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The Electron Optical Properties of the Round Magnetic Electron Lens

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ABSTRACT

Five magnetic electron lenses have been suggested. Each one has round cross section of the iron circuit and of the energizing coil. The axial magnetic flux density distribution and the trajectory of flux lines of these lenses have been studied and the objective and the projector optical properties have been computed as well. The study reveals that these lenses have the electron optical properties different from that of the other lenses of the traditional design.

الخواص الالكترونية البصرية للعدسات الالكترونية المغناطيسية المدورة

الملخص

تم اقتراح خمسة أشكال لعدسات الكترونية مغناطيسية كل واحدة من هذه العدسـات تمتلـك دائـرة حديدية وملف ذي مقطع عرضي دائري الشكل. وقد تمت دراسة توزيـع كثافـة الفـيض المغناطيـسي المحوري ومسار خطوط الفيض المغناطيسي داخل تلك العدسات وكذلك تم احتساب الخـواص البـصرية الشيئية والمسقطية لتلك العدسات. وقد تبين من الدراسة ان تلك العدسات تمتلك خواص بصرية الكترونية مختلفة عن مثيلاتها من العدسات التقليدية.

INTRODUCTION

The extensive studies of the field of electron optics have been held to develop the magnetic electron lens geometry; so, many models of the magnetic electron lenses have been introduced. The aim of the work was to achieve the best lens model which provides a high quality image and the lower aberration coefficients. However, the low aberration of the magnetic electron lens required a higher flux density with a lower half width (Mulvey, 1982). For example, the symmetrical lens has been successfully adopted in almost high resolution electrons microscopes (Coselt et al., 1979). The design of the unconventional magnetic single polepiece lens, which was performed and presented by (Mulvey, 1982), brought a considerable improvement to the scanning of electron microscope. Zero bore single polepiece lens is the useful electron probe forming lens, this may be employed in various electron optical instrument (Juma, 1986). Superconducting lens presented as an objective lens to produce the high magnetic flux density at high values of the current density greater than 10^4 A/cm^2 (Septier and Bonjour, 1973). Iron-free lens also was introduced as an objective lens (Alamir, 1992) or as a projector lens

(Al-Hialey, 2005), this kind of lenses significantly have the low aberration coefficients at the high values of the current density.

Recently many studies emphasized that the geometrical shape of the coil has significant effect on the objective lens (Al-Abdullah, 1997) and on the projector lens (Al-Khashab, 2001), these studies demonstrate many models of the coil geometry and also determine their effect on the magnetization characteristics of the magnetic lenses. In this research work, the rounded cross section magnetic electron lenses were introduced as an objective and projector magnetic electron lens. The reason behind choosing this shape model is to get a highly uniform magnetic flux lines trajectory through the magnetic circuit of the lens. The axial magnetic flux density distribution, the magnetic flux lines trajectory, the objective and the projector properties are computed and compared for a set of the round magnetic lenses. The study and the calculation are handled with the aid of PC so that many computer programs are employed in order to understand the behaviour of the magnetic lens system.

DESIGN CONSIDERATION

Five types of the symmetrical double polepiece magnetic electron lenses have been designed. Each lens has round cross section of the iron circuit and the coil windings and posses different dimensions. Figure (1), shows the design model and the shape parameter of the symmetrical double polepiece magnetic round lens denoted by (L1). The choice of the favourable parameters for this lens was based on several published papers. The shape of the polepiece is in the form of truncated cone model (Wenxiong, 1988), the polepiece angle is taken equal to 63^{o} (Al-Khashab and Ahmed, 2004), the ratio of the air gap to the bore diameter (S/D) has been taken equal to one (Al-Khashab and Abbas, 1997). The radius of the lens (L1) is represented by two variable factors (a) and (b) both factors are equal to (80 mm) in the case of lens (L1). Figure (2), shows five of the symmetrical double polepiece round lenses denoted by (L1, L2, L3, L4 and L5) respectively. These lenses have the same parameters previously mentioned for the lens (L1) but each one of them has different values of (a) and (b) as shown in Figure(2) which are [a = (80, 100, 120, 60, 40) mm] and [b = (80, 60, 40, 100, 120) mm] respectively, so that all the round lenses have the same cross section area ($A = \pi [(a + b)/2]^2$) of both the iron circuit and the coil windings. The area of the energizing coil and the iron circuit (yoke) for each lens approximately equals to (4000 mm^2) and (16000 mm^2) respectively. It should be noticed that the total area of the iron circuit and the coil were maintained constant and equaling to (20000 mm^2).

