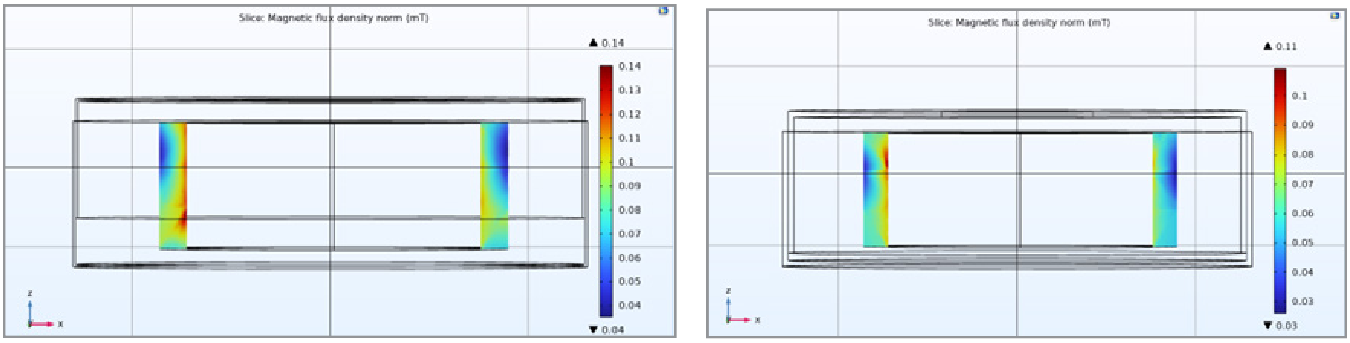


V5_1 (min. (left) and max. (right) values)

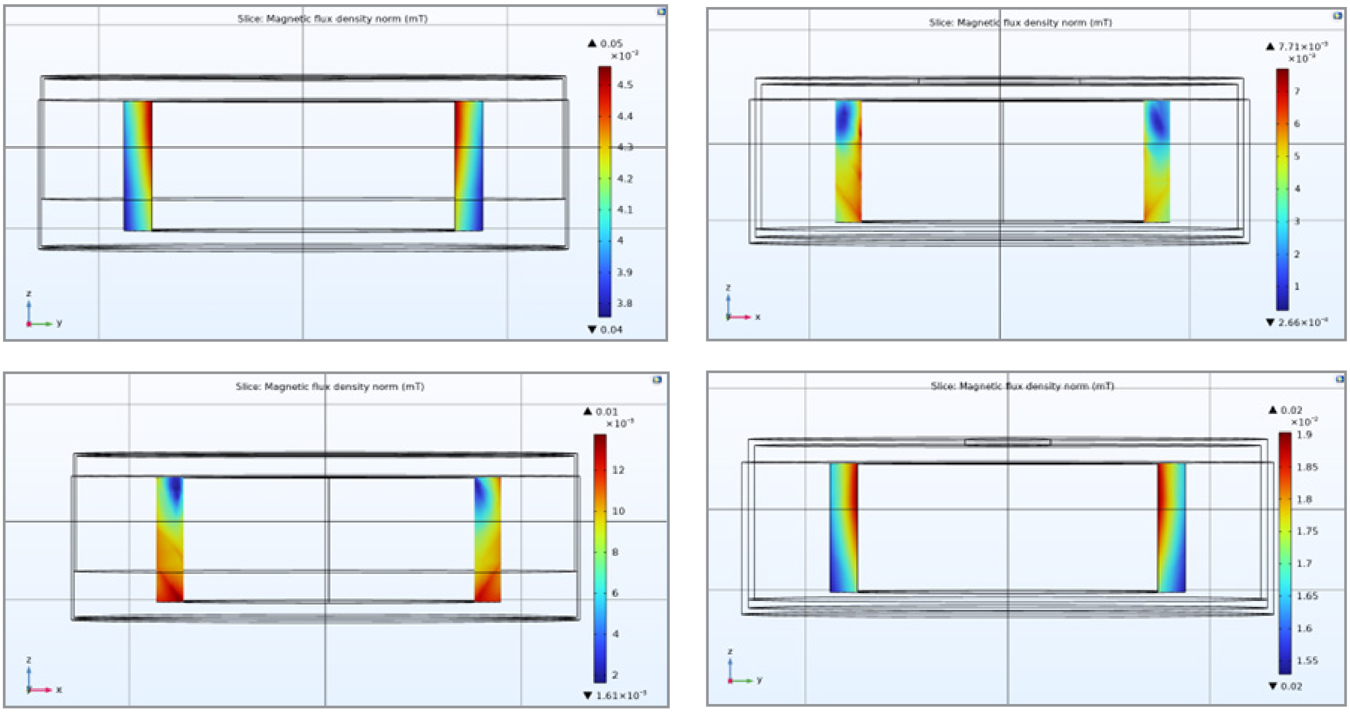


V5_2 (min. (left) and max. (right) values)

