------ Raf. Jour. Sci., Vol. 16, No. 1 Physics, Special Issue, pp. 95-104, 2005 ------

The Effect of Coil Geometry and Magnetic Circuit on the Flux Lines Trajectory of the Magnetic Lenses

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(Received 3/10/2004 ; Accepted 27/12/2004)

ABSTRACT

The present research includes studying the effect of position and geometrical shape of the coil on magnetic flux lines trajectory also on the shape of the magnetic flux density distribution of a single polepiece lens where by its objective focal properties were designed and studied previously by researchers.

It has been noticed that the change in coil position in comparison with the original design causes important improvement in the magnetic flux lines distribution inside the structure of the lens and clearly increasing the value of the magnetic flux density peak.

Besides, the conical and vertical iron shroud was introduced to the original lens giving a clear effect in improving the lens performance and magnetic flux lines path, furthermore, increasing the magnetic flux peak as well as decreasing the half-width as a result the objective focal properties of the lens lead to a large improvement in lens performance comparing with the optical properties of the original lens design.

تأثير الشكل الهندسي للملف و الدائرة المغناطيسية على مسار خطوط الفيض للعدسات المغناطيسية

الملخص

يتضمن البحث دراسة تأثير موقع وشكل الملف الهندسي على مسار خطوط الفيض المغناطيسي وعلى شكل وتوزيع كثافة الفيض المغناطيسي لعدسة أحادية القطب صممت ودرست خواصها البؤرية الشيئية سابقا من قبل الباحثين.

وقد تبين ان تغير موقع الملف عما كان عليه في التصميم الأصلي أدى الى تحسين ملحوظ في مسار خطوط الفيض المغناطيسي داخل تركيب العدسة والى زيادة واضحة في ذروة القيمة العظمى لكثافة الفيض المغناطيسي.

فضلا عن ذلك تم اضافة الذراع الحديدي الى العدسة الاصلية بنوعيه القائم و المائل وقد لوحظ ان وجود الذراع ذات تأثير بارز في تحسين اداء العدسة من ناحية مسار خطوط الفيض المغناطيسي مما ادى الى زيادة ذروة القيمة العظمى للفيض المغناطيسي وتقليص العرض النصفي وقد انعكس هذا على تحسين الخواص البؤرية الشيئية للعدسة الذي ادى بدوره الى تحسين كبير في اداء العدسة بشكل عام بالمقارنة مع خواصها البصرية في التصميم الاصلي.

INTRODUCTION

Ever since the end of 19th century it has been known that an axially symmetric magnetic field has a focusing effect on an electron beam in a cathode ray oscillograph, it acts as a lens. This effect is similar to that of a glass lens on a light beam. The effect was first investigated by Busch in 1926 for both theoretical and experimental fields. Two important results were described in his theory. The first is that the focal length of the lens decreases with an increasing of magnetic flux density peak; this means that if a lens is made not just of a coil of wire, but from a coil wrapped around a ferromagnetic yoke the concentration of the magnetic flux density with an iron yoke makes a very effective lens. The second is that, the electron beam rotates in the magnetic field, the rotation is simply proportional to the integral of the field strength and does not depend on the field distribution. The concentration of the magnetic field made it possible to produce an electron microscope with higher magnification. Their idea of the magnetic lens is still the basis of lenses at present (Mulvey, 1984).

Both (Hill and Smith, 1982) proposed the type of a single polepiece magnetic lens which is illustrated in Figure (1). The lens polepiece is located in front of the specimen and the incident beam illuminates the specimen through the objective lens. The characteristics of the single polepiece lens firstly have a large specimen area due to the polepiece region which is located near the specimen position and secondly have low aberrations due to the immersion of the specimen in the lens field (Marai and Mulvey, 1976).

Shao and Lin (1989) had applied a version of the lens model previously shown in Figure 1 at low voltage SEM (Tusno, 1997).

In the magnetic lenses design of the present work a much higher flux density peak can be obtained than it is possible in the lens of a traditional coil shape and position proposed by (Hill and Smith, 1982). Two main factors can limit the performance of the magnetic lens; firstly, the flux density peak of the axial field distribution and, secondly the trajectory of magnetic flux lines throughout the polepiece structure and coil windings both are considered in this paper to examine the performance of the lens design.

The aim of this paper is to introduce the factors above into the practical design situation in order to see if there is an operational region in which a developed lens design can be superior to a traditional one proposed by (Hill and Smith, 1982). This work also aims at finding out a reliable simple design of lens coil shape and position which makes it possible to increase the axial flux density of the field. It is also intended to investigate the effect of the iron shroud on the lens performance.

