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Simulation of Magnetic Electron Lenses

Zaman Hameed Kareem Al-Rubaye
Ali Hadi Hassan Al-Batat
Department of Physics, College of Education, The University of Al-Mustansiriya.

Abstract:

A computational investigation on the simulation and design of symmetrical double polepiece magnetic electron lens using optimization by synthesis approach has been done. The field formula and its related axial functions requaired for synthesis design of the charged particle lens have been determined with aid of Simulation environment in Matlab. The objective focal properties of the double polepiece magnetic lenses with respect to the image space have been studied under the effect of the field parameters.

الخلاصة :

اجريت الدراسة باستخدام اسوب المحاكاة الحاسوبية لتصميم عدسة مغناطيسية ثنائية القطب متناظرة بأستخدام اسلوب امثلية التوليف. وبأستخدام بيئة المحاكاة في الماتلاب تم تحديد صيغة المجال والدوال المرتبطة به والمطلوبة لتصميم عدسة الجسيمات المشحونة. تم دراسة تأثير معاملات المجال على الخواص البؤرية الشيئية نسبة الى فضاء الصورة للعدسات المغناطيسية ثنائية القطب المتناظرة.

Key words: Simulink, Modeling, Electron optics, Synthesis procedure

1. Introduction

The period of the charged particle optics science dates back to the mid-1800$_s$, when some of the first studies examined the effects of the electric current in the gases, and later when cathode ray tubes were studied. However, the imaging electrostatic and/or magnetic field applications depending on accelerated and guided charged particle beams have been developed to build the theoretical fundamentals for the first electron microscope in 1930$_{S.}$

The electron microscope (EM) is a scientific instrument that uses a high-energetic electron beam to examine objects on a very fine scale. Early EM$_S$ had a resolution somewhat better than that of a light microscope .Through decades of development, the EM has evolved to a complex and powerful instrument. At the end of last century, the resolution in a conventional transmission electron microscope (CTEM) could reach the Angstrom scale. At the beginning of the 21st century, with the availability of aberration–correctors, e.g. spherical-aberration correctors and monochromators, high spatial resolution at the sub-Angstrom scale was made possible **[Wentao Yu 2009]**. As it is well known that the point resolution of transmission electron microscope (TEM) is limited by the spherical and chromatic aberration of the imaging lens. Electron microscopes have been at the forefront of the nanotechnology revolution, and it is now widely believed that improvement in the optical performance of these microscopes can only be achieved in correcting aberrations **[Michiel van der stam et al 2005].**

2.Image Aberrations in Electron Microscopy

It is well known that the effect of aberrations degrade the charged particle beam optics. Generating aberrations is inevitable when the charged particle beams are extracted, accelerated, transmitted, and focused with electrostatic and magnetic fields. For charged particle optical instruments in the field of electron microscopes and focused ion beam systems, aberrations degrade the focused beam spot, limiting the spatial resolution of these instruments. Therefore, in developing the charged particle optical instruments, many authors have studied the aberrations due to electrostatic lens, magnetic lens, and space charge effect **[Miyamoto and Hatayama 2009].**

The task of decreasing spherical and chromatic aberrations is currently important in the development of electron and ion optics of axis symmetric electron-optical system (EOS_S). There were numerous attempts, more or less successful, at decreasing these aberrations both in purely electrostatic or magnetic EOS_S and in combined systems through optimization of spatial arrangement of the field sources. For EOS_S of the first two types, some general principles for reducing aberrations were formulated. Unfortunately, no such general principles were established for the more complicated combined systems **[Zhukov et al 2001].**

Geometrical aberration lead to well defined phase shift of electron rays. The phase shifts depend on the geometrical ray parameters that define a given ray. Rays of different ray parameters can thus undergo different phase shifts. There are additional aberrations whose effects can become resolution-limiting. In fact there is always at least one aberration which limits the optical resolution of the microscope.