THE MAGNETIC FLUX DENSITY AND THE MAGNETIC FLUX LINES TRAJECTORY

In order to demonstrate the performance of the previous lenses, the axial magnetic flux density distributions have been computed by the aid of program AMAG (Lencova', 1986), using the finite element method. The values of the axial magnetic flux density distribution of these lenses are computed at an excitation equal to (50 kA-t) is illustrated in Figure (3). It is clear that the lens (L4) acquires the highest peak value of the axial magnetic flux density distribution followed by the lens (L2). Moreover, the lens (L3) acquires the lowest peak value of the axial magnetic flux density distribution.

In order to study the magnetization characteristics of the previous lenses, the magnetic flux lines trajectory are computed by the aid of FLUX program (Munro, 1975). Figure (4 and 5), show the magnetic flux lines trajectories through the iron circuit of the previous lenses calculated at NI = 50 kA-t. From these figures, the lines trajectories take the highly uniform distribution shapes inside the round magnetic electron lenses and this fact gives this type of lenses an advantage of improving their optical properties. In the case of the lens (L4) and (L5) there is a magnetic stray leakage (in different degrees) out of the yoke of the lens structure; this means that the thin iron shell in both sides of the lenses makes the flux lines spread from the polepiece region are pushed outside the yoke region. It should be mentioned that all the lenses have the same amount of the iron materials.

THE OBJECTIVE PROPERTIES

The objective focal properties and the resolving power of the previous lenses are calculated by the aid of Munro program (Munro, 1975), at constant accelerating voltage (V_a=2 MV) where V_a is calculated from the relation [$V_r = V_a (1 + 10^{-6} V_a)$] and V_r is the relativistically corrected accelerating voltage in volts. The values of the spherical aberration coefficient (C_s), chromatic aberration coefficient (C_c), the objective focal length (f_o) and the resolving power (δ_p) of these lenses shown in Figure (2), are compared as a function of the current density (σ) as indicated in Figure (6). This figure shows that the lenses (L1), (L2) and (L4) have acquired the lower values of (C_s), (C_c), (f_o) and (δ_p) over a whole range of (σ) in comparison with the other round magnetic lenses and the values of C_s dose not exceed over (2.7 mm) in all the ranges of (σ) values and that once again give the round magnetic lenses another operational advantages as an objective lens in comparison with the other type of lenses.

THE PROJECTOR PROPERTIES

The most important electron optical properties of the final projector lens in an electron microscope are its shorter focal lengths. The final projector lens is usually operated in the region of the minimum projector focal length for obtained a maximum image of the magnification.

The projector electron optical properties of the previous lenses are calculated by the aid of PROJECTOR program (Marai and Mulvey, 1976). Figure (7), shows a comparison of the previous lenses between the values of the projector focal length (f_p), the radial distortion (D_{rd}) and the spiral distortion (D_{sp}) as a function of the excitation parameter ($NI/\sqrt{Vr}$) at constant excitation (NI =5 kA-t). It should be noticed from Figure (7a), that the previous lenses have approximately the same minimum value of the projector focal length (f_{pmin}) at the same corresponding value of the excitation parameter (14 $A\text{-}t/V^{1/2}$) where ($f_{pmin} \approx 2$ mm). Figures (7b), shows that the lens (L2) acquired the minimum values of radial distortion. Figures (7c), shows that the lens (L3) acquired the minimum values of spiral distortion.

LENSES PERFORMANCE

Table (1) shows a comparison between the spherical aberration coefficients (C_s) of the symmetrical magnetic objective lenses studied by the present research work L1, L2 and L3 with those of the identical objective lenses studied by other researchers, T (Tahir, 1985), Y (Yin and Mulvey, 1987), A2 (Al-Khashab and Al-Khashab, 1997), A3 (Al-Abdullah, 1997), as well as with the iron-free magnetic electron lens A1 (Alamir, 1992), the spherical aberration coefficients of these lenses have been presented as a function of the current density (σ) at constant accelerating voltage (V_a = 2 MV). This table shows that the magnetic round lenses L1, L2 and L4 have relatively the lowest values of (C_s) especially at the low and medium values of (σ). It should be mentioned that the performance of the magnetic lenses at the low values of (σ) essentially depends on the geometrical shape of the iron contour.

