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Shape Optimization of Conducting Shields for Low Frequency Magnetic Fields

INTRODUCTION

Efficient shields are often required in medicine, physics, when making electric and magnetic measurements of high sensitivity in order to prevent them from electromagnetic interference [1]. In this paper a shape optimization technique for low frequency magnetic field problem has been developed [2]. We show how genetic algorithms and finite element method can be used to compute the optimal shape of a conducting shield, on purpose to minimize the magnetic field in the region of interest.

PROBLEM DESCRIPTION

We wish to produce a magnetic-field-free-region in a pulsating homogeneous magnetic field. The field is in the direction of the z-axis and its time response is given by the equation: $\mathbf{B}_0 = B_0\, e^{j\omega t}\, \mathbf{1}_z$, where ω is the angular frequency. The volume of interest – cylinder of radius r_e and height h with axis of revolution coinciding with z-axis, is surrounded by an axisymmetrical shield made of material of conductivity σ and magnetic permeability μ_0. In the analysis, a constant shield area D_0 and a constant thickness d have been considered, under the assumption that $D_0 < 2\pi r_e(r_e + h)$. It means that the shield is not of the form of a perfectly closed cylindrical can. We assume that the shield – in a geometrical sense – is generated by rotating a plane curve C about the z-axis external to C and on the same plane. It is obvious that the curve C cannot cut through the protected region. Two classes of curves C have been considered in the paper, namely: a segment and a circular sector. The aim of our work is to optimise the shield geometry with a given excitation frequency and material properties. The design of the shield is performed by minimising a cost function. This cost function includes the maximal norm of the magnetic flux density B in the whole protected region (at the chosen “measurement points”). Minimising the magnetic flux density is equivalent to maximising the shielding factor defined as:

$$S(\%) = (B_0 - B_i)/B_0 \cdot 100\,, \qquad (1)$$

where: B_0 is the flux density without a shield, and B_i is the flux density at a given point with the shield in place.

In this paper a genetic algorithm, GA, technique (it models the biological genetic process by including crossover and mutation operators) is proposed to find an optimal shape of the shield in the frame of the two classes of shield surfaces. A modified version of GA presented in [3] has been implemented in MATLAB. The flow chart of the optimization procedure is shown in Fig. 1.