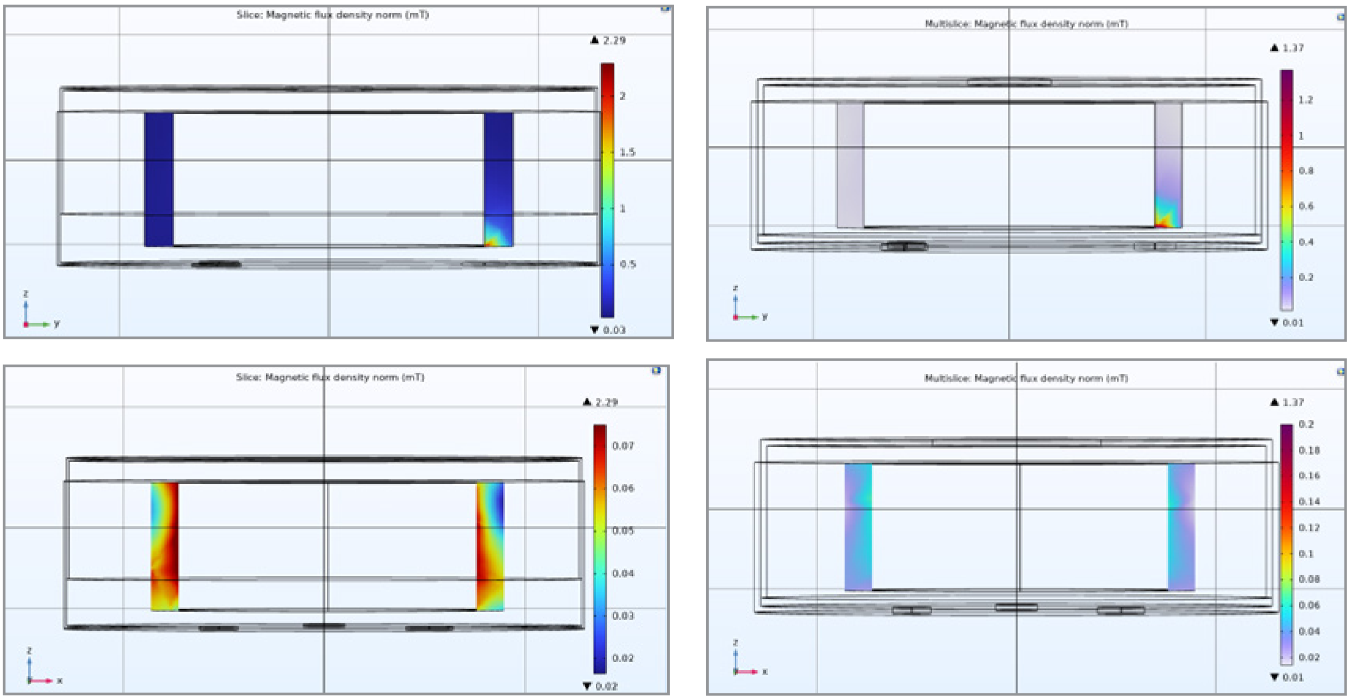




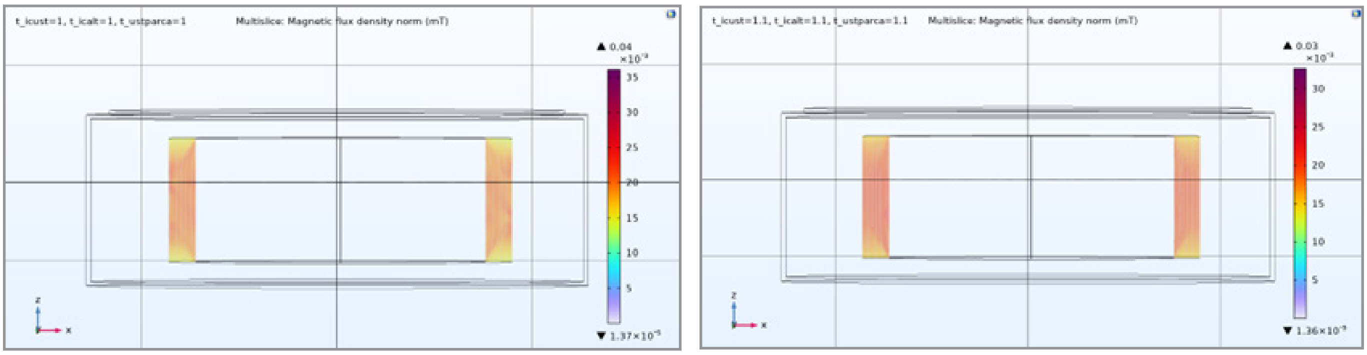
V5_3 (min. (left) and max. (right) values)