Fig. 1: Schematic diagram of cross section of the single polepiece magnetic lens design used by Hill and Smith (1982) (original lens).

MAGNETIC LENS DESIGN

The design of a magnetic lens consists of two parts, firstly, the electron optical design and ampere-turns under given external conditions. Secondly, the design of the magnetic circuit includes poles, iron shroud and coils geometry (Lenc, 1982). Hill and Smith, (1982) proposed the type of single polepiece lens as shown in Figure (1). The lens is located in front of the specimen region and the incident beam illuminates the specimen through the objective lens facing the polepiece side. This lens is designed without iron shroud. The magnetic field of this lens is generated by a coil of rectangular shape which has an area equals (1862 mm^2) and dimensions of (38mm×49mm) as shown in Figure (1), (original lens).

In order to improve the field of the magnetic lens design the coil shape and position of the original lens, shown in Figure (1) are changed to increase the flux density peak and consequently avoid high flux density in the inside parts of the polepiece region which causes the broadening of the field and a considerable waste of ampere-turns. Therefore, in designing lenses it is important to check the flux density distribution in the polepiece region throughout the changing of coil position.

Attention has been concentrated on two aspects of the design model firstly the coil geometry and its position due to the polepiece tip, secondly the iron shroud effect on the axial flux density distribution. The principal purpose of the iron shroud is to reduce the flux leakage out of the magnetic circuit and thereby concentrate the magnetomotive force flowing through a coil into a space of the pole face. An external iron shroud of the lens has been changed to a conical shape in order to examine its effect on the flux density peak and half – width of the axial field of the new lens design. It is important to mention that, all typical lenses posses the same area of coil windings (A=1862 mm^2), these configurations are illustrated in Figure (2).

Fig. 2: Typical configurations of the lens design with different coils shape and position.

MAGNETIC FLUX DENSITY

In order to demonstrate the performance of the previous lenses which is shown in Figure (2) and compare their efficiency, the axial magnetic flux density distributions have been computed for these lenses by the aid of program AMAG (Lencova, 1986) using the Finite Element Method. The values of the axial magnetic flux density distribution B_z are plotted as a function of Z as given in Figure 3a. It is noticed that lens 3 has acquired higher magnetic flux peak value in comparison with that of original lens ,this means that the position of coil center (Z=0) near the tip of pole causes an increase in magnetic flux density peak value (B_{peak} = 0.42 Tesla) at (NI = 10 kA-t).It can be noticed that the insertion of vertical iron shroud in lens 4 causes a higher value of the magnetic flux density peak (B_{peak} = 0.85 Tesla) at excitation (NI = 10 kA-t),in comparison with lens 5 of the conical iron shroud shape which acquires a highest value of the magnetic flux density peak and with a smallest half-width at low excitation (NI = 10 kA-t) as shown in Figure (3a).

The magnetic flux density distribution B_z was advisable , for a given excitation ,to maximize this quantity by arranging the lens design to produce a large axial magnetic flux density peak as possible together with a small effective axial half-width (Mulvey, 1982). Finally, the same results were computed at higher excitation (NI = 500 kA-t), the optimum result is obtained from lens 5 which has a higher flux density peak (B_{peak} = 7.45 Tesla) at (NI = 500 kA-t) and lower half-width comparing with the other lenses as illustrated in Figure (3b).

In order to evaluate the effect of the coil position and the iron shroud shape on the magnetic flux density distribution of the previously mentioned lenses, intensive investigations have been carried out on these lenses. The most satisfactory way of computing the properties of more complex magnetic lenses in which the coil itself contributes appreciably to the flux density distribution is undoubtedly by means of the flux lines taking into account the position and geometry of the coil and the current density in the windings (Al- Khashab, 2001).Figure (4) shows the results of the flux lines trajectories of these lenses system computed by the aid of Flux program (Munro, 1975) and modified by (Murad,1999).This program specifies the equipotential values of flux lines which are to be plotted . Figure 4 also illustrates these typical lenses with localized coils having the same area but of different position .All the flux lines are plotted at constant excitation (NI= 500 kA-t), therefore, each lens attains the same current density δ in the windings.

The flux lines are in the form of circular shapes concentrated round the center of the polepiece system and the shape of their coil geometry is affected by its roundness .It should be noticed that the conical iron shroud and the shape and position of the coil in the lens 5 Figure (4) leads to converging these lines towards the polepiece bore region ,as well as, these lines are perpendicular to the direction of iron shroud side while the coil position in the original lens design leads to diverge the flux lines away from the polepiece bore region which causes a flux leakage out of the magnetic circurt (see Figure 4).