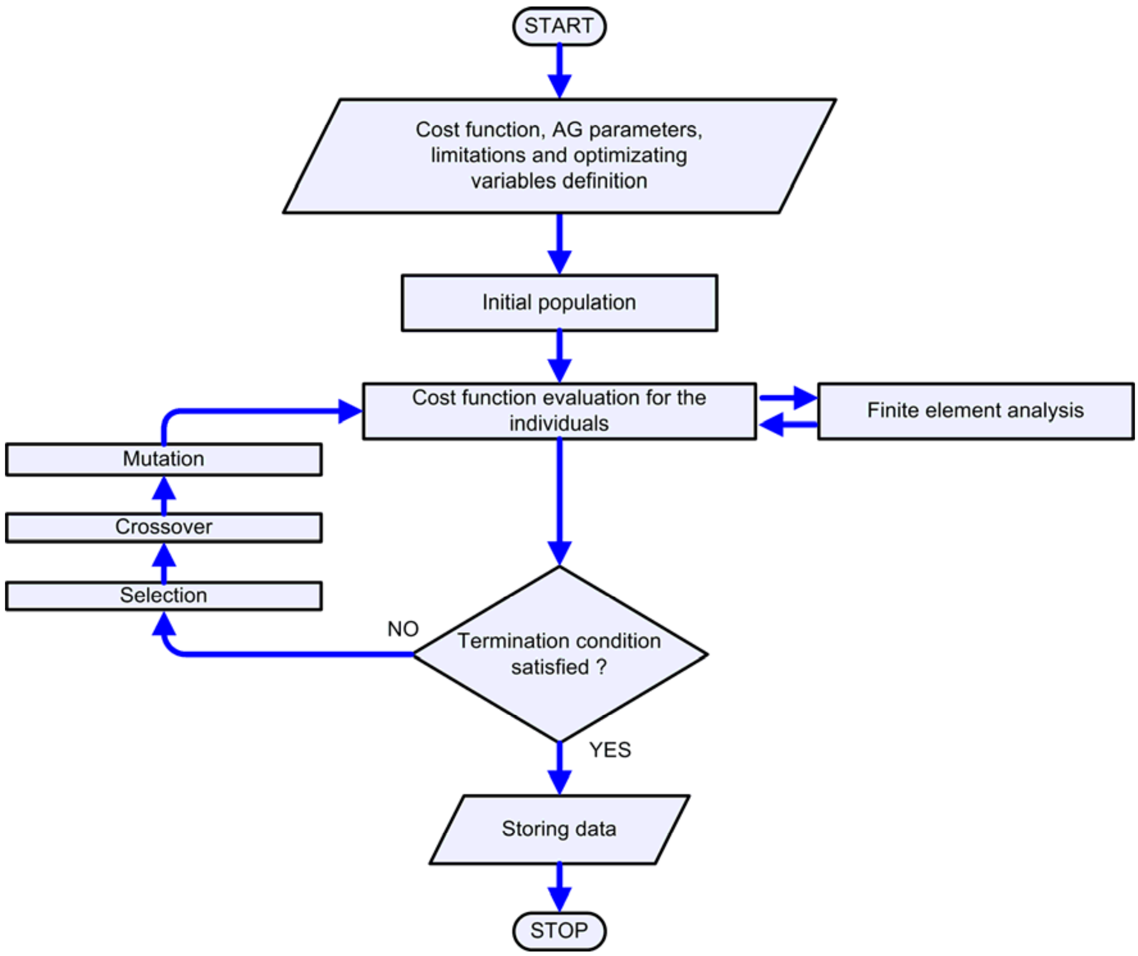

Fig. 1 Flow chart of the optimization procedure based on genetic algorithm

There are two functional bodies which continuously interact, namely: search algorithm (genetic algorithm) and analysis tool for calculation of the magnetic flux density distribution. The field equations are solved using commercial software FEMLAB,where finite elements are used for the solution [4].

NUMERICAL RESULTS

The genetic algorithm has been used to optimize the shape of electromagnetic shields in a quantitative way. Let us assume that it is desirable to produce a magnetic-field-free-region: $r \le 8$ cm, -2 cm $\le z \le$ -8 cm, in cylindrical coordinate system (r, ϕ, z), when the pulsating homogeneous magnetic field of frequency f is in the direction of the z-axis. The shields considered are made of sheet cooper (conductivity $\sigma = 5.7 \cdot 10^7$ S/m, magnetic permeability $\mu = \mu_0$, thickness d = 1mm, area $D_0 = 0.05\ m^2$). Geometrically the shields are generated by rotating a segment and a circular sector about the z-axis. The design of the shields is performed by minimising the maximal norm of the magnetic flux density in the whole protected region (maximizing the shielding factor). In practice the values of the magnetic flux density normalized to B_0 (amplitude of the external magnetic flux density) were checked at the chosen "measurement points" as shown in Table 1.

Table 1 Coordinates (r, z), in cm, of the „measurement points" where the normalized values of the magnetic induction were checked

P_1 (2,-2)	P_2 (4,-2)	P_3 (6,-2)	P_4 (8,-2)
P_5 (2,-4)	P_6 (4,-4)	P_7 (6,-4)	P_8 (8,-4)
P_9 (2,-6)	P_{10} (4,-6)	P_{11} (6,-6)	P_{12} (8,-6)
P_{13} (2,-8)	P_{14} (4,-8)	P_{15} (6,-8)	P_{16} (8,-8)

A. Curve C as a segment – the shield has a shape of a truncated cone lateral surface

The shield considered is shown in Fig. 2. There are 3 design parameters: α_0, r_0 and z_0 (position of the point Q can be found taking into account the condition that the area of the shield is equal to D_0). All possible values of the parameters under consideration (search space) are shown in Table 2.

