International Journal of Engineering & Technology, 7 (4) (2018) 3591-3594

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i4.19326
Research paper

Optimization of asymmetrical magnetic lenses with the aid of EOD program

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Abstract

A common method used for the design of magnetic lenses is the analysis optimization procedure that using the finite element method with the aid of the Munro programs. The latter way has been applied in the present work to investigate asymmetrical magnetic lenses in conjunction with Electron Optical Design software(EOD). The influence of two important geometrical parameters, namely the axial bore diameter and the air gap, on the objective and projector properties. Our results show that all of the optical properties has been studied minutely are improved at the lowest values of these two parameters.

Keywords: *Charge-Particle Optics; EOD Program; Finite Element Method; Asymmetrical Magnetic Lenses.*

1. Introduction

Electron lenses are considered to be the most important parts in the electron microscope, and they are also very common in all electron-optical devices. There are three main types of this lens: (1) the electrostatic or electric lens; (2) the permanent magnet lens; (3) and the electromagnetic lens also known as magnetic lens. The latter used commercially more than the previous types, due to ease and accuracy of its work, simple manufacture, and low cost. Unfortunately, the electron lens suffers from several defects associated with its operation that are called "aberrations". These aberrations are due to a failure of the lens- system to concentrate all charged particles of a beam, that is emitted from one point in the object plane, into one point in the Gaussian image plane. As a result the image will appear either blurred or distorted. Hence, the presence of these defects leads to a deterioration of the quality of the charge particle optical devices. Therefore, the failure in obtaining an aberration-free lens system has led to the development of methods in order to try to alleviate this problem, such as the so-called optimization. There are two entirely different optimization procedures: ANALYSIS and SYNTHESIS. In the latter one begins with a set of performance criteria and designs an instrument to meet them [1]. An abundant literature exist about this procedure, see [2-3]. In the first one the designer starts with actual lens design and calculates its optical properties. If the resultant properties are not electron- optically acceptable, the physical and geometrical parameters of the considered design have to be changed. The process is repeated until satisfactory values are obtained. Hence, this procedure is based on trial and error. Optimization by analysis has been given more attention beginning from the middle of the last century. Since that time, several different ideas have been adopted concerning the analysis procedure, such as the effect of pole pieces saturation in the focal properties to the objective lens [4], and the influence of the axial magnetic field distribution on the asymmetrical objective lens with high voltage electron microscopy [5,6]. More examples about this procedure can be found in Refs. [7-13]. All of the previous studies have been conducted with the aid of Munro programs [14]. The present investigation is carried out by EOD program [15] to design and investigate an asymmetrical magnetic lens by varying some geometrical parameters.

2. EOD program and finite element method

The EOD is a software introduced by Lencova [15] for designing an electron lens with complicated geometry and for computing its magnetic field distribution and optical properties with high accuracy. This software depends on the finite element method (FEM) and is a computing technology introduced for the first time by Munro [14] in the field of electron optics to this method utilized in the analysis of all magnetic lenses regardless of the geometry of their pole pieces. Hence, it is applied to calculate the magnetic field of the round lenses [16] and successfully on the electrostatic lenses [17] that have wide applications in engineering and physics. In this method, the area that required to analyze is divided to a large number of very small secondary areas, known as finite elements, that can be triangles, or squares, or more complex forms. The area that is required to be divided in the magnetic lens can be specified according to the lens type. Hence, a quarter of a lens with the optical axis are taken in the symmetrical lens, while the upper half with the axial axis are considered in the asymmetrical lens. It is worth mentioning, that the accuracy of the accounts depends on the correct choice of the grid lines (mesh) where this distribution is increasingly important as we get closer to the pole, especially at it top [18].

