# The Magnetization of the Single Polepiece Magnetic Electron Lens Using Different Coil Models

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(Received 1/12/2005 , Accepted 27/2/2006)

## ABSTRACT

New models of coil geometry are proposed to energize the single polepiece magnetic electron lens. Systematic studies have been applied to determine the magnetic and optical properties for a set of the lenses of identical parameters but each one is energized by different coil geometry. It has been found that the selection of the proper type of the coil geometry improves the performance of the magnetic single polepiece lens for equal value of the current density.

# التمغنط في العدسة الالكترونية المغناطيسية أحادية القطب باستخدام نماذج الملفات

## الملخص

تم اقتراح اشكال هندسية جديدة من الملفات لتهييج العدسات المغناطيسية الالكترونية أحادية القطب. أجريت عدة دراسات نظرية لحساب الخواص البصرية والمغناطيسية لمجموعة من العدسات متماثلة الأبعاد الهندسية وتمت مغنطة كل عدسة بملف ذي شكل هندسي مختلف مع مراعاة ظروف التشغيل الأولية. تبين من هذه الدراسات ان اختيار الشكل المناسب للملف يحسن من أداء العدسات الالكترونية المغناطيسية أحادية القطب عند قيمة ثابتة من كثافة التيار.

## INTRODUCTION

The optimum design of the magnetic electron lens with low aberration coefficients is of a considerable interest in various field of electron optics. The consideration has been basically concentrated on the reduction of the aberrations values as much as possible to form a high quality image. However, low aberration magnetic electron lens has been found to require a high flux density with low half width (Mulvey, 1982). Intensive studies have been rigorously carried out to optimize the geometrical structure and the dimensions of the magnetic electron lens. The optimization of the polepiece shape of an asymmetrical single polepiece lens was demonstrated by (Al-Khashab and Abbas, 1991). The effect of axial bore angle and polepiece angle on the objective focal properties was demonstrated by (Al-Khashab and Al-Obaidy, 2000). The shape and the position of the iron shroud of the single polepiece lens were studied by (Al-Abdullah, 1997), in which the flux leakage in the single polepiece lens was avoided by letting the magnetic iron shroud geometry have a form of conical shape. The influence of the shape and position of the coil geometry on the projector properties of the symmetrical double polepiece lens and asymmetrical single polepiece lens are studied by (Al-Khashab, 2001).

This paper is mainly concerned with the magnetization effects of the polepiece and the iron circuit of the single polepiece magnetic electron lens by using the different coil geometries, so that the new types of coil geometries (have not been suggested previously) were introduced to energize the single polepiece lens. The importance of the optimization of the coil geometry is mainly due to the fact that the performance of the lens at the high flux density values is mainly due to the contribution of the flux issuing from the coil only.

Accordingly, we shall assume the new models of coil geometry to energize the single polepiece magnetic electron lens, which are to be used as objective lens in the transmission electron microscope. The properties of the new coil models are compared with that of the other model having a traditional coil geometry (rectangular cross section) at the same saturation condition.

The investigation has required extensive calculations based on several physical and mathematical concepts. The design work and the calculation are accordingly handled with the aid of personal computer, so that many computer programs are being employed in order to understand the behaviour of the magnetic electron system. A technique for calculating the magnetic flux lines due to the effect of coil geometry on the single polepiece magnetic electron lens is also presented. Each shape is illustrated by a typical computer result on graphical screen.

## DESIGN CONSIDERATION

Four types of the asymmetrical single polepiece magnetic electron lenses have been designed with identical geometrical parameters of the iron circuit and the polepiece region, energized by different coil geometries. Figure (1), shows the schematic diagram of the cross section and the geometrical dimensions of the iron circuit and the polepiece region of the lens denoted by (L1) energized by a coil of traditional rectangular cross section. Figure (2), shows the cross section of the four types of coil shape and its geometrical dimensions. Each one is of the same cross section of area equals (480 $mm^2$). These coils are denoted by C1, C2, C3 and C4, is proposed to energize the lenses denoted by L1, L2, L3 and L4, respectively. The choice of the favourable parameter of these lenses was based on several published papers. The shape of the polepiece is in the form of truncated cone model (Wenxiong, 1988), the polepiece and the axial bore angles are taken equal to $60^o$ and $10^o$ respectively (Al-Obaidy, 1996), the polepiece bore diameter equals 2 mm (Al-Khashab and Abbas, 1997).