Table 2 Search space (minimal and maximal values of all parameters under consideration)

Parameter	p_{lo_j}	p_{hi_j}
j = 1, α_0 (°)	- 110	110
j = 2, r_0 (cm)	0,0	16,0
j = 3, z_0 (cm)	- 8,0	8,0

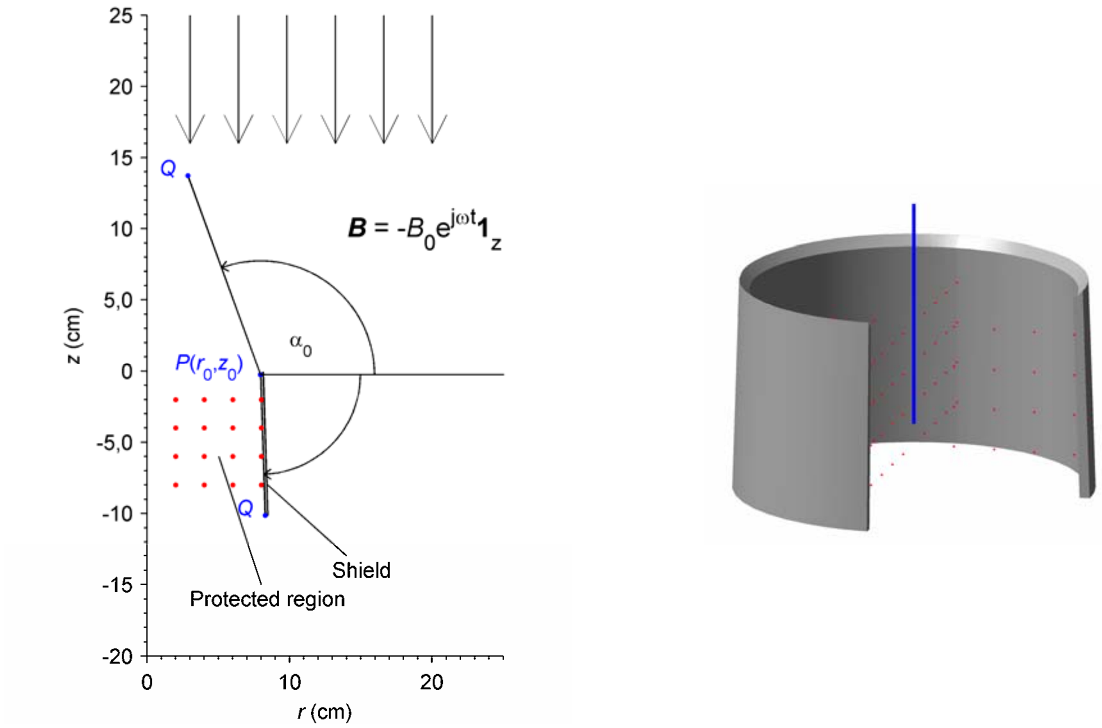

Fig. 2 A conducting shield in an external pulsating magnetic field (the shield is generated by rotating a segment about the *z*-axis)

Exemplary results of calculations for different frequencies are shown in Fig. 3 and in Table 3.