The present investigation deals with determining the most important two defects (spherical c_s and chromatic c_c) of the objective magnetic electron lenses depending on the optimization by synthesis. These two defects can be calculating for any axially symmetric magnetic lens from the following integrals**[Munro 1975]**.

$$c_s = \frac{\eta}{128 V_r}\int_{z_o}^{z_i}\left[\frac{3\eta}{V_r}B^4(z)r_\alpha^4(z) + 8B'^z(z)r_\alpha^4(z) - 8B^2(z)r_\alpha^2(z)r_\alpha'^2(z)\right]dz \text{ -------}(1)$$

$$c_c = \frac{\eta}{8V_r}\int_{zo}^{zi} B_Z^2(z)r_\alpha^2(z)dz\text{--}(2)$$

Where z_o and z_i are the object and the image planes respectively, η is the charge-to-mass quotient, V_r is the relativistically corrected accelerating voltage, r_α is the solution of the following paraxial ray equation

$$r'' + \frac{e}{8mV_r} r B_z^2 = 0 \text{ ---}(3)$$

3. Mathematical Field Model

The magnetic field distribution of rotationally double polepiece magnetic lens along the optical axis can approximated by the following target function **[Mahafza 2000]**

$$B_z(z) = \frac{\pi b^4 c^2}{[a^2\sin^2 z + c^2\cos^2 z]^2} \text{ --- }(4)$$

where z is the lens interval, $\Omega=\pi/z_s$, and a, b, and c are optimization parameters, the maximum flux density value denoted by B_{max} at the center of the lens (i.e., at the symmetry plane $z=((2n+1)\pi/2)$ relates to these parameters by the formula **[Al-Rubaye 2011]**:

The field formula can be modified to be more suitable in the field of electron and ion optics by calibrated it to be as follows:

$$B_z(z) = \frac{\pi b^4 c^2}{[a^2\sin^2\Omega z + c^2\cos^2\Omega z]^2} \text{ ---}(5)$$

$$B_{max}=\frac{\pi b^4 c^2}{a^4} \text{ -- (6)}$$

With aid of equation ($B_z=-\mu_o \frac{dV(z)}{dz}$) and using the trigonometric substitution integration method, the axial magnetic scalar potential distributionV(z) is given by :

$$V(z) = \frac{1}{\mu_o}\left[\frac{u}{2N}\left\{\tan^{-1}\left(\frac{\tan Z}{m}\right)+\frac{1}{2}\sin[2\tan^{-1}(\tan z/m)]\right\} + \frac{u}{2F}\left\{\tan^{-1}\left(\frac{\tan Z}{m}\right)-\frac{1}{2}\sin[2\tan^{-1}(\tan z/m)]\right\}\right] \text{ ----------- } (7)$$

Where $u = \pi b^4 c^2$, m=c/a, $N = a^4 m^3$ and $F = a^4 m$

In this paper the proposed target function (equation 4) represents the axial magnetic field distribution of a double polepiece magnetic lens would be investigating the field of the charged particle optics by means of the optimization by synthesis

The shape of the equipotential surfaces (polepiece) can be reconstructed by using the following formula[Szilagyi 1988].

$$R_p(z) = 2\left[\frac{V(z)-V_p}{V''(z)}\right]^{\frac{1}{2}} \text{ ---(8)}$$

Where V(z) is the axial magnetic scalar potential distribution, $V''(z)$ is the second derivative of V(z) with respect to z, $R_p(z)$ is the radial height of the reconstructed polepiece shape, and $V_p = NI/2$ if the field of a double polepiece lens is symmetric.