In order to demonstrate the performance of the above lenses energized by different coil geometries and compare their efficiency, the axial magnetic flux density distributions have been computed by the aid of AMAG program (Lencova', 1986), using the finite element method. Figure (3), shows the values of the axial magnetic field profile calculated at constant excitations (10 kA-t) and (100 kA-t). It is clear that the lens (L4) acquired the highest value of the magnetic flux density peak ($B_m$) at the low excitation (10 kA-t), while the lens (L2) acquired the highest value of ($B_m$) at the high excitation (100 kA-t).

At any point on the lens axis the axial magnetic flux density ($B_z$) is the sum of the flux density due to the energizing coil ($B_c$) plus the flux density due to the iron magnetization ($B_{Fe}$), thus, the magnetization of the iron circuit can be obtained from the relation ($B_{Fe} = B_z - B_c$). The variation of the peak flux density due to the iron magnetization ($B_{Fe}$) are plotted against a wide range of the lens excitations (NI) as shown in Figure (4). From this figure, it can be seen that the coil of conical shape (C4) has donated a better magnetization to the lens (L4) at the low values of the excitations ($NI < 30$ kA-t) while the coil of the thick ends (C2) has donated a better magnetization to the lens (L2) at the high values of the excitations ($NI > 150$ kA-t). So we can conclude that the goodness of coil (C2) appears at the high values of the excitations i.e. when the lens is saturated, while the coil (C4) gives a better magnetization at the low values of the excitations i.e. when the lens is unsaturated.

In order to investigate the performance of the above coils on the lenses it is important to compute the magnetic flux lines trajectories inside the structure of these lenses.

The magnetic flux lines trajectories of the previous lenses are calculated by the aid of program FLUX (Munro, 1975), which is modified by (Murad, 1998), using the magnetic flux density values at each mesh point as input data at constant excitation (NI=100 kA-t) as illustrated in Figure (5); It is seen from this figure that the coil of the thick ends (C2) concentrates the magnetic flux lines near the polepiece region better than those of the traditional rectangular coil (C1) and the thin ends coil (C3). Moreover, the coil of conical shape (C4) concentrates the magnetic flux lines inside the lens toward the back plate.

Before a commitment is made as to which one of the lenses is the most suitable, the objective focal properties must be investigated.

