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Study the negative spherical aberration coefficients for the magnetic lens

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ABSTRACT

A theoretical investigation has been carried out to study the optical properties of a magnetic lens with the aid of analytical method. An analytical expression for paraxial trajectory of an electron in a magnetic lens is used to reach to the negative values of the spherical aberration coefficient. The Glaser's bell-shaped model is adopted to represent the axial flux density distribution of the magnetic lens. The optimization role is achieved by changes some of the effective parameters as the half-width at half maximum (a = 2.01, 2.02, 2.03 and 2.04 mm) and the maximum magnetic flux density (B_m = 0.001, 0.002, 0.003 and 0.004 Tesla). The calculations appear that the values of the negative spherical aberration coefficient are found and these coefficients are very senestive to these effective parameters and one can use this design of the magnetic lens as corrector in the optical systems.

Keywords: Magnetic Lens, Negative Spherical Aberration Coefficient, Glase, Bell – Shaped Model.

INTRODUCTION

Aberration correction is the long story of many seemingly fruitless efforts to improve the resolution of electron microscopes by compensating for the unavoidable resolution-limiting aberrations of round electron lenses over a period of 50 years. The successful breakthrough, in 1997, can be considered as a quantum step in electron microscopy because it provides a genuine atomic resolution approaching the size of the radius of the hydrogen atom. The additional realization of monochromators, aberration-free imaging energy filters and spectrometers has been leading to a new generation of analytical electron microscopes providing elemental and electronic information about the object on an atomic scale [1].

The availability of spherical aberration (C_s) correction has opened up a large field of applied material research for high-resolution transmission electron microscopy (HRTEM). The first application of spherical aberration (C_s) corrected electron microscopy aimed at the minimization of previously unavoidable contrast delocalization artifacts by employing a spherical aberration (C_s) value close to zero [2].

In a further step, optimum imaging conditions were derived based on the tenability of the spherical aberration, which provide minimum contrast delocalization and maximum phase contrast at the same time[3]. Under such optimized conditions the point resolution is extended up to the information limit of the instrument. A third decisive step on the way to modern aberration-corrected electron microscopy was the finding that an unusually high image contrast is obtained when employing a negative value of the spherical aberration in conjunction with an over focus[4]. The related negative spherical aberration imaging (NCSI) mode yields a negative phase contrast of atomic objects, with atomic columns appearing bright against a darker background. For thin objects, the novel NCSI mode leads to a substantially higher contrast compared to the dark atom images formed under the traditional positive spherical aberration imaging (PCSI) mode (positive phase contrast) [5]. The benefit of the negative-spherical-aberration imaging technique is used to correct the aberration transmission electron microscopy to reach a high-resolution transmission electron microscope (HRTEM). Where the spherical aberration C_s was be tuned to negative values, resulting in a novel imaging technique, which is called the negative spherical aberration coefficients C_s imaging (NCSI) technique [6].

The high resolution transmission electron microscope which is depending on negative spherical aberration coefficient imaging (NCSI) open wide range of the different applications [7, 8, 5].

The aim of the present work is studying the negative spherical aberration coefficients of magnetic lens using analytical method, where this magnetic lens can be used as corrector in the optical systems. The analytical method is used to study the optical properties of magnetic lens; the axial flux density distribution is represented by Glaser's bell-shaped model which gives rise to the optimum spherical aberration coefficients. The optimization calculation is achieved via changing some parameters as the maximum magnetic flux density and the half-width at the half maximum.

The Trajectory Equation

The paraxial–ray equation of an electron in a magnetic field of axial symmetry is given by [9]:

$$r'' + \frac{e}{8mV_r} B^2(z)\, r = 0 \tag{1}$$

where B(z) is the magnetic flux density distribution, r(z) is the radial displacement of the beam from the optical axis z, e is the charge of the electron, m is the mass of the electron and V_r is the relativistically corrected accelerating voltage which is given by [9]:

$$V_r = V_a (1 + 0.978\times10^{-6} V_a) \tag{2}$$

where V_a is the accelerating voltage.