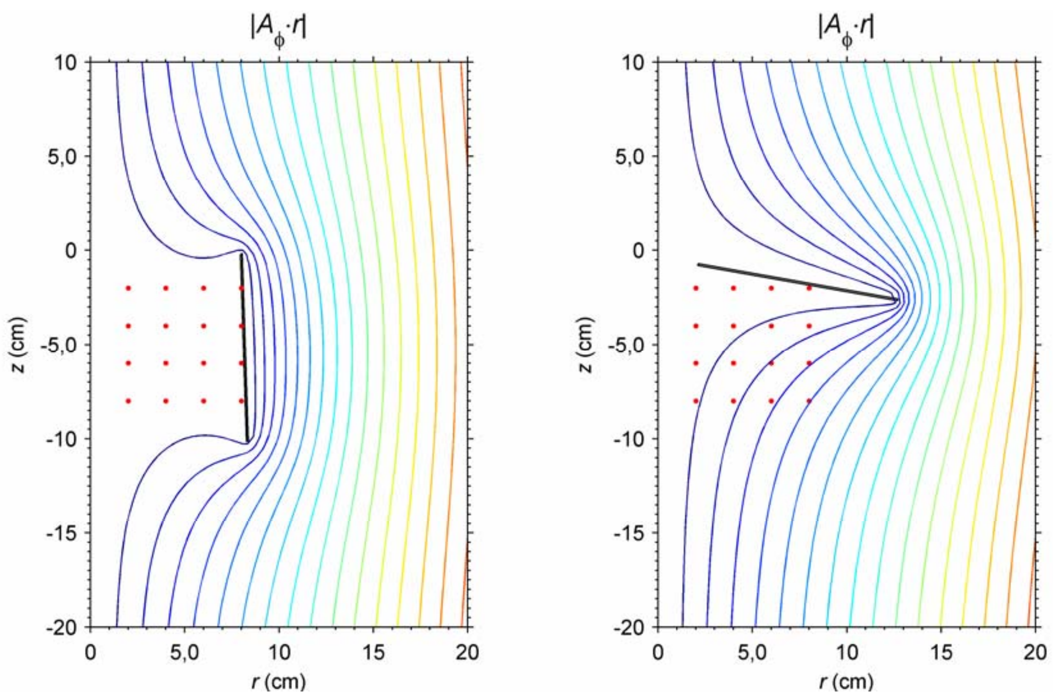

Fig. 3 Comparison of magnetic flux lines for two different conducting shields of the same area, on the left is the optimal shield; f = 100 kHz

Table 3 Shielding factors and optimal parameters of the shields for different frequencies

Frequency f (Hz)	**Shielding factor S (%)**			**Optimal parameters**		
	S_{min}	S_{mean}	S_{max}	α_0 (°)	r_0 (cm)	z_0 (cm)
50	10,38	10,91	11,86	- 99,55	11,906	- 1,35
100	27,33	28,91	31,72	- 98,03	11,86	- 1,37
5 k	82,81	89,58	96,15	- 88,10	7,95	- 0,24
100 k	83,94	90,21	96,89	- 88,11	7,94	- 0,25

B. Curve C as a circular sector

The shield considered is shown in Fig. 4. There are 4 design parameters: r_0, z_0, R_0 and β_0. Point $P(r_0, z_0)$ lies on a sector of circle of radius R_0. Positions of the end points of the circular sector, Q_1 and Q_2, are found taking into account the condition that the area of the shield is equal to D_0, and additionally assuming that the surface area of a surface of revolution generated by rotating sectors PQ_1 and PQ_2 about z-axis are equal. The parameter β_0 is an angle between the r-axis and the straight line connecting points P and O, where $O(r_c, z_c)$ is a centre of the circle of radius R_0 and:

$$r_c = r_0 - R_0 \cos\beta_0, \; z_c = z_0 - R_0 \sin\beta_0. \qquad (2)$$

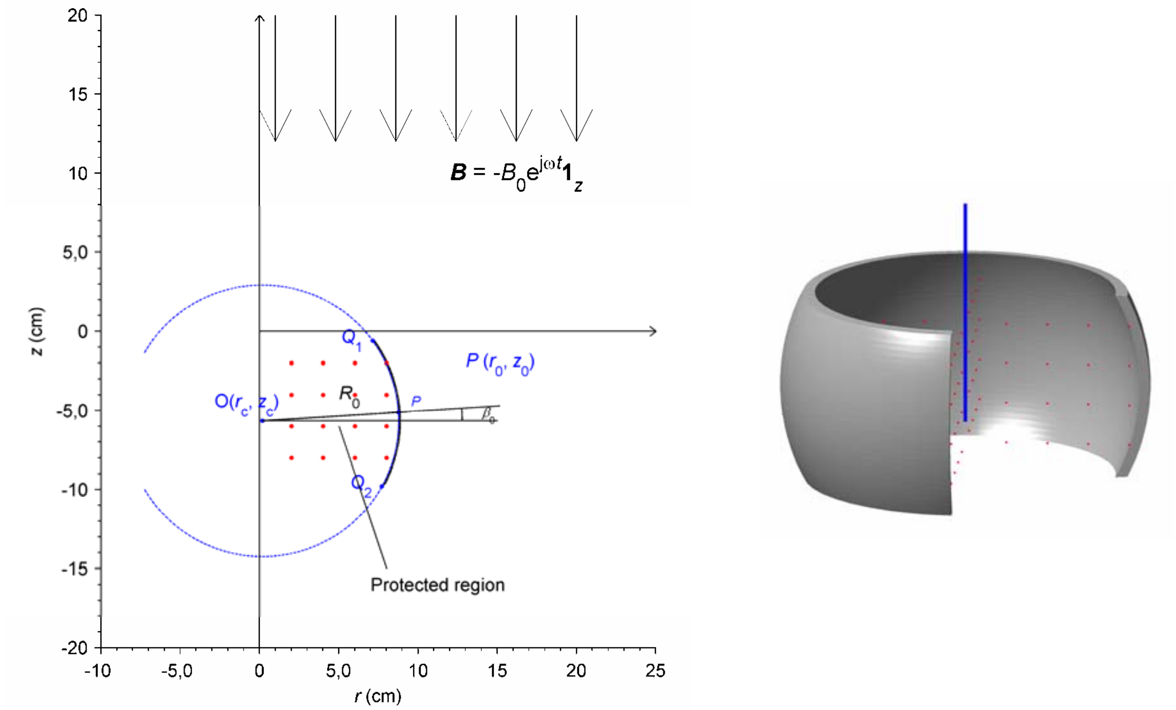

Fig. 4 A conducting shield in an external pulsating magnetic field (the shield is generated by rotating a circular sector about the *z*-axis)

All possible values of the parameters under consideration (search space) are shown in Table 4.

Table 4. Search space (minimal and maximal values of all parameters under consideration)

Parametr	p_{lo_j}	p_{hi_j}
j = 1, β_0 (°)	-55	55
j = 2, R_0 (cm)	2,0	16,0
j = 3, r_0 (cm)	8,2	16,0
j = 3, z_0 (cm)	-8,0	0

Exemplary results of calculations for different frequencies are shown in Fig. 5 and in Table 5.