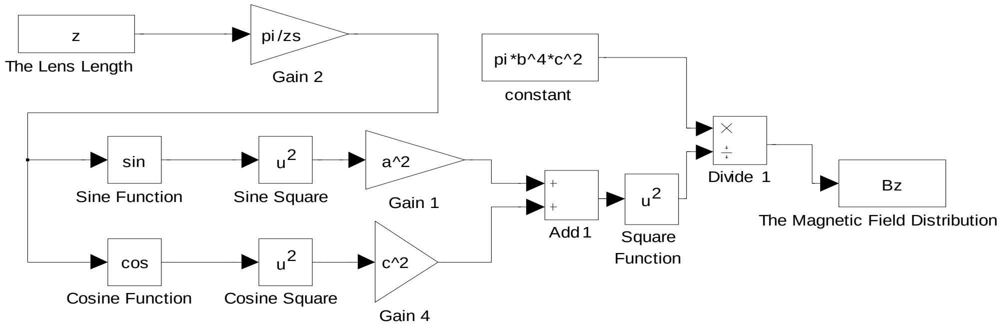
4.Simulation Environment

The Simulink is a companion application to Matlab, it deals with the engineering and scientific problems in terms of complete models. The Simulink can be considered as a powerful tool to solve different problems in terms of various blocks. Simulink in Matlab including comprehensive libraries. However, each library contains different specific blocks. Each block may be correspondent to a mathematical operation, such as: the addition, subtraction, multiplication, division, or matrices operations. Also, there are some blocks represents constants, signals, integrator, derivatives, gains, and waves. The input and output of each model can be obtained by specific blocks, such as: 'From workspace', 'To workspace', 'Scope' block, and 'XY Graph' block. The Simulink produces a powerful complete models in the image processing, signal processing, communications, etc. Where, there are specific blocks determining the conversion, transformation, filtering, etc. All special mathematical functions, such as: trigonometric functions, inverse trigonometric functions, hyperbolic, inverse hyperbolic, exponential, logarithmic functions can be determined with aid of special blocks. Linear and nonlinear mathematical functions as well as polynomials also can be calculated with aid of Simulink. All logic and bit operations can be execuited by special blocks, for more details see [Karris 2006].

The Matlab and Simulink environments are integrated into one entity, and thus we can analyze, simulate, and revise our models in either environment at any point. Each model can fulfill with the aid of specific blocks according to the problem under considerations. It is noted that the time required for the model execution in the Simulink can be neglected compared to that in the Matlab or other mentioned programming languages.

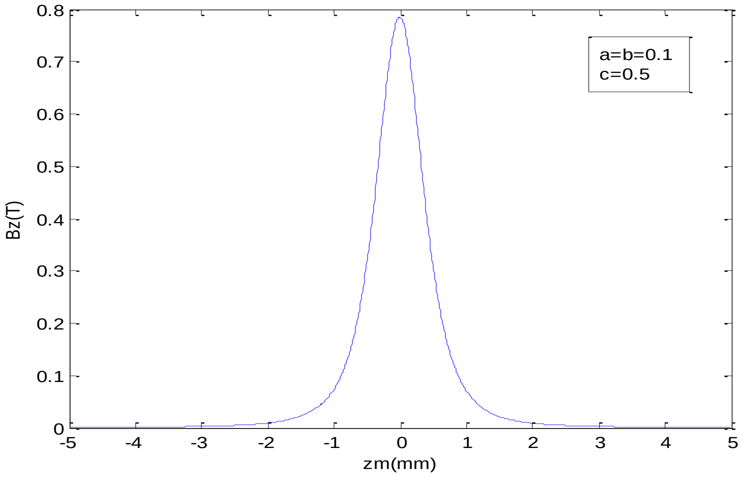
5. Direct Simulink Method

This method would be used to buildup different models including the determination of the field distribution of the magnetic lens and its related distributions. Figure(1) shows a model aiming to create the axial magnetic field distribution BZ(z) of the lens based on the suggested mathematical target function (equation 5).



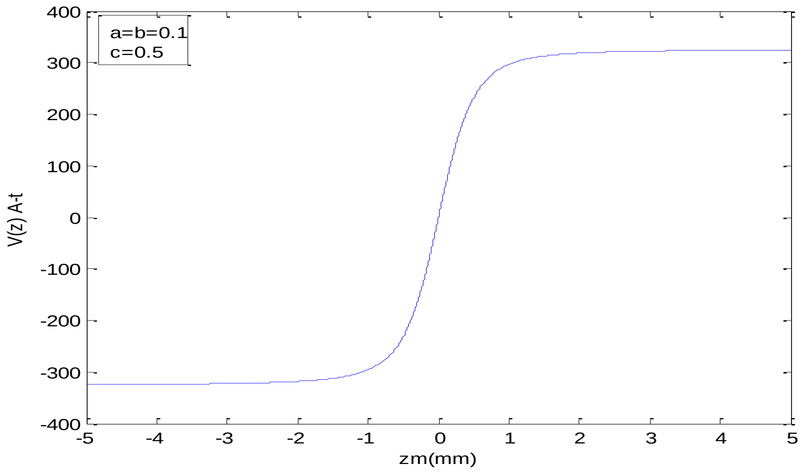
Figure(1):Model for the magnetic field target function.

This model depends on the input data which are the parameters a, b, and c and the length of the lens which can be defined in the command window on the environment of Matlab for the block "Lens length" as a data in terms of row vector for the closed axial hnterval [10,20]mm.The output of the model is the axial magnetic field distribution shown in figure(2) determined whene the parametersa,b and c are fixed at the following values 0.1, 0.1 and 0.5 respectively.



Figure(2): The axial magnetic field distribution along the optical axis about the symmetry plane z=0.