## THE OBJECTIVE FOCAL PROPERTIES

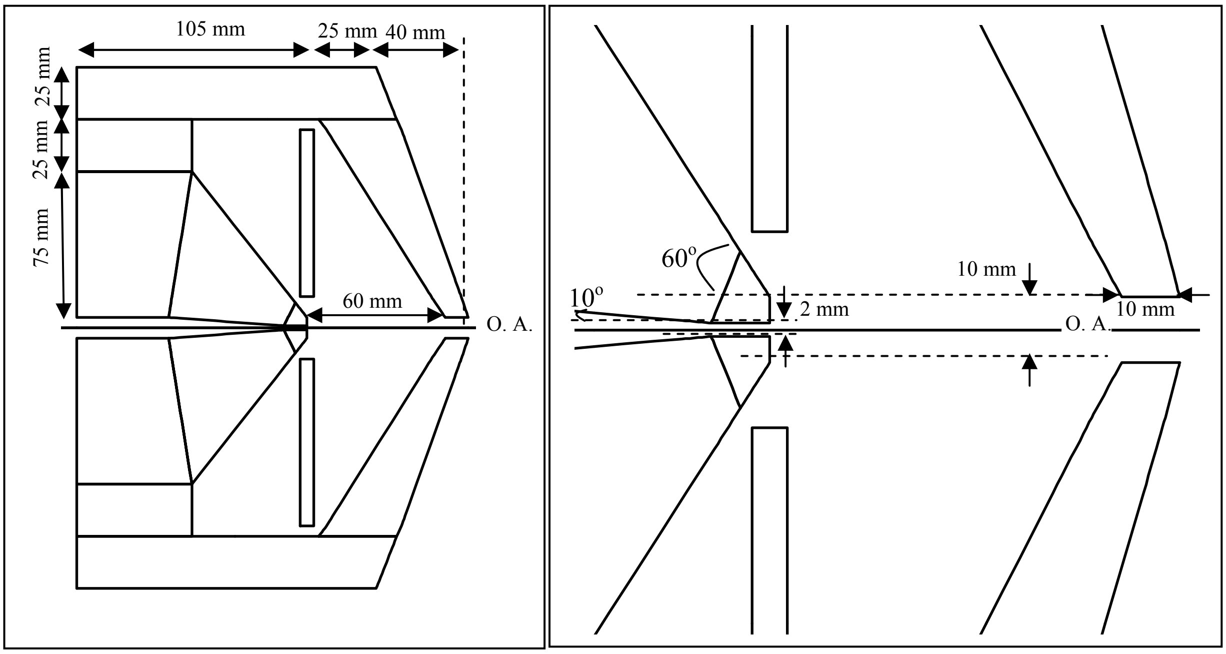
In order to evaluate the effect of the coil geometry on the electron optical properties of the previous lenses, the objective focal properties and the resolving power have been calculated by the aid of Munro program (Munro, 1975), at constant accelerating voltage ($V_a = 2$ MV) where ($V_a$) was calculated from the relation [$V_r = V_a\ (1 + (e/2mc^2)\ V_a)$] and ($V_r$) is the relativistically corrected accelerating voltage in volts. The study has been applied in the two directions of operation, first: in the Ray 1 direction of operation (the incident electron beam facing the back plate), second: in the Ray 2 direction of operation (the incident electron beam facing the polepiece).

Figure (6), shows a comparison between the objective focal properties values, the spherical aberration coefficient ($C_s$), the chromatic aberration coefficient ($C_c$), the objective focal length ($f_o$) and the resolving power ($\delta_p$) of the lenses L1, L2, L3 and L4 against the current density ($\sigma$) calculated at constant accelerating voltage ($V_a$=2 MV) for Ray 1 direction of operation; This figure shows that there is a cross over point of the curves at ($\sigma \approx 10^4$ A-t/cm$^2$ ), when ($\sigma < 10^4$ A-t/cm$^2$) the lens (L4) obtained the lower values of $C_s$, $C_c$, $f_o$ and $\delta_p$ while at ($\sigma > 10^4$ A-t/cm$^2$) the lens (L2) acquired the lower values of $C_s$, $C_c$, $f_o$ and $\delta_p$.

Figure (7), shows a comparison between the objective focal properties and the resolving power ($C_s$, $C_c$, $f_o$ and $\delta_p$) of the previous lenses against the current density ($\sigma$) calculated at constant accelerating voltage ($V_a$= 2 MV) for Ray 2 direction of operation, this figure shows that the lens (L4) acquired the lowest values of the objective focal properties and the resolving power for the whole range of the current density in comparison with that of the other lenses and this is due to the coil of conical shape (C4) which shifted the magnetic flux lines toward the back plate of the lens (see Figure 5), so that, the electron beam will face magnetic flux density distribution of the thinner part of the half width (as given in Figure 3).

## CONCLUSIONS

In the present investigation, we have developed a new coil models as it has been found that the coil geometry has a very important effect on the magnetization characteristics of the single polepiece magnetic electron lens and consequently on its objective focal properties. Therefore, the single polepiece magnetic electron lenses energized by a new coil model are found to be of a better performance than those of the other single polepiece magnetic electron lenses energized by a conventional one under the same operation conditions.



( a ) Lens L1

( b ) Polepiece Region

Figure 1: Schematic diagram and the geometrical dimensions of the cross section of (a): The lens L1; (b): Magnified part of the polepiece region.