3. Lens design

To calculate the axial magnetic-field distribution of the lens and its corresponding objective properties by the EOD [15] program, the dimensions and grid-lines distribution (mesh) are identified by FEM as shown in figure 1. The lens consist of a circular coil with cross-section at area 4500 mm^2 which is penetrated by two magnetic pole pieces made of soft iron, each of them having a diameter D=5 mm. The air gap between them or so called action region, S=5 mm which is where most magnetic flux is concentrated. In order to prevent the leakage of magnetic field outside the lens, the coil and the magnetic polepieces are surrounded by a soft iron circuit

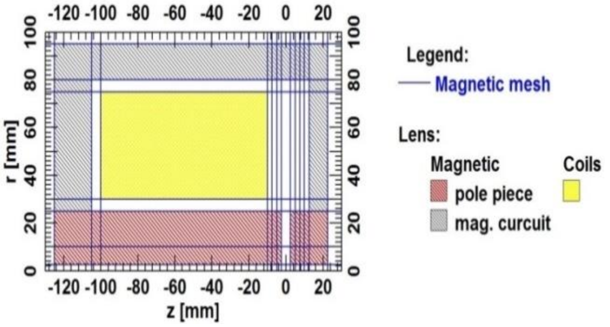

Fig. 1:.The Finite Element Meshes on the Upper Half of the Asymmetrical Magnetic Lens.

The geometrical design and magnetic flux lines distribution of the asymmetrical magnetic lens are plotted in figure 2. The axial flux density is computed at constant lens excitation (NI=2000 A.t), N being the total number of turns of the energizing coil carrying a current I. The current density is σ = 0.494A/mm^2

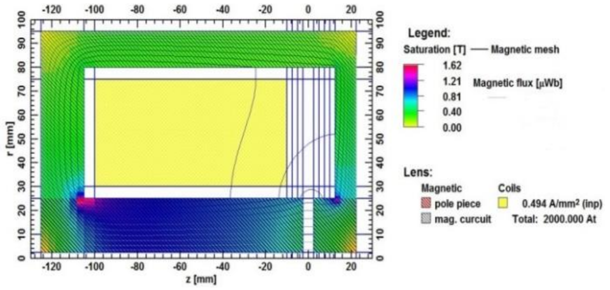

Fig. 2: The Geometrical Design with Magnetic Flux Lines Distribution of the Upper Half of the Asymmetrical Proposed Lens.

Further demonstration, Fig.3 displays a three-dimensional section of the lens.

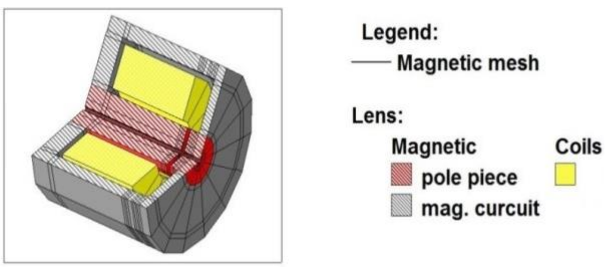

Fig. 3: Cross Section of the Suggested Asymmetrical Magnetic Lens in Three Dimensions.

4. Evaluation of properties

It is well known, that the spherical and chromatic aberration coefficients are the main factors that limit the resolution of an objective lens. Throughout the present investigation, the spherical C_S and the chromatic C_C aberration coefficients have been calculated via [14]

$$C_S = \left[\frac{\eta}{128V_r}\right]\int_{z_1}^{z_2}\left[\left(\frac{3\eta}{V_r}\right)B_z^4 r_\alpha^4 + 8B_z'^2 r_\alpha^4 - 8B_z^2 r_\alpha^2 r_\alpha'^2\right]dz \quad (1)$$

$$C_C = \left[\frac{\eta}{8V_r}\right]\int_{z_1}^{z_2} B_z^2 r_\alpha^2 dz \quad (2)$$

In addition, the spiral D_S and the radial D_r distortion coefficients are the most effective factors that limit the resolution of the projector lenses. Therefore these two distortions have been considered in present work and are given by [19]

$$D_r = \left[\frac{\eta}{128V_r}\right]\int_{z_1}^{z_2}\left[\left(\frac{3\eta}{V_r}B_z'' + 8B_z'^2\right)r_\alpha r_\gamma^3 - 4B_z^2\left(r_\gamma'^2 r_\alpha r_\gamma + r_\gamma' r^2 r_\alpha'\right)\right]dz \quad (3)$$

$$D_S = \int_{z_1}^{z_2}\left[\frac{3}{128}\left(\frac{\eta}{V_r}\right)^{\frac{3}{2}} r_\alpha^2 B_z^2 + \frac{1}{16}\left(\frac{\eta}{V_r}\right)^{\frac{1}{2}} r_\alpha'^2 B_z\right]dz \quad (4)$$