With the aid of equation (7), the Simulink model shown in figure (3) gives the main steps for determining the axial magnetic scalar potential distribution. According to the characteristic of the field formula, the potential Simulink model determines the potential along the following separated closed axial intervals [z_1=-5,0] and [z_2=0,5].
Figure (4) shows the computed axial magnetic scalar potential distribution at the fixed parameters values, a=0.1, b=a, c=0.5 along the original axial extension [z=−5,5].



Figure(4):The axial magnetic scalar potential along the optical axis about z=0.

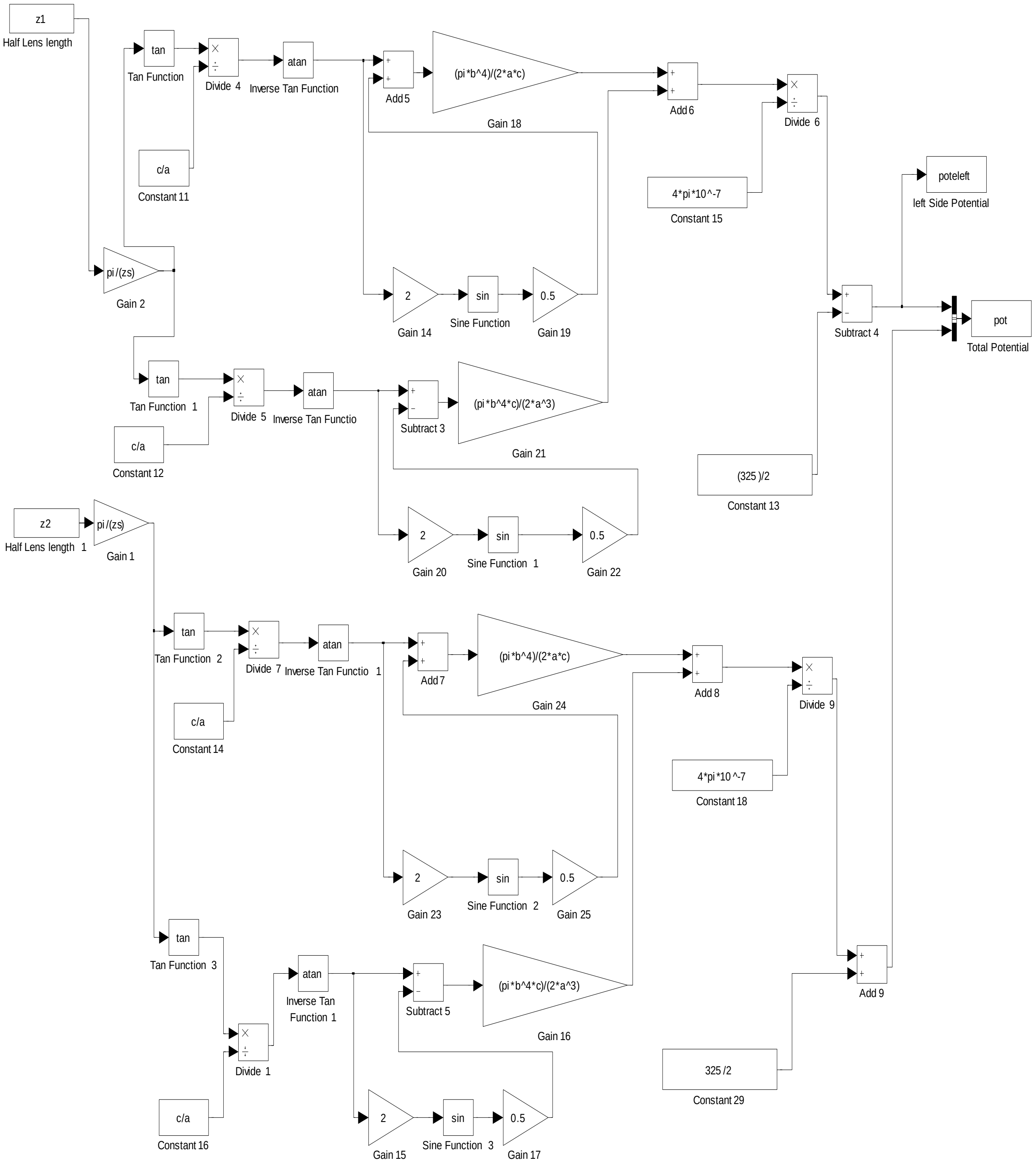
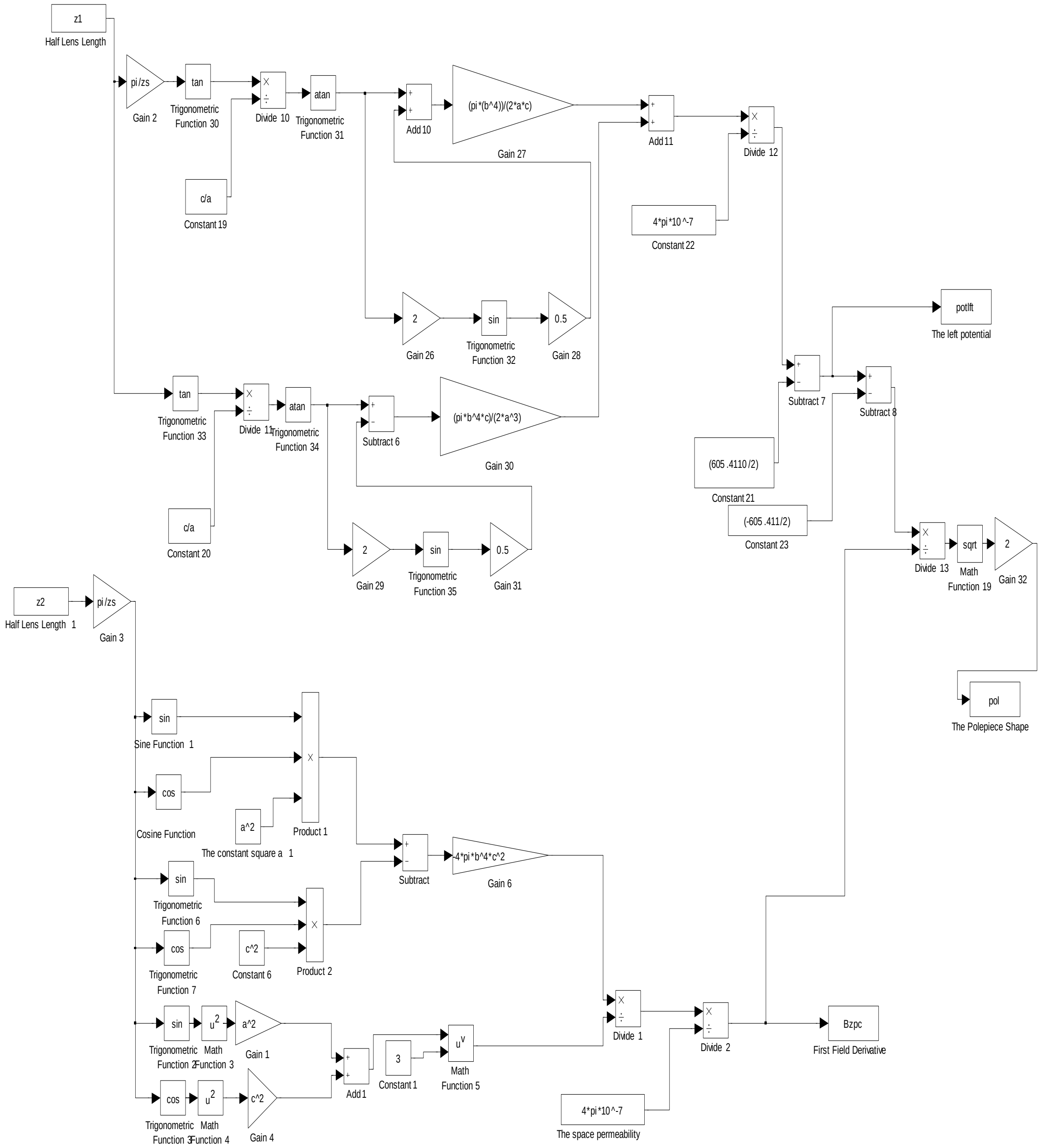