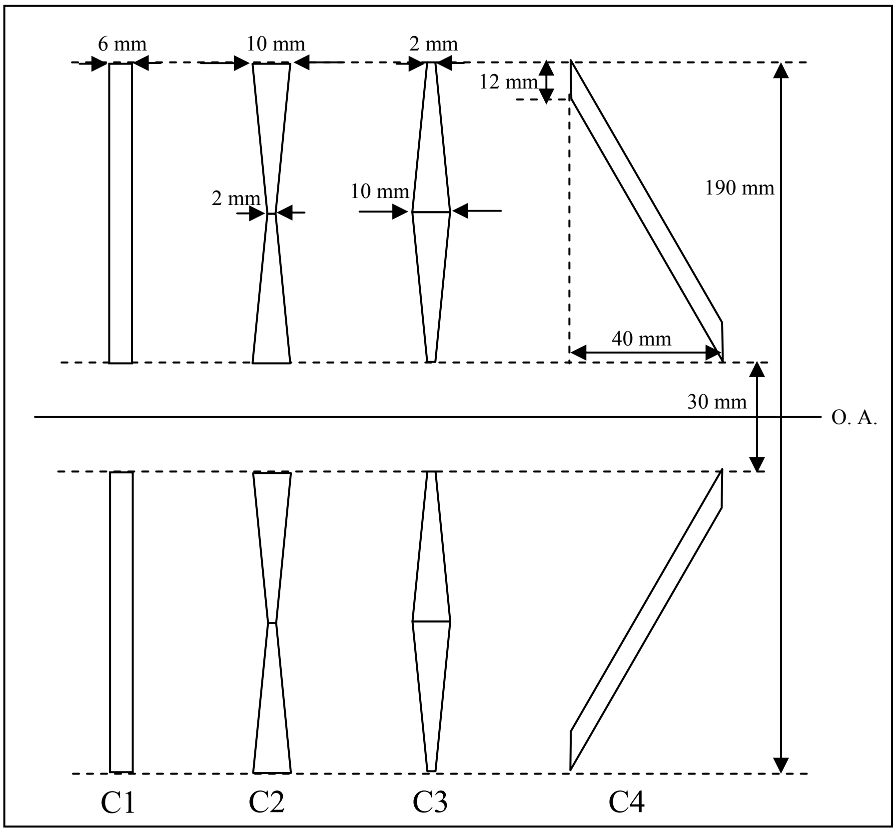


Figure 2 : Schematic diagram of the cross section and the geometrical dimensions of the four coils (C1, C2, C3 and C4) having the same area ($A = 480\ mm^2$ ).