Fig. 3a: The axial magnetic flux density distribution B_z of the lenses calculated at constant excitation (NI = 10 kA-t).

Fig. 3b: The axial magnetic flux density distribution B_z of the lenses calculated at constant excitation (NI = 500 kA-t).

Fig. 4: Flux lines distribution throughout the magnetic circuit and coil windings of the lenses (1-5) in comparison with the original lens at constant excitation (NI = 500 kA-t).

ELECTRON OPTICAL PROPERTIES

In order to compare the performance of the previous lenses with that of the original lens (Hill and Smith,1982), a systematic investigation has been carried out on the effect of the position of coil and iron shroud shape on the electron optical properties .The objective focal properties of these lenses were computed by using Munro program (Munro,1975) .Therefore,the spherical aberration coefficient C_s and the chromatic aberration coefficient C_c together with the resolving power δ_P and the flux density peak B_{peak} of the lenses (2 - 5)* of the present work have been compared with that of the original lens design studied by (Hill and Smith,1982).The properties of these lenses have been presented at constant excitation (NI =2000 A-t) as indicated in Table 1. It can be noticed that the performance of the lenses (2 – 5) of the present work are much better than that of the original lens studied by other researchers.Lens 5 of the conical iron shroud acquired the highest value of flux density peak and consequently lowest values of aberration coefficients in comparison with other lenses (see Table 1).

It is interesting to mention that there are progressive developments in the lens design. Lens 5 is excellent because of its smaller aberration coefficient and its higher resolution with out any flux leakage out of the lens structure.

Table 1. Comparison between the aberration coefficients (C_s and C_c) and the resolving power δ_P of the single polepiece lenses (2–5) with the original lens (Hill and Smith, 1982) at constant excitation (NI =2000 A-t).

	B_{peak} (Tesla) at NI=500 kA-t	**C_s (mm)**	**C_c (mm)**	**δ_P (nm)**
Original lens	3.34	1.30	1.00	1.70
Lens 2	3.30	0.24	0.33	0.34
Lens 3	4.06	0.20	0.26	0.34
Lens 4	7.10	0.20	0.26	0.26
Lens 5	7.45	0.21	0.28	0.26

Note:* Lens1 is neglected because it has a very bad objective focal properties.

CONCLUSION

Improvements in the performance of the lens can be obtained by the attention of the position and geometry of the coil ,as well as, of the external geometry of the iron shroud. The new lens design has more economical advantages than Hill and Smith lens design. Such a useful objective lens of many advantages can be produced.

REFERENCES

Al–Khashab,M.A., 2001.New development of electron projector lenses,Eng.Technology, No.10, Vol.20, pp.591-601.

Busch, H., 1926. Ann. Phys. (Leipzig), 81, pp.974-993.

Hill,R. and Smith,K.C.A., 1982. The single – pole lens as a scanning electron microscope objective, in scanning Electron Microscopy 2, SEM, Inc., Amfo, Hare,Chicago, pp.465-471.

Lenc, F., 1982. Properties of electron lenses, Magnetic Electron lenses, Ed.P.W. Hawkes (Berlin: Springer), pp.119-161.

Lencova, B., 1986. Program AMAG for computation of vector potential in rotationally symmetric magnetic electron lenses by the finite element method, Inst., Sci, Instru., Czech. Acad. Bmo. Czechoslovakia, 1-58 p.

Marai, F.Z. and Mulvey, T., 1976. Developments in electron microscopy and analysis, ed. J.A. Venables, (London ; Academic press.), pp.43-46.

Mulvey, T., 1982. Unconventional lens design, Magnetic electron lenses,ed.P.W. Hawkes (Berlin: Springer), pp.359-410.

Mulvey, T., 1984.Magnetic electron lens 2, Electron optical systems, SEM. Inc., Chicago, pp.15-27.

Munro, E., 1975. A set of computer programs for calculating the properties of electron lenses, Cambridge Univ., Eng., Report, CUED/ B- ELECT/ TR45.

Murad, W., 1999. Design of iron-free magnetic electron lenses, MSc. Thesis, University of Mosul, Iraq.

Shao, Z. and Lin, P.S.D., 1989. High-resolution low-voltage electron optical system for very large specimens, Rev. Sci. Instrum., 60(11), pp.3434- 3441.

Tsuno, K., 1997. Magnetic lenses for electron Microscopy, book Hand of charged particle optics, ed. J. Orloff, pp.143-175.