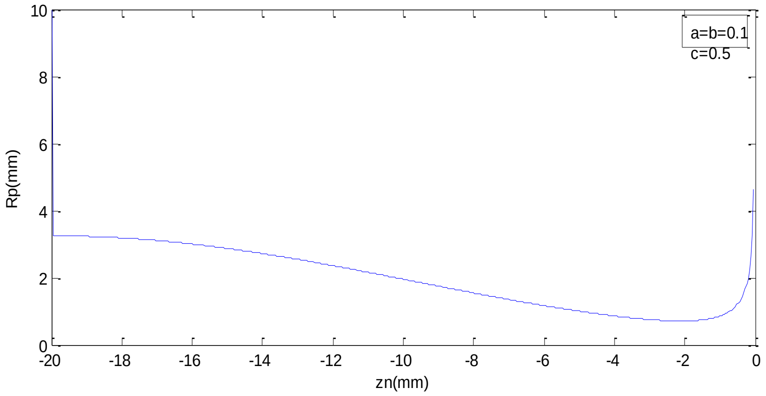
Figure (3):Simulink model for the axial magnetic scalar potential distribution.

Figure (5) shows a Simulink model for polepiece shape determination depending on the equipotential surfaces equation (7). Since $''(z) = -\frac{B_Z'}{\mu_o}$, however, this model can be divided into two parts, one for calculating $V''(z)$ with aid of the lower diagram, while the upper part calculates the potential distribution V(z).



Figure(5):Simulink model for polepiece shape

The polepiece shape corresponding to the parameters a=0.1, b=a, c=0.5is shown in figure (6).

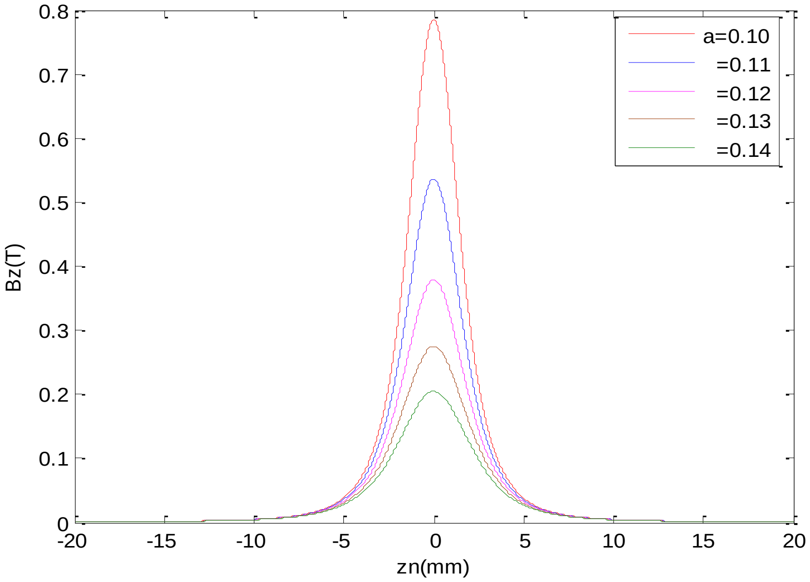


Figure(6):The polepiece shape along the optical axis z.

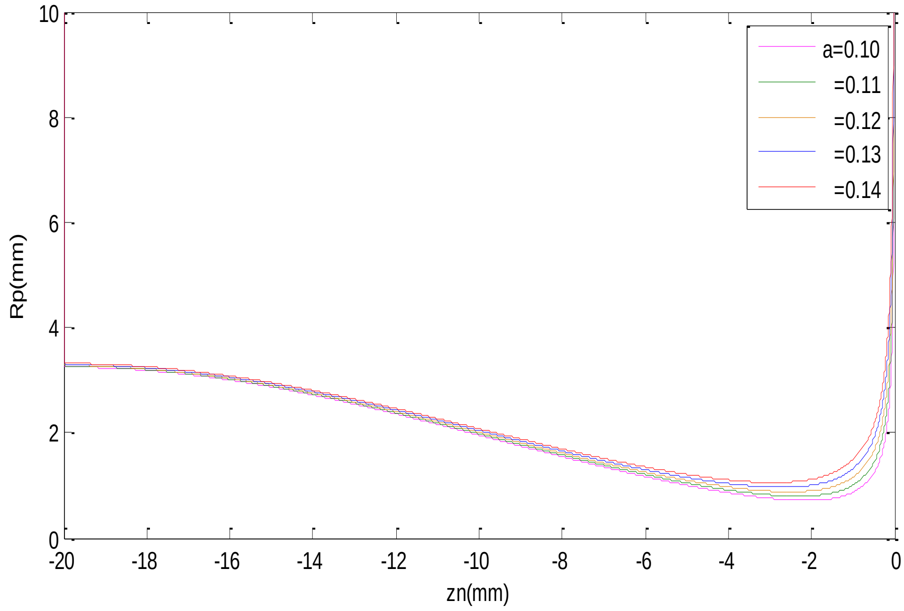
6.Objective Focal properties

With aid of optimization by synthesis procedure a double polepiece unsaturated magnetic lenses have been investigated, depending on a new target function to approximate the axial magnetic field (equation 5). The effect of each field parameter on the field distribution and the objective optical focal properties has been studied.