Table 1:Comparison between C_s values of the magnetic objective lenses L1, L2, L4, T, Y, A1, A2 and A3 at constant accelerating voltage V_a= 2 MV.

σ A-t /cm²	**C_s (mm)**							
	L1	**L2**	**L4**	**T**	**Y**	**A1**	**A2**	**A3**
10^2	1.9	1.9	1.9	100.0	10.0	28.0	7.0	4.5
10^3	1.9	1.4	1.3	20.0	3.0	10.0	2.9	2.1
10^4	1.8	2.4	2.2	2.5	1.5	3.0	1.8	1.8
10^5	1.1	1.2	1.6	1.0	0.8	1.0	1.8	1.8

Table (2) shows the comparison between the (f_{pmin}) values and the excitation parameter ($NI/\sqrt{Vr}$) of the symmetrical magnetic objective lenses studied in the present research work L1, L2, L3, L4 and L5 with those of the identical projector lenses studied by other researchers, K1 (Al-Hilly and Mulvey, 1982), K2 (Al-Saady, 1990), K3 (Ahmad, 1998), K4 (Mohammed, 1999), K5 (Al-Khashab and Ahmad, 2004), presented at constant excitation (NI = 2 kA-t). This table shows that the lens (L2) acquired the lowest value of the projector focal length among the other lenses.

Table 2: Comparison between f_{pmin} values of the magnetic projector lenses L1, L2, L3, L4, L5, K1, K2, K3,K4 and K5 at constant excitation NI = 2 kA-t.

Lens	$NI/\sqrt{Vr}$ $(A\text{-}t/V^{1/2})$	**f_{pmin} (mm)**
L1	13	1.3
L2	13	1.2
L3	13	1.3
L4	13	1.5
L5	13	1.3
K1	12	2.3
K2	13	3.5
K3	13	1.4
K4	13	1.4
K5	13	1.4

CONCLUSIONS

A new type of the magnetic electron lenses has been introduced of the round cross section. It has been found from this investigation that the round magnetic lens produce a relatively high peak value of the axial magnetic flux density distribution and the uniform magnetic flux lines trajectories. Furthermore, it has a relatively very low objective focal properties and projector distortion values. This kind of lenses can be used as an objective or projector lens in transmission electron microscope.