The solution of the paraxial – ray equation (eq. 1) is given by [10]:

$$r_b(z) = r_o \left[u_2{}^2 + \sqrt{\frac{e}{8m\,V_r}}\, B(z_o)^2\, u_1{}^2 \right]^{1/2} \tag{3}$$

Since r_o is the object point and for the trajectory of an electron starting from the specimen go through the magnetic lens described by Glaser's bell-shaped field distribution the parameters u_1 and u_2 have the following form [10]:

$$u_1 = \frac{-a}{w} \sin\left[w(\phi - \phi_o)\right] \sin(\phi_o) \sin(\phi) \quad (4) \qquad u_2 = \frac{\sin(\phi_o)\sin\left[w(\phi-\phi_o)\right]}{\sin\phi} \sin\left[w(\phi-\phi_o)\right] \quad (5)$$

and

$$z = \cot\phi \quad , \quad z_o = \cot\phi_o \tag{6}$$

The electron beam trajectory along the magnetic lens is computed for different values of the half width at half maximum (*a* = 2.01, 2.02, 2.03 and 2.04 mm) by using (eq. 3) and the results are shown in figure (1). The computations appear that when the values of the half width at half maximum (a) increase the electron beam trajectory becomes more smooth , i.e. the fluctuation between the upper and lower values of the displacement from the optical axis reduce. The variation in the upper and lower values of r_b/r_o of the trajectory for whole range of the relative optical path *z/a* is small when the values of the half-width at half maximum (*a*) are high. In general the results of the present work illustrated in figure (1) has the same behaviour as the results in the work of Melnikov and Potapkin [10].

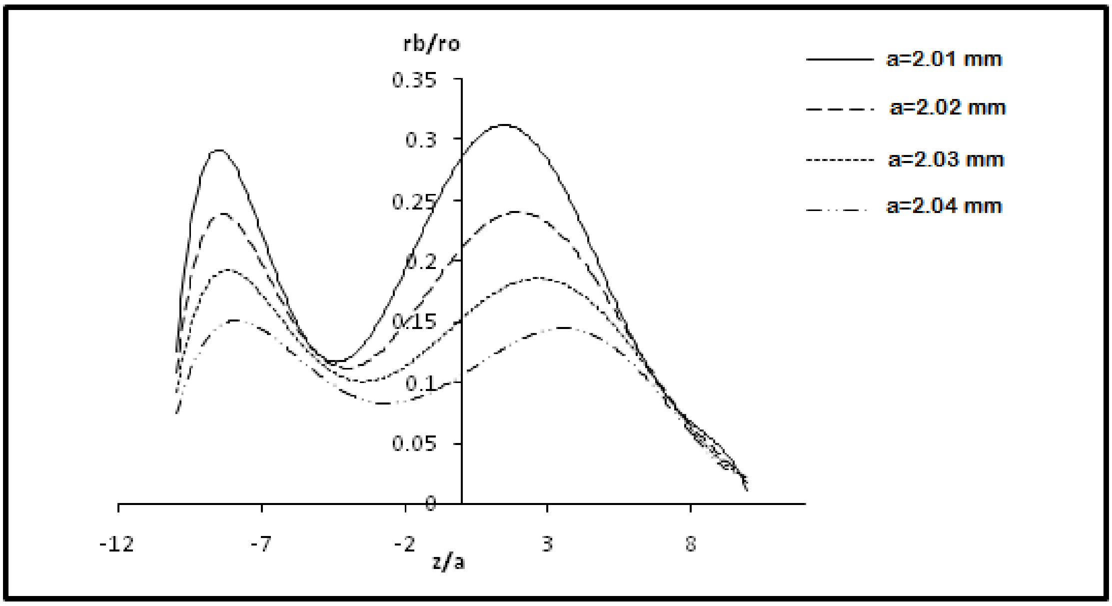

Figure1. The electron beam trajectory at various values of the half-width at half maximum(a)

The spherical aberration coefficient

The spherical aberration coefficient C_s of an axially symmetric magnetic lens is given by [11]:

$$C_s = (e/128\, m V_r) \int_{z_o}^{z_i} r^4 \left[(3e/mV_r)\, B^2(z) + 8\, B^{'2}(z) - 8\, B^2(z)\,(r/r)^{'2} \right] dz \qquad (7)$$

where *r* is the solution of the paraxial ray equation with an initial condition depending of the operation mode. The integration covers the whole interval form object plane z_o to image plane z_i.