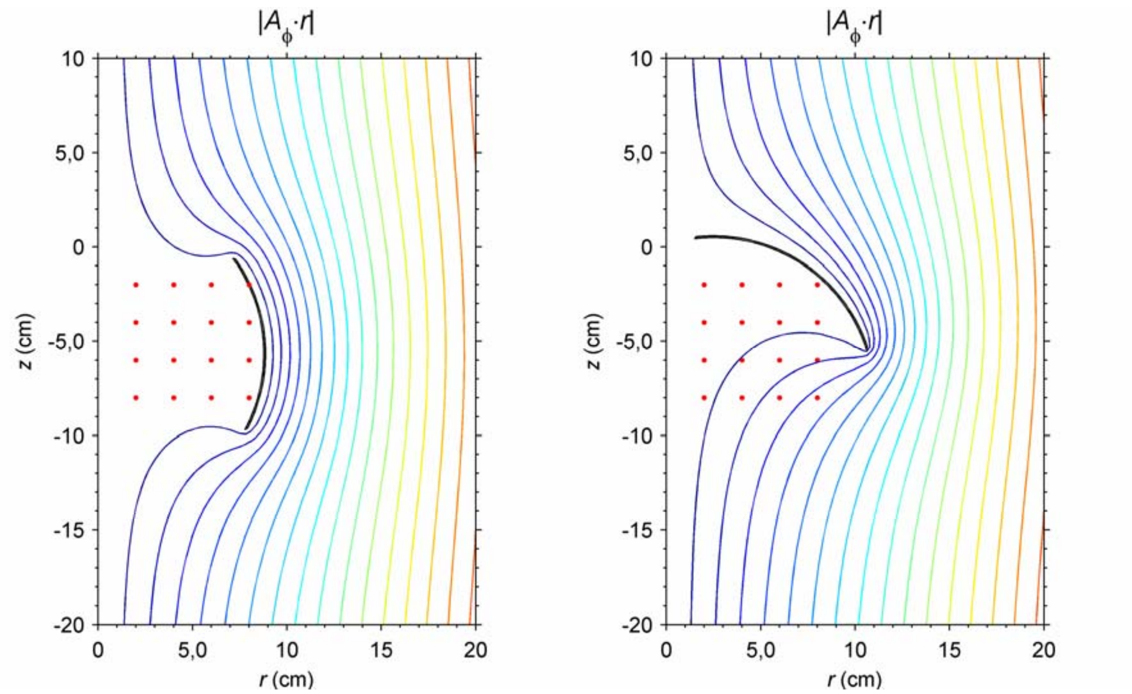

Fig. 5 Comparison of magnetic flux lines for two different conducting shields of the same area, on the left is the optimal shield; f = 100 kHz

Table 5 Shielding factors and optimal parameters of the shields for different frequencies

Frequency ***f*** **(Hz)**	**Shielding factor** ***S*** **(%)**			**Optimal parameters**			
	S_{min}	S_{mean}	S_{max}	β_0 (°)	R_0 (cm)	r_0 (cm)	z_0 (cm)
50	11,41	12,20	13,47	6,22	1,30	12,89	- 4,85
100	28,59	30,64	34,41	49,48	1,30	12,55	- 4,02
1 k	79,94	85,73	91,58	1,27	8,55	8,61	- 5,02
5 k	83,11	90,21	96,55	0,83	6,40	8,77	- 4,98
100 k	84,32	90,30	97,45	3,63	8,59	8,75	- 5,11

Figure 6a shows the shielding factor distribution for excitation frequency equal to 100 kHz in case of the shield of optimal parameters obtained for frequency equal to 50 Hz. Figure 6b presents the opposite situation.