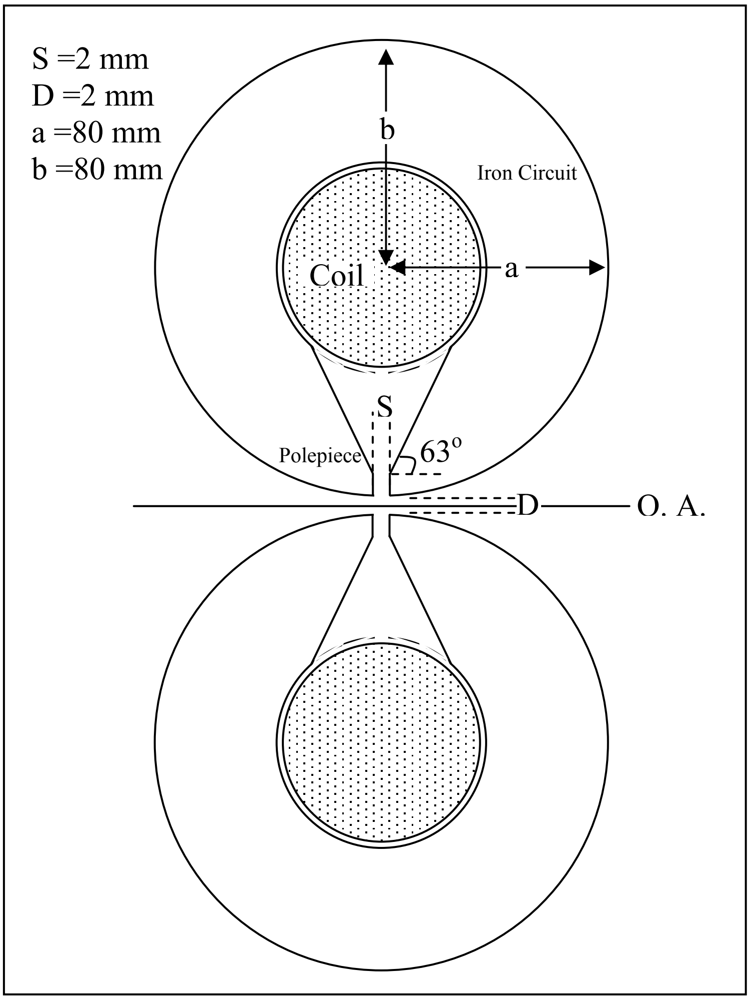
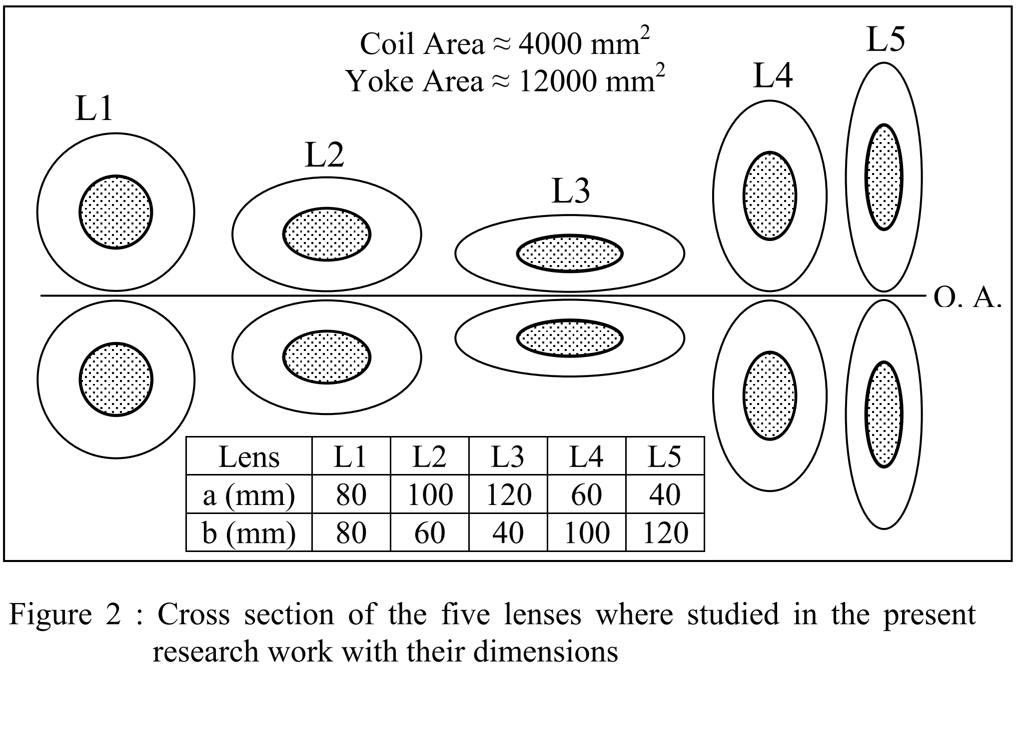


Figure 1: Cross section of the round magnetic electron lens L1 and its dimensions



Lens	L1	L2	L3	L4	L5
a (mm)	80	100	120	60	40
b (mm)	80	60	40	100	120

Figure 2 : Cross section of the five lenses where studied in the present research work with their dimensions