The relative spherical aberration coefficients are computed by using (eq. 7) and the effects of variation of the half-width at half maximum (*a*) and the maximum magnetic flux density (B_m) are studied. From figure (2) one can see that the values of the relative spherical aberration coefficients C_s/fo decrease as the excitation parameter $(\frac{NI}{\sqrt{V_r}})$ increases. Also, the results show that at the low values of excitation parameter $(\frac{NI}{\sqrt{V_r}})$, the values of relative spherical aberration coefficients are closed to each other for different values of the maximum magnetic flux density, and the values of the relative spherical aberration coefficients values diverge at the range of high excitation parameter $(\frac{NI}{\sqrt{V_r}})$. In figure (2), the values of the relative spherical aberration coefficients C_s/fo decrease when the maximum magnetic flux density (B_m) is increasing, and at the maximum magnetic flux density (B_m= 0.004 Tesla) one can find the best results. This behavior is shown clearly in figure (3), where the relative spherical aberration coefficients are plotted as a function of the maximum magnetic flux density for constant value of the excitation parameter $(\frac{NI}{\sqrt{V_r}}) = 11.068 (Amp.turn/\sqrt{V_r})$.

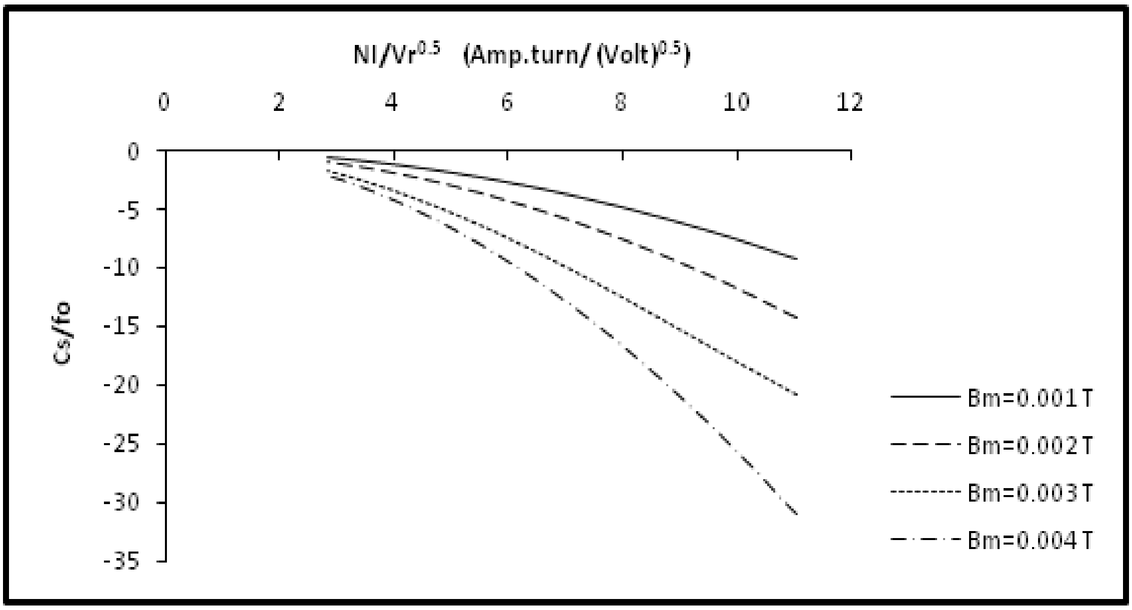

Figure 2. The relative spherical aberration coefficients as a function of the excitation parameter $(\frac{NI}{\sqrt{V_r}})$