Where z_1 and z_2 are the axial points at which magnetic field vanishes, η is the electron charge-to-mass ratio, and V_r is the relativistically corrected accelerating voltage. B_Z is the axial magnetic flux density distribution, B_Z', B_Z'' are their first and second derivatives, respectively, and r_α is the solution of the paraxial-ray equation (5). In order to calculate B_z(z) that is required to obtain C_S, C_C, D_r and D_S [see Eqs. 1, 2, 3 and 4] respectively, the paraxial ray equation

$$r''(z) + \frac{\eta}{8V_r}B_Z^2 r(z) = 0 \quad (5)$$

Used. It should be mentioned, that throughout the present work the cubic spline differentiation technique and Simpson′s rule have been applied to evaluate the derivatives and integrals.

5. Results and discussion

5.1. The axial bore D

First the effect of D on the optical properties is presented, since this parameter has considerable effect on the magnetic field magnitude. Four values of D have been used ranging from 5 to 20 mm (see Table 1), while the air gap has been kept constant at S=5 mm. Figs 4 and 5 show B_Z (z) and the geometrical designs for the different values of D, respectively. It is found that increasing D leads to a decrease in the maximum value of magnetic field B_{max} , and a rise in the half width W of B_Z (z) .

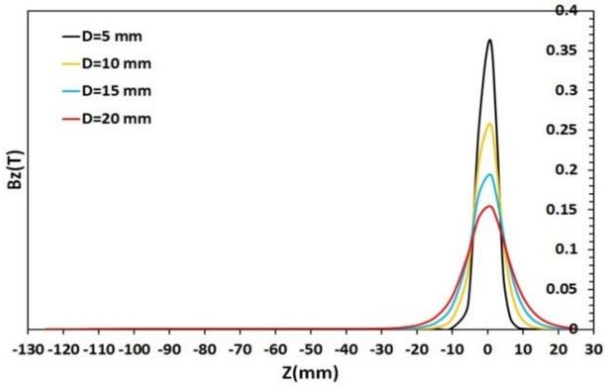

Fig. 4: The Magnetic Field Distribution B_Z(Z) At Various Values of D.