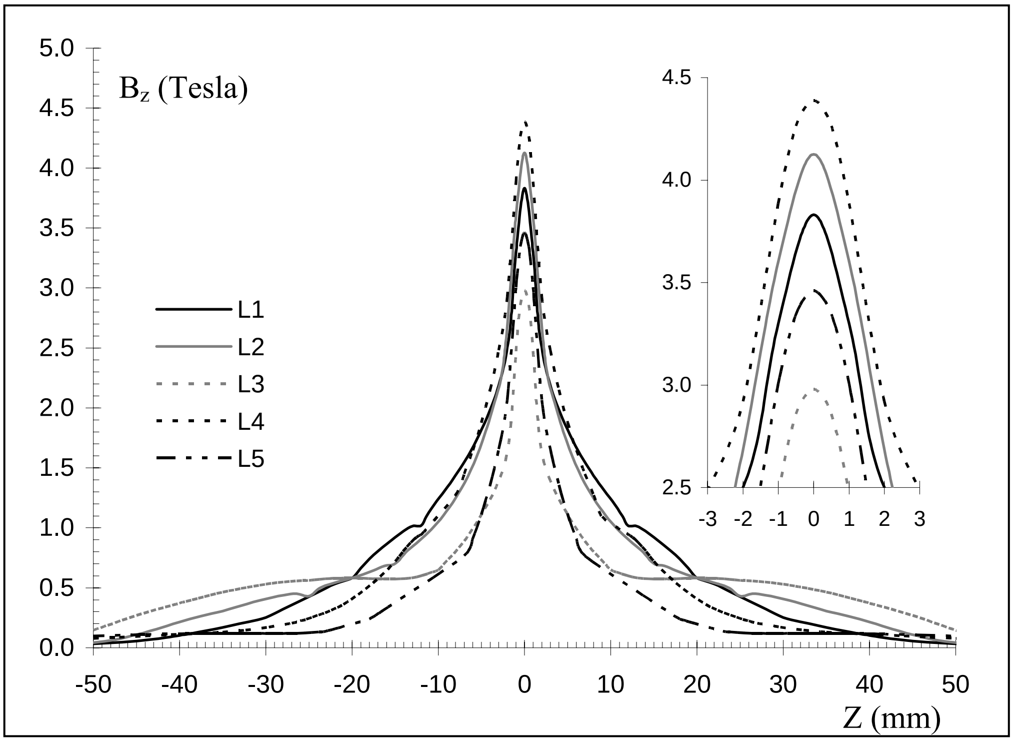


Figure 3 : The axial magnetic flux density distribution B_z of the lenses L1, L2, L3, L4 and L5 as a function of the axial distance Z at constant excitation NI=50 kA-t.

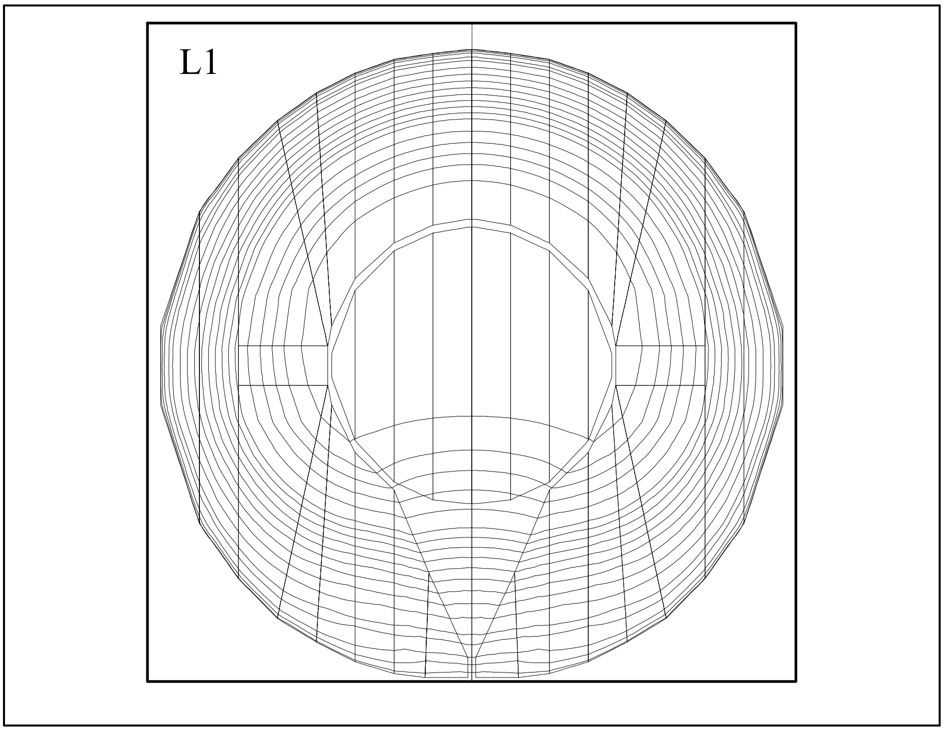


Figure 4 : The magnetic flux lines trajectories through the magnetic circuit of the lens L1 calculated at constant NI=50 kA-t