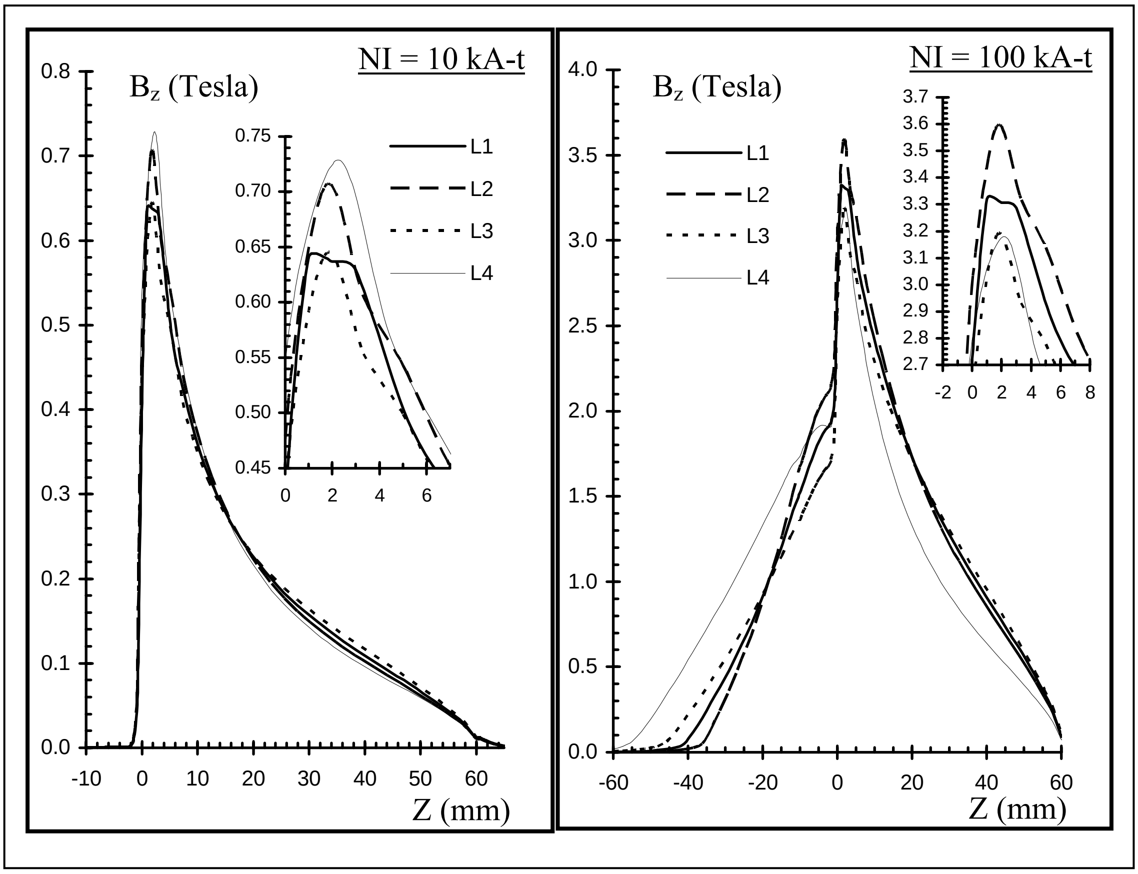


Figure 3: Comparison between the axial magnetic flux density distribution of the lenses L1, L2, L3 and L4 with magnified part of the peaks region calculated at NI = 10 kA-t and 100 kA-t.

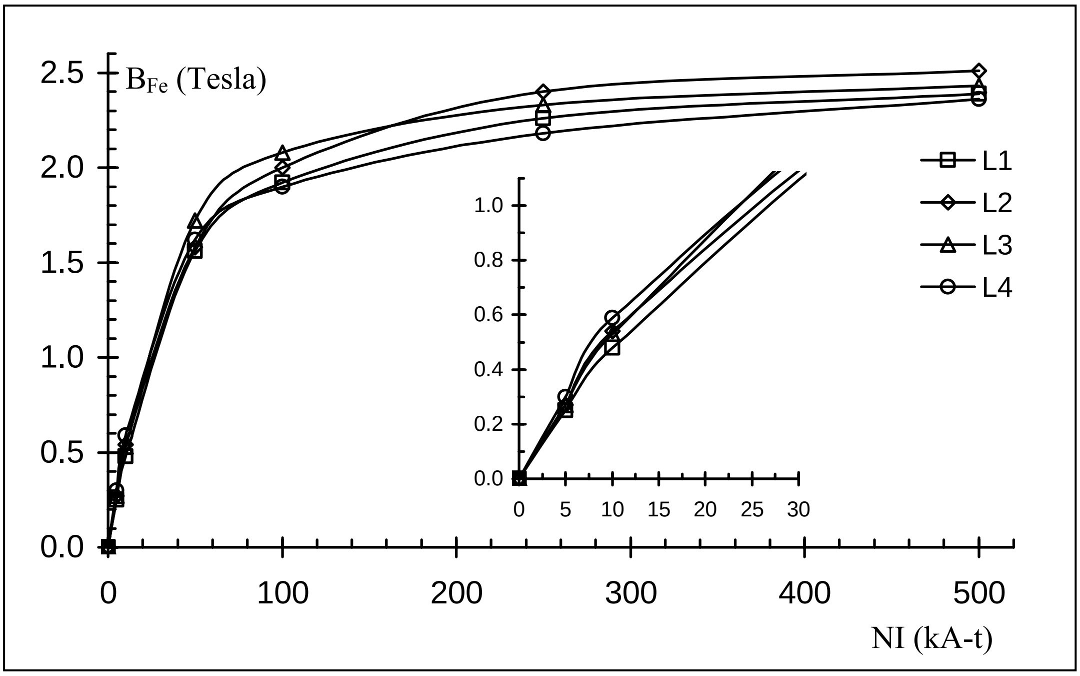


Figure 4: The iron magnetization ($B_{Fe}$) of the lenses L1, L2, L3 and L4 at different excitations (NI) with magnified part of the low values of NI