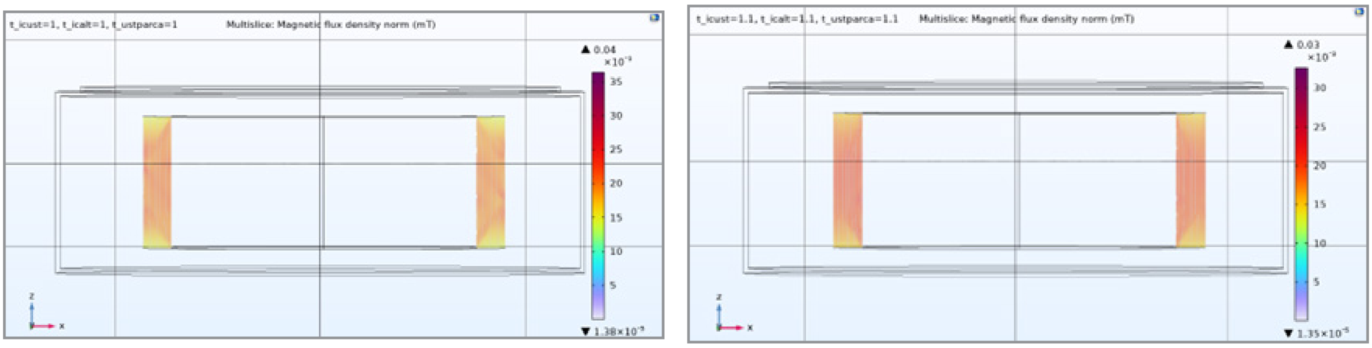
V6 (min. (left) and max. (right) values)



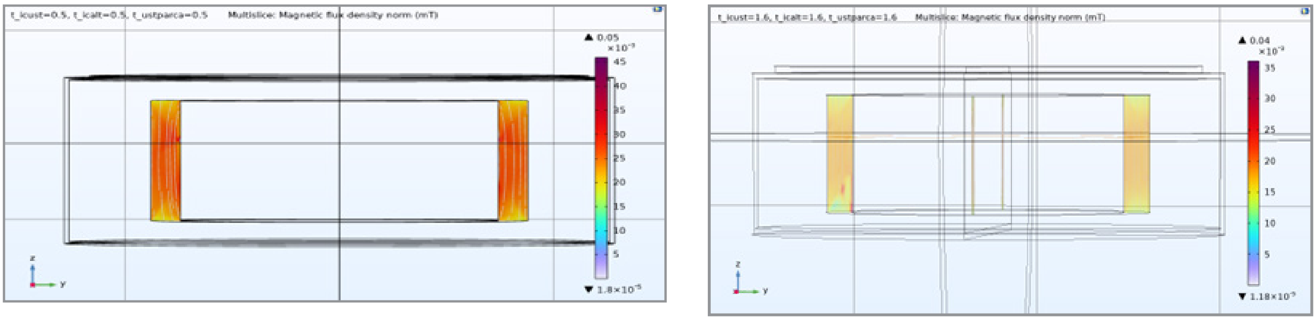
V7_1_1 (min. (left) and max. (right) values)



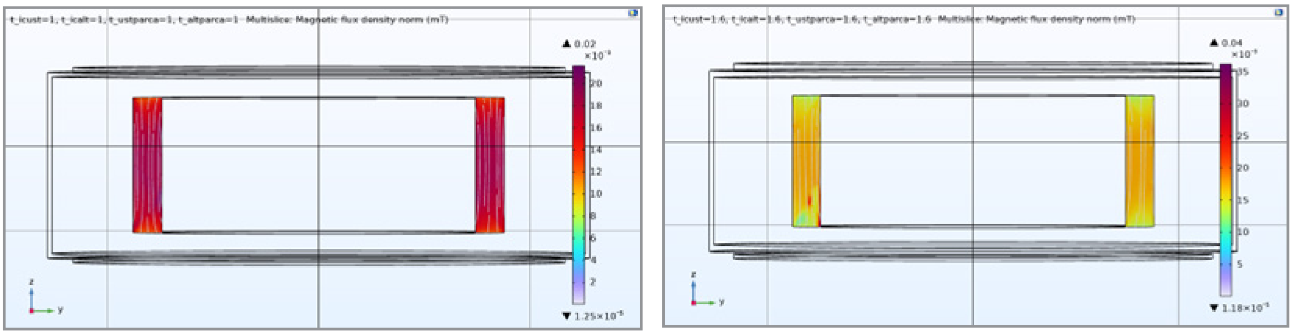
V7_1_2 (min. (left) and max. (right) values)



V7_1_3 (min. (left) and max. (right) values)



V7_2 (min. (left) and max. (right) values)



V7_3 (min. (left) and max. (right) values)