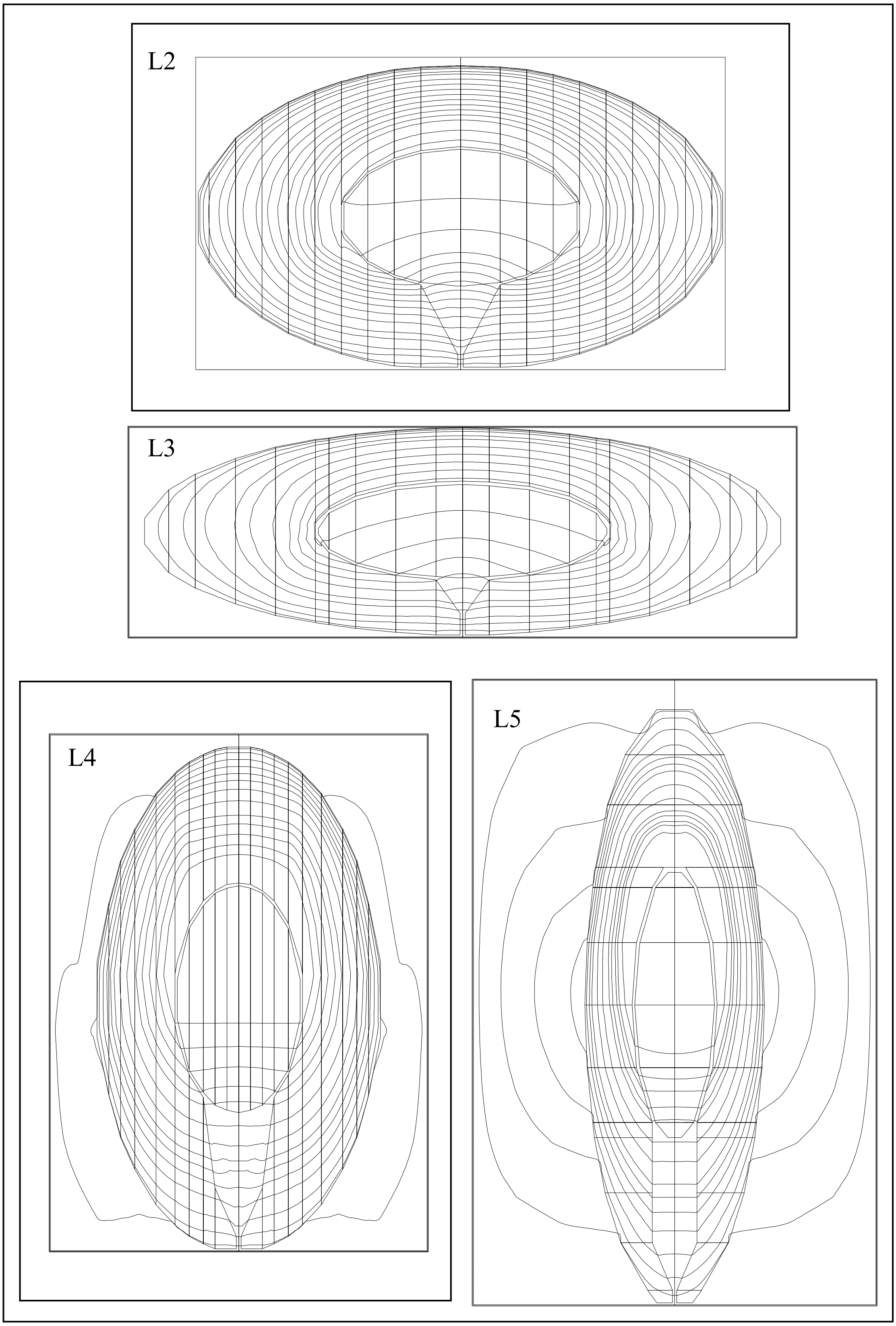


Figure 5 : The magnetic flux Lines trajectories through the magnetic circuit of the lenses L2, L3, L4 and L5 at constant NI = 50 kA-t.