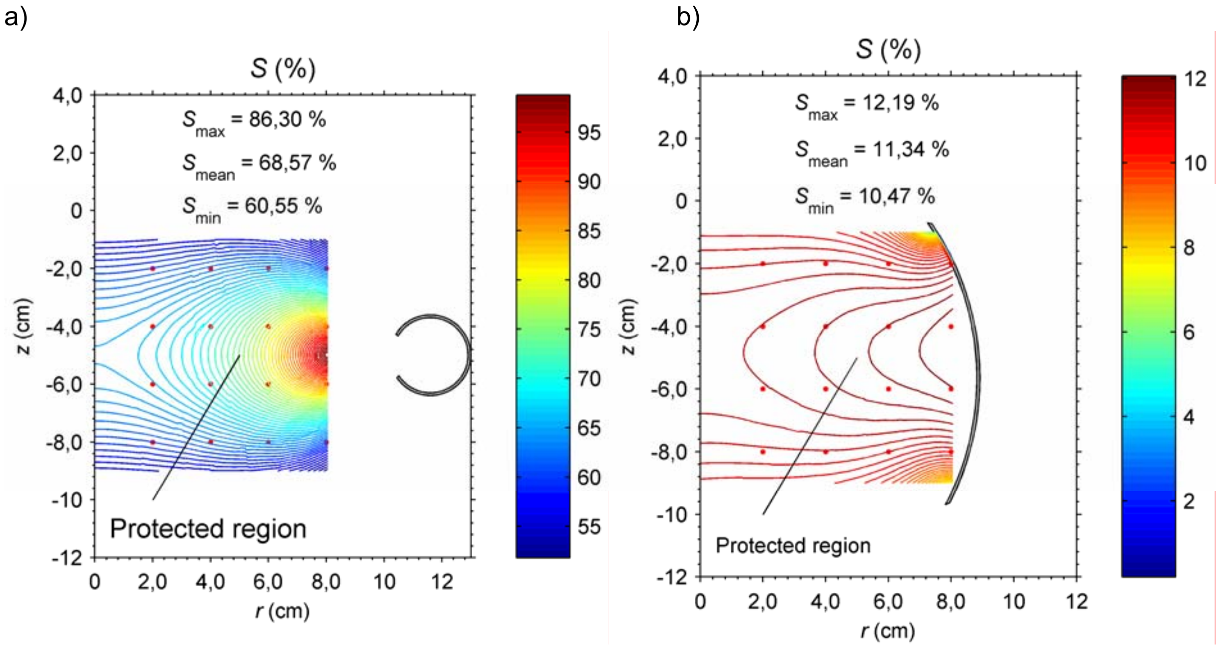

Fig. 6 Distribution of the shielding factor: a) excitation frequency f = 100 kHz, parameters of the shield obtained for frequency f = 50 Hz; b) excitation frequency f = 50 Hz, parameters of the shield obtained for frequency f = 100 kHz

It is interesting to note that assuming a negative value of the parameter R_0 in Table 4 one can obtain another shape of the shield as shown in Fig. 7, however, generally the shielding factor is smaller in such a case.

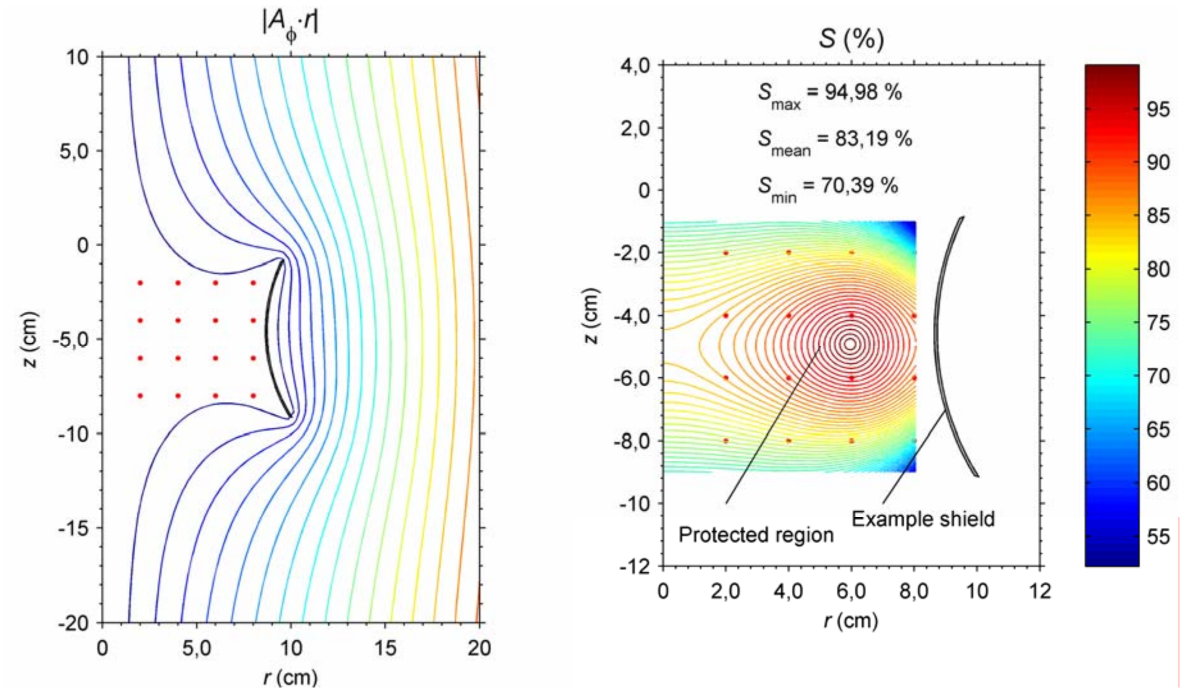

Fig. 7 Magnetic flux lines and distribution of the shielding factor for the exemplary shield (not optimal) when taking a negative value of the parameter R_0, f = 100 kHz

CONCLUSIONS

A genetic algorithm has been implemented in MATLAB, coupled with FEMLAB and applied to the design of the optimal shape of electromagnetic shields. Two classes of the shield surfaces have been considered, namely: generated by rotating a segment and a circular sector about the symmetry axis.

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