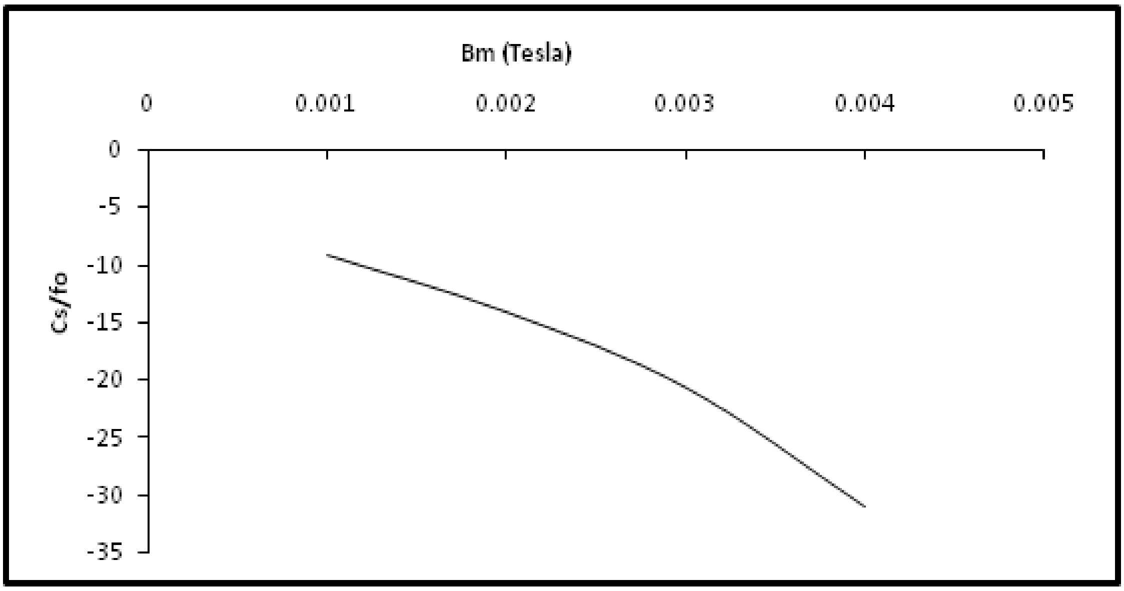

Figure 3. The variation of the relative spherical aberration coefficients C_s/fo as a function of the maximum magnetic flux density

Figure (4) shows that at the low values of excitation parameter $(\frac{NI}{\sqrt{V_r}})$ the values of the relative spherical aberration coefficients are closed to each other for different values of the half-width at half maximum, and the relative spherical aberration coefficients values diverge at the range of high excitation parameter $(\frac{NI}{\sqrt{V_r}})$. Also, the values of the relative spherical aberration coefficients C_s/fo decrease when the half-width at half maximum (*a*) increases and at the half-width at half maximum (*a* = 2.04 mm) one can find the lowest values. This behavior is shown clearly in figure (5), where the relative spherical aberration coefficients are plotted as a function of the half-width at half maximum for constant value of the excitation parameter $(\frac{NI}{\sqrt{V_r}}) = 11.068(Amp.turn/\sqrt{V_r})$.

From the above results and for the range under investigation of the half-width at half maximum and the maximum magnetic flux density, the optimum values of the relative spherical aberration coefficients can be found at the half-width at half maximum equal to 2.04 mm and the maximum magnetic flux density equal to 0.004 Tesla.