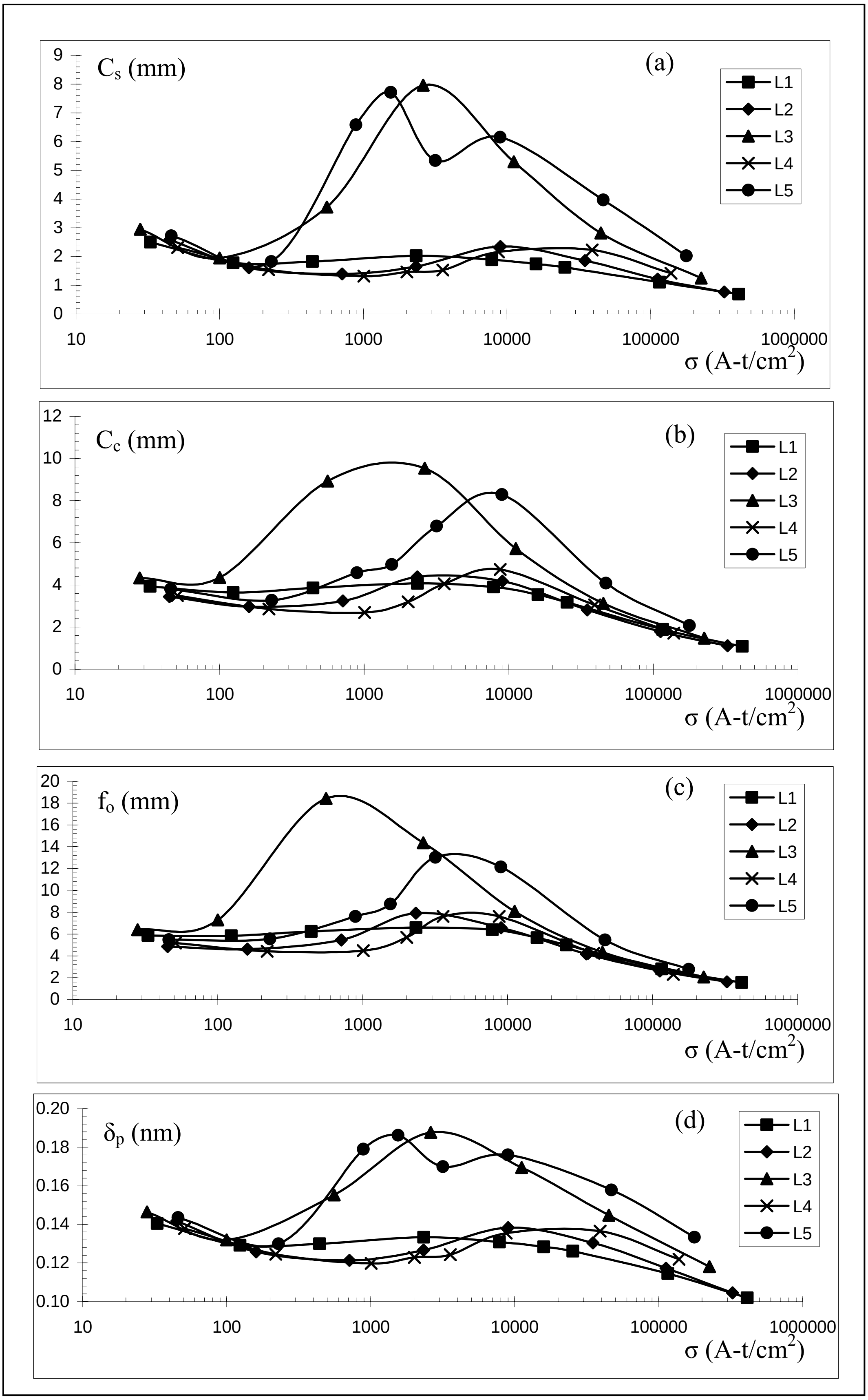


Figure 6 : The objective focal properties and the resolving power of the lenses L1, L2, L3, L4 and L5 as a function of the current density scaled at constant accelerating voltage $V_a = 2$ MV.