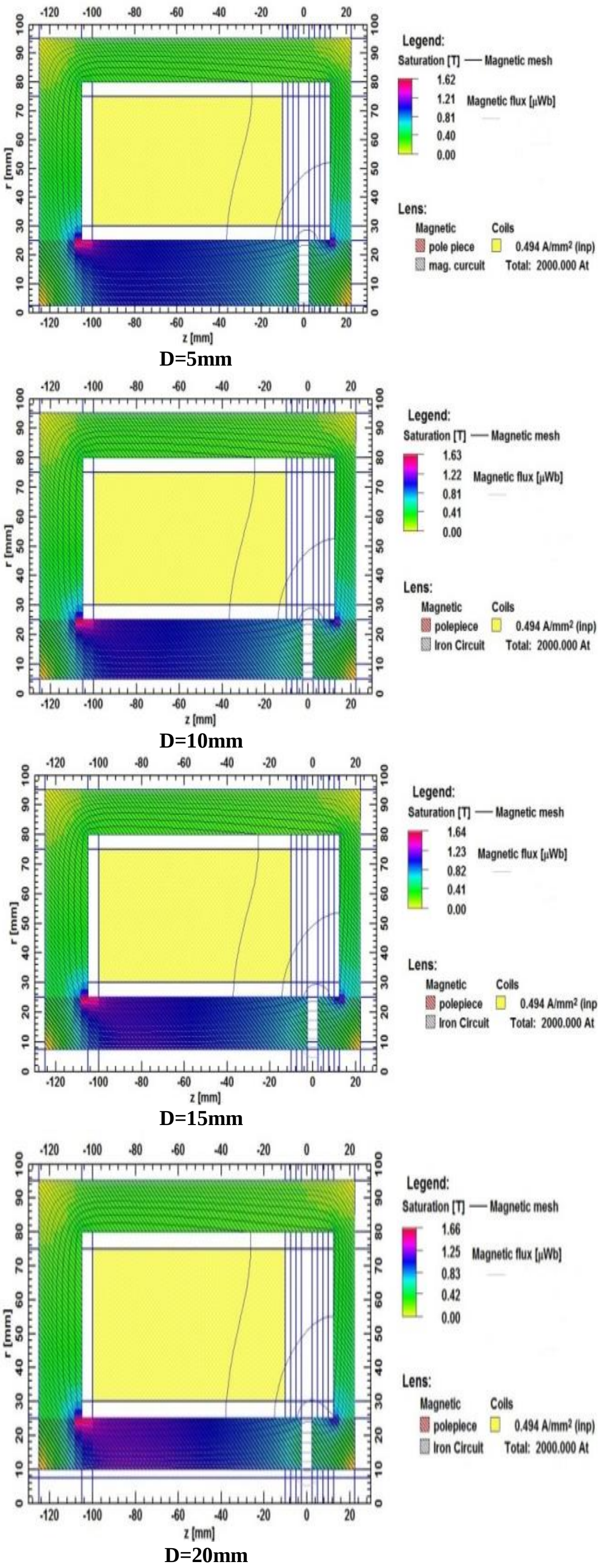

Fig. 5: Geometrical Designs of the Upper Half of the Lens for Different Value of D.

The objective optical properties are taken at $NI/\sqrt{V_r}=20$ at which the objective lenses usually operate [20]. In Table 1 it is demonstrated that by varying the axial bores of the pole piece, C_S, C_C, and the focal length f_o are found to worsen clearly as D is increased.

Table 1: Objective Optical Properties for the Deduced Imaging Fields Versus the Parameter D at $NI/\sqrt{V_R}=20$

D(mm)	C_c(mm)	C_s(mm)	f_o(mm)	W(mm)	$B_{max} \times 10^{-1}$(T)
5	1.653	1.402	2.317	6.547	3.68377
10	2.159	1.689	3.058	8.278	2.62293
15	2.909	2.063	4.216	10.609	1.96867
20	3.704	2.533	5.407	13.309	1.56112

In Table 2 on the other hand, the projector optical properties specified at the minimum value of projector focal length $(f_P)_{min}$, that is D_r and D_s improve gently with the increase of D.

Table 2: Projector Optical Properties for the Deduced Imaging Fields versus the Parameter D at the Minimum Value of FP

D (mm)	$(f_p)_{min}$ (mm)	D_r (1/mm^2)	D_s (1/mm^2)
5	3.455	0.0075	0.098
10	4.531	0.0072	0.055
15	6.112	0.0049	0.030
20	7.782	0.0030	0.018

5.2. Air gap S

Tables 3 and 4 display the influence of S on the objective and projector properties, respectively, at constant D = 5 mm. One can see that a variation of S strongly influences the imaging field properties. This behavior may be thought of as a consequence of decreasing lens power due to the increase in the action region as shown in Fig. 6.

Hence the lowest (i.e best) values of the objective focal properties are obtained at the smallest values of D and S, whereas the best projector properties at the largest D and S values, respectively.

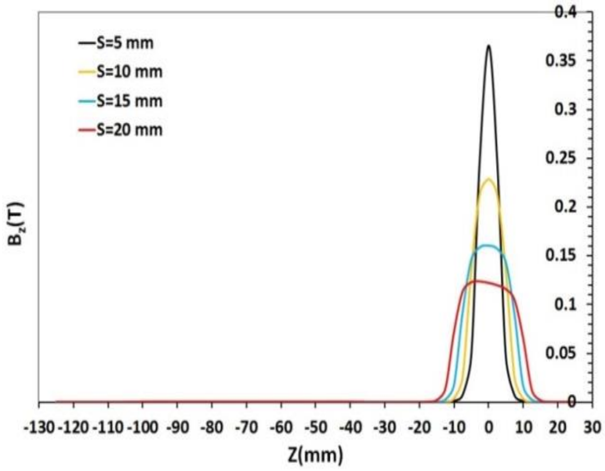

Fig. 6: Magnetic Field Distribution B_Z at Various Values of S.