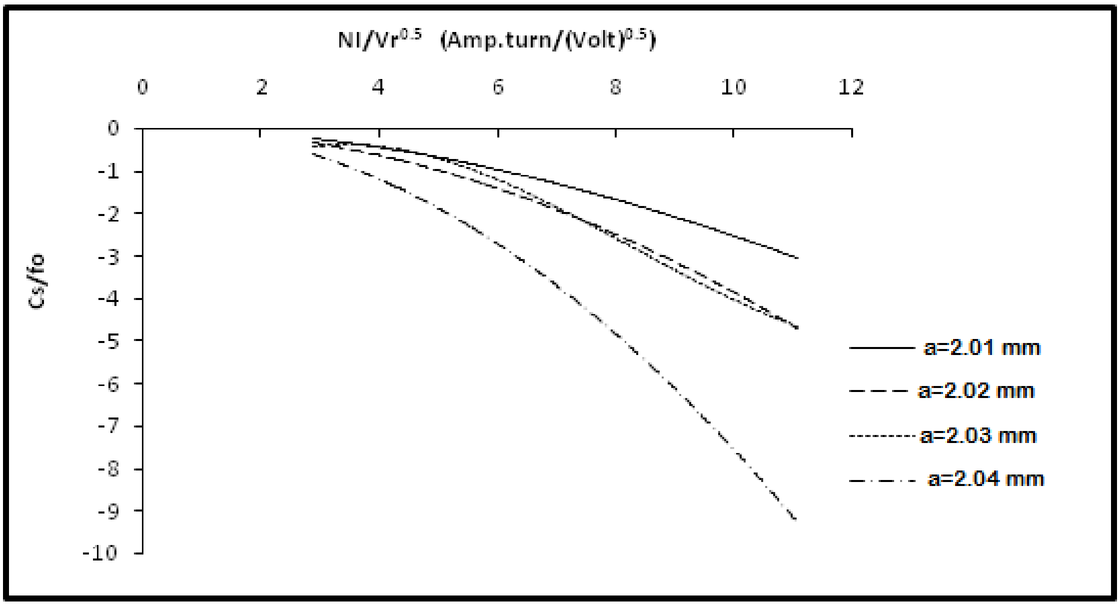

Figure 4. The relative spherical aberration coefficients as a function of the excitation parameter $(\frac{NI}{\sqrt{V_r}})$

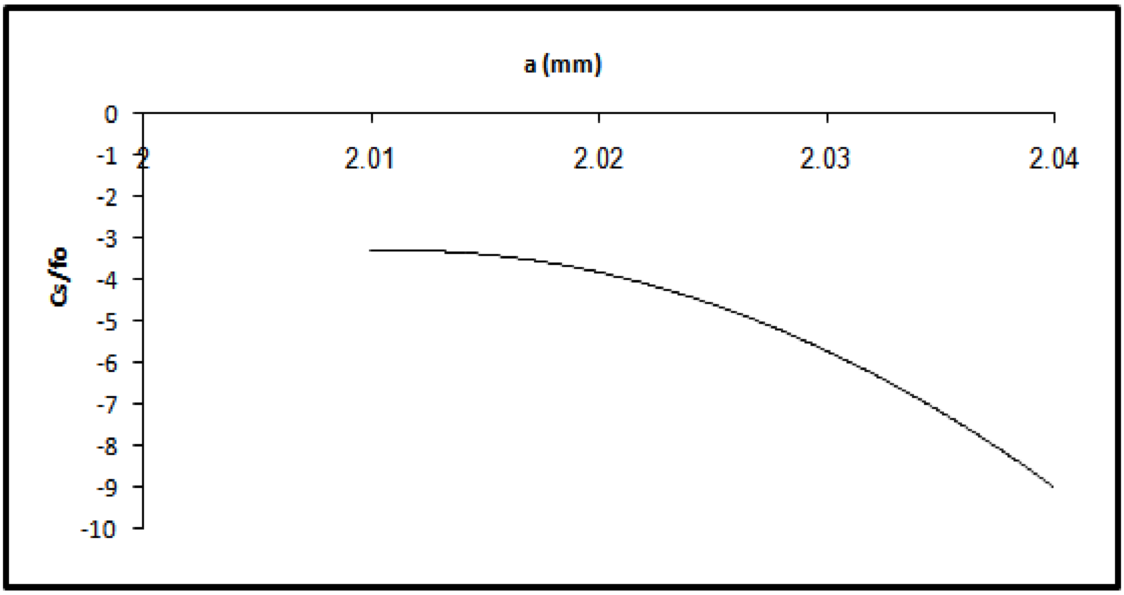

Figure 5. The variation of the relative spherical aberration coefficients C_s/fo as a function of the half-width at half maximum

CONCLUSION

The results show that the values of the spherical aberration coefficients are negative and this results can be used to design the magnetic lens which can be play the role of the corrector in the electron optical system. The analytical method can be used to give good description to the electron beam trajectory, and this trajectory can be used to find the optimum optical properties of the magnetic lens. The optimization role can be achieved via changing some effective parameters as the half width at half maximum (a) and the maximum magnetic flux density (B_m). Also, the calculations appear that the values of the spherical aberration coefficients are very sensitive to the changing of the effective parameter.

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