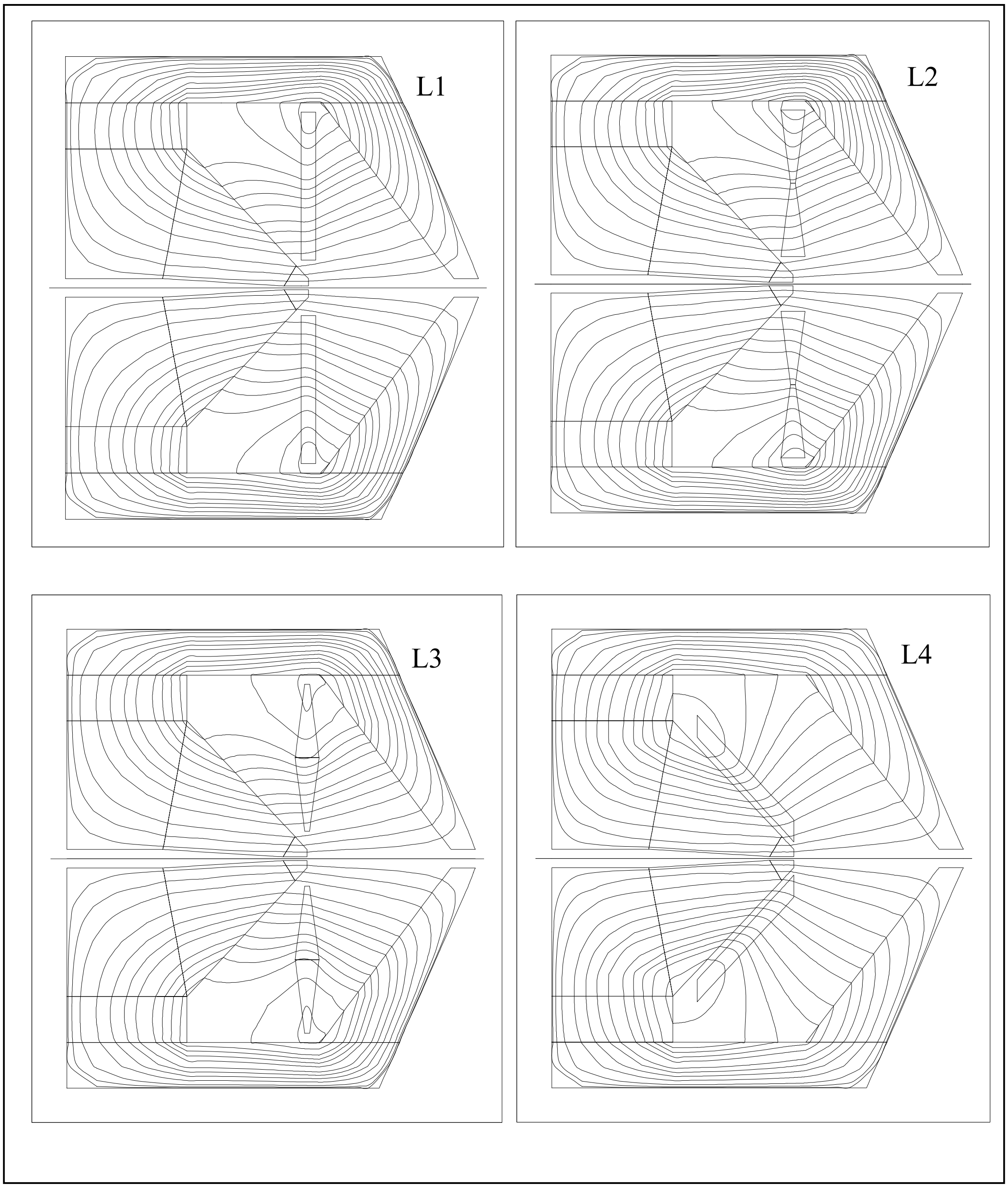


Figure 5: The magnetic flux lines trajectories of the lenses L1, L2, L3 and L4 calculated at (NI=100 kA-t).