Table 3: Objective Optical Properties for the Deduced Imaging Fields Versus the Parameters S at $NI/\sqrt{VR}=20$

S(mm)	$(f_p)_{min}$ (mm)	D_r (1/mm^2)	D_s (1/mm^2)
5	3.36	0.040	0.100
10	5.41	0.0037	0.038
15	7.79	0.0035	0.018
20	10.32	0.0033	0.010

Fig. 7 shows the geometrical designs for the proposed lens with magnetic flux distributions at different values of S. This figure displays the increase of the magnetic flux density at the lowest value of S=5mm.

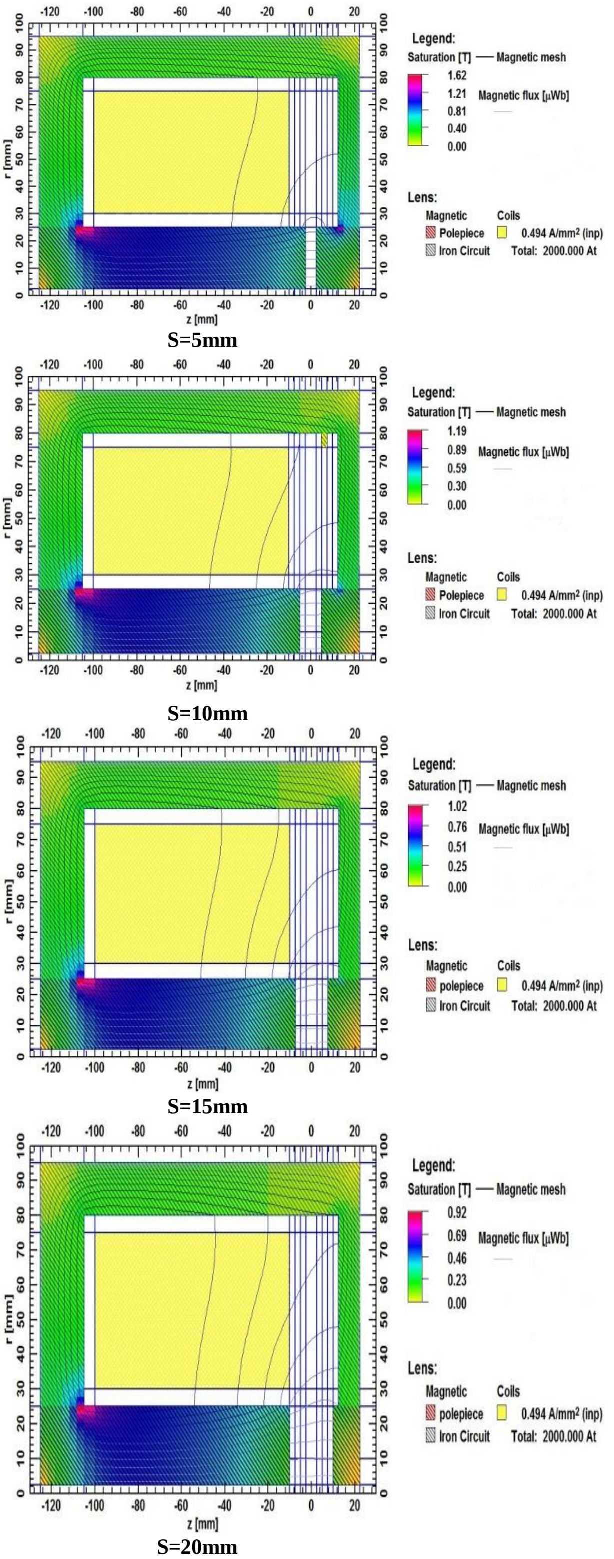

Fig. 7: Geometrical Designs of the Upper Half of the Lens for Different Values of S.

6. Conclusion

According to the results in the present work, each of the axial bore of the pole pieces and the air gap play a significant role in the optimum design of the asymmetrical magnetic lens. There is large difference in the effects of each them, and obviously, the air gap displays the greater one. The objective focal properties improved effectively at the reduction of D and S, while the corresponding improvement of the projector properties was at a lower rate. This result is consistent with all previous studies presented in the design of asymmetrical magnetic lenses by using Munro's programs. Hence, the EOD program can be considered as a good tool to get optimum asymmetrical magnetic lenses with high accurately.

Acknowledgment

We would like to thank Asaad Sakhel for a critical reading of the manuscript.

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