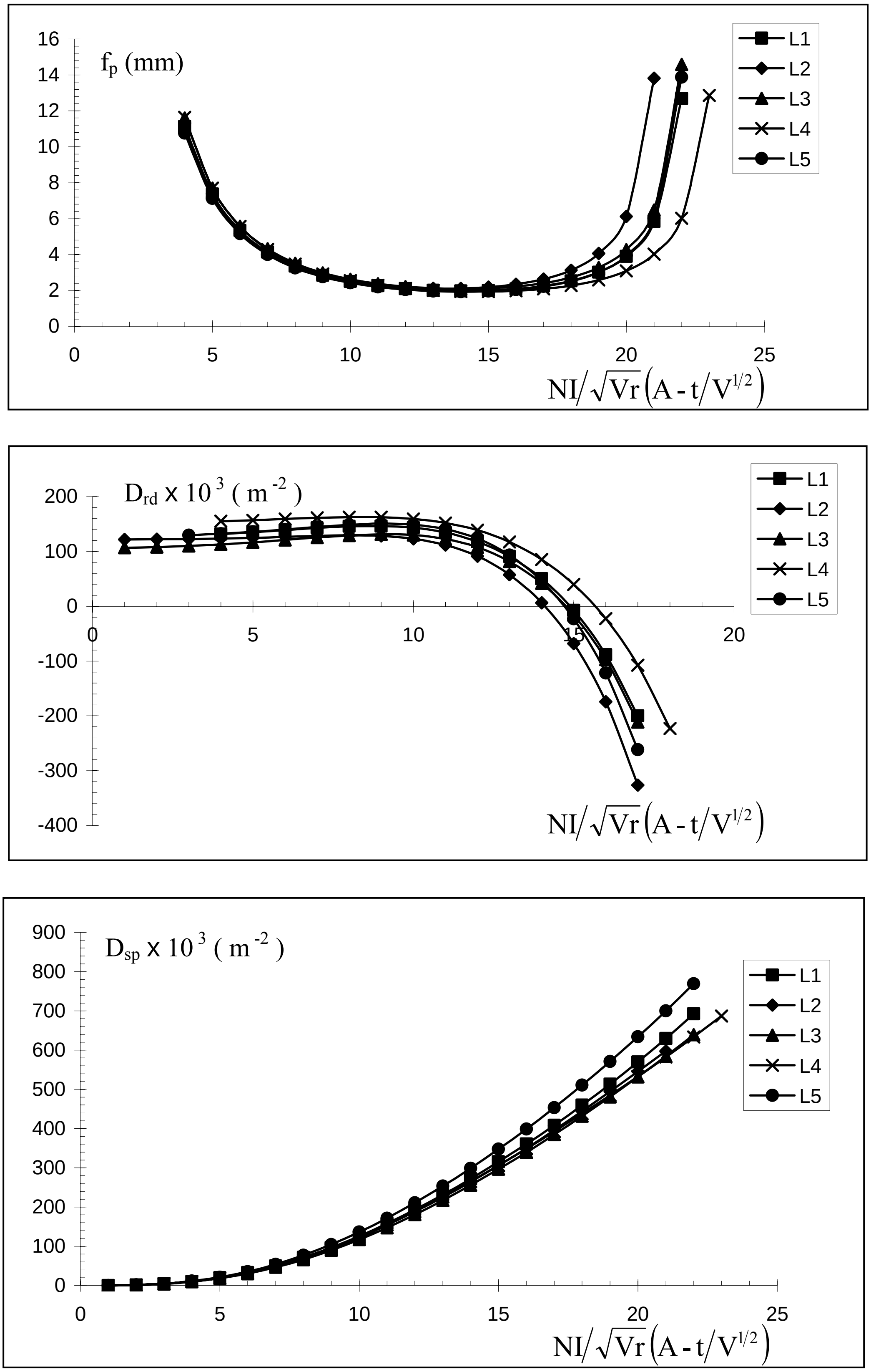


Figure 7 : Comparison between f_p, D_{rd} and D_{sp} of the lenses L1, L2, L3, L4 and L5 as a function of the excitation parameter at NI=5 kA-t

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