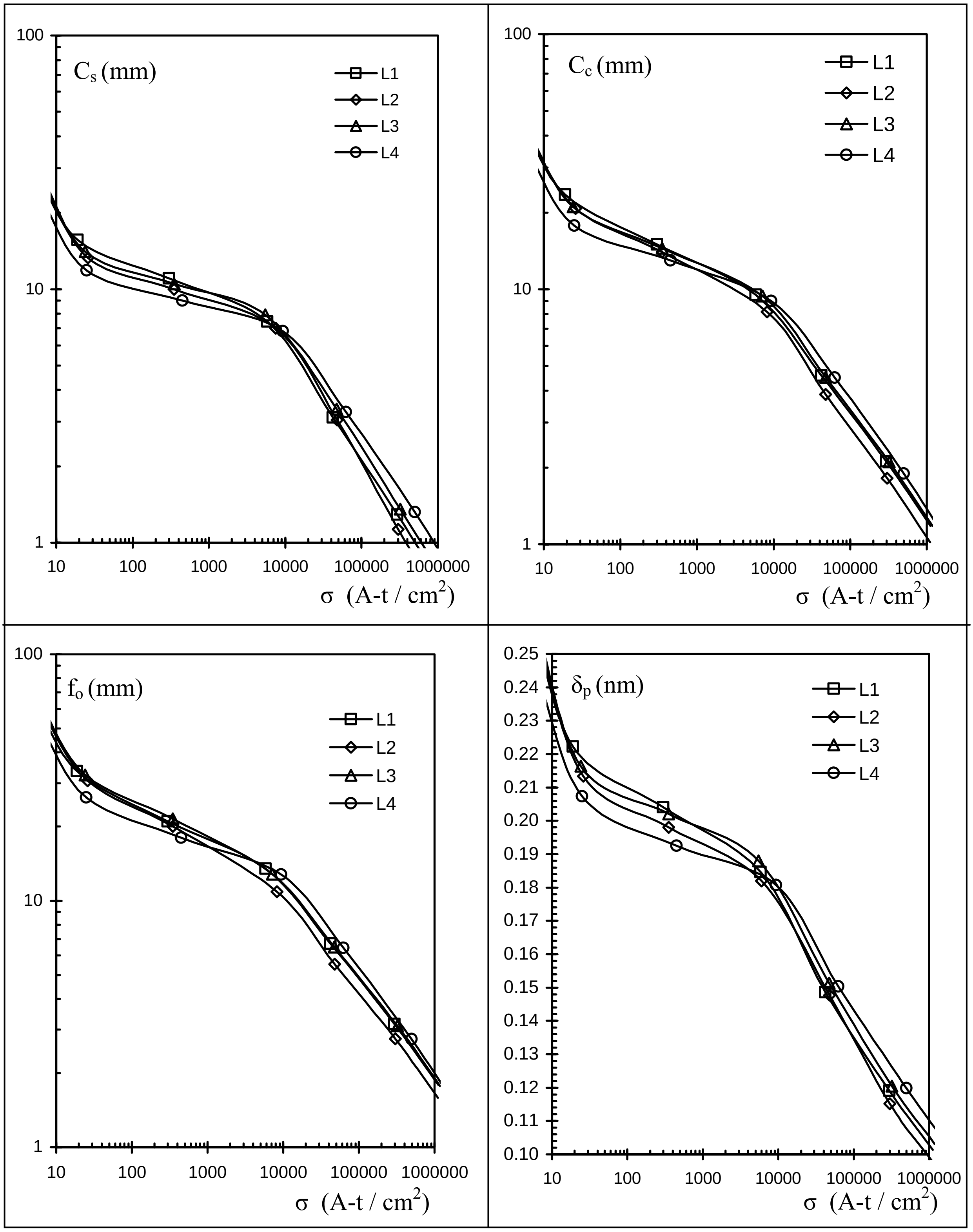


Figure 6: Comparison between the objective focal properties $C_s$, $C_c$ and $f_o$ and the resolving power $\delta_p$ of the lenses L1, L2, L3 and L4 against the current density $\sigma$ for Ray 1 direction , at constant $V_a$=2 MV.

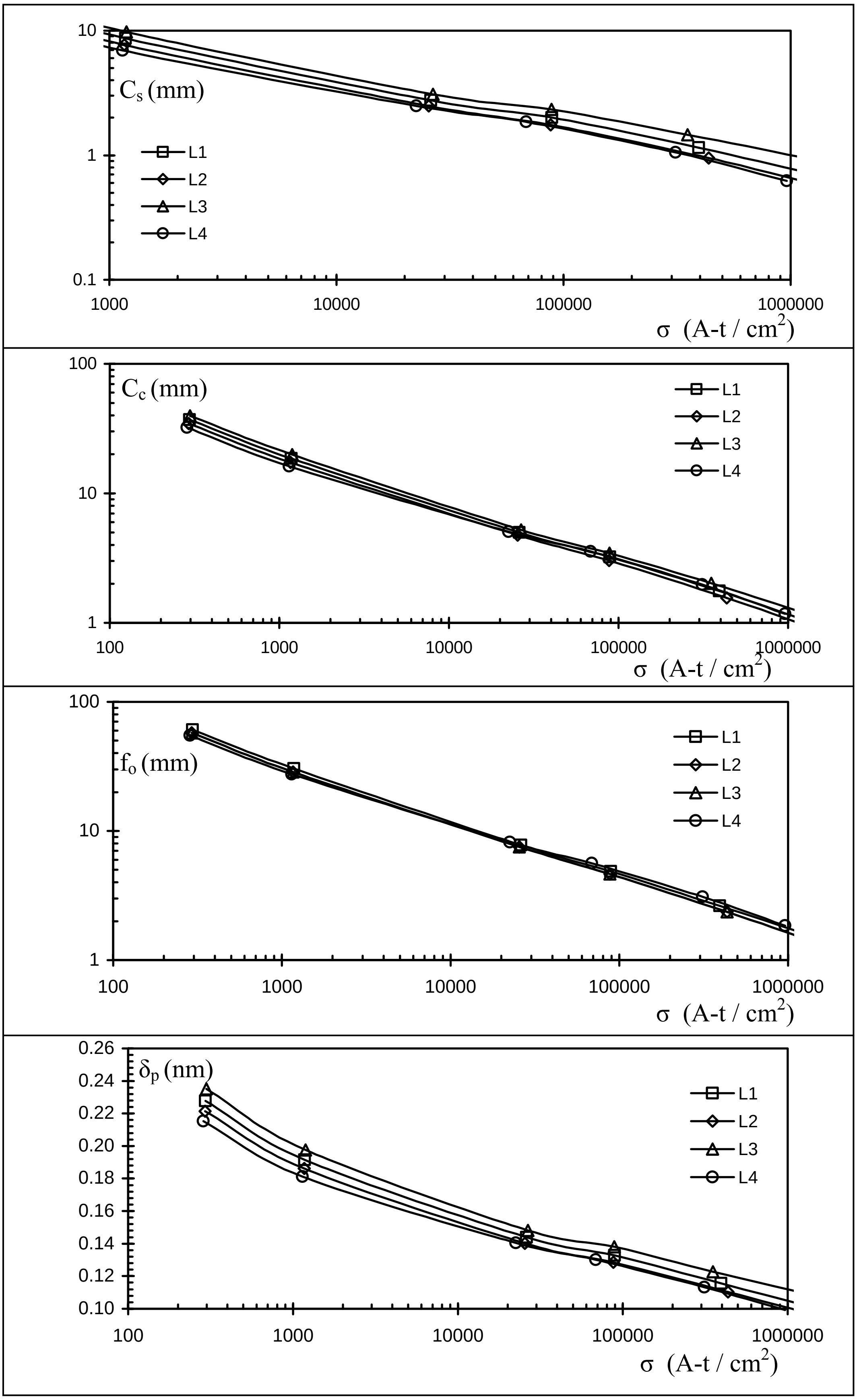


Figure 7: Comparison between the objective focal properties $C_s$, $C_c$ and $f_o$ and the resolving power $\delta_p$ of the lenses L1, L2, L3 and L4 against the current density σ for Ray 2 direction, at constant $V_a = 2$ MV.

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