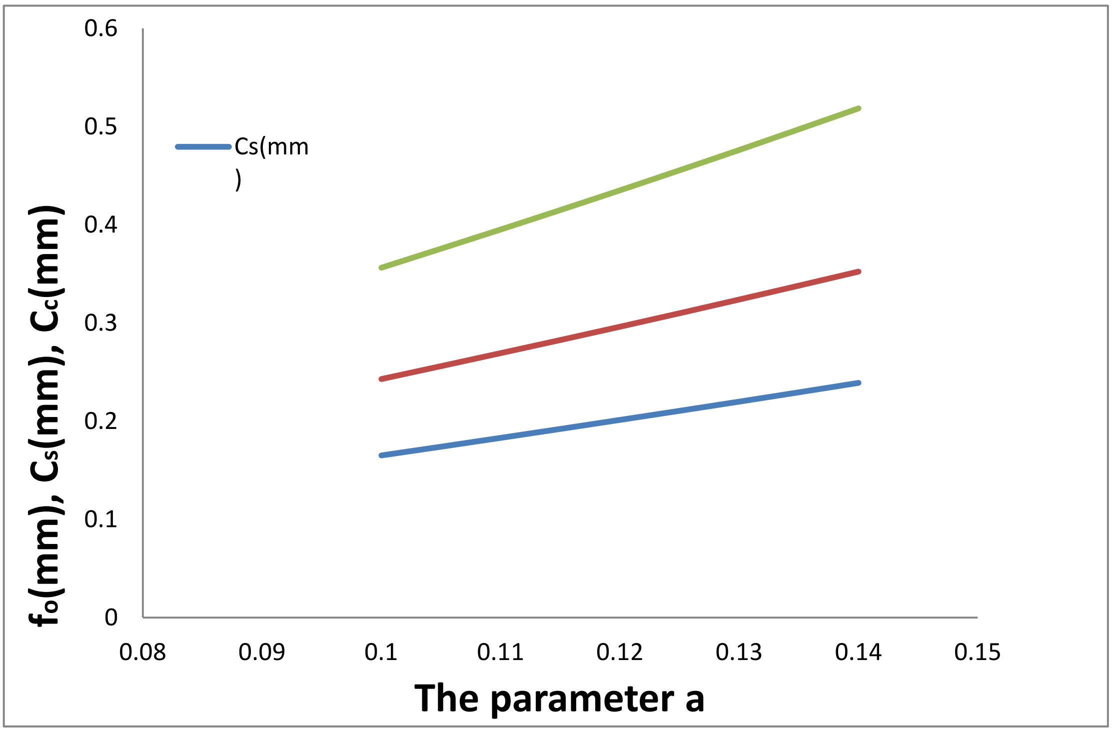
By using the simulink models for determining the field and the first and the second derivative, figure (7) shows different field distributions corresponding to fifferent a values (i.e., 0.1, 0.11, 0.12, 0.13, 0.14) at b=0.1and c=0.5. The corresponding polepiece profile of the fields in figure(7) are shown in figure (8). The objective focal properties f_o, c_s, and c_c with the parameter a at $NI/V_r^{1/2}$=20 under zero magnification condition are shown in figure (9).



Figure(7): The $B_Z(z)$ curves for different a values along the axial length [-5, 5].



Figure(8): The reconstruction of the polepieces as a function of the parameter a.



Figure(9): Variation of f_o, c_s, and c_c with the parameter a under zero magnification condition at $NI/v_r^{1/2}$.

Figure (10) shows different magnetic field distributions for different c values (c=0.30, 0.32, 0.34, 0.36, 0.38) at a=b=0.1. Variation of maximum flux density value B_{max}, the halfwidth W, and the excitation of the lens NI with the parameter c are shown in figure (11). It is noted that the objective focal properties f_o, c_s, and c_c decrease with increasing the parameter c as shown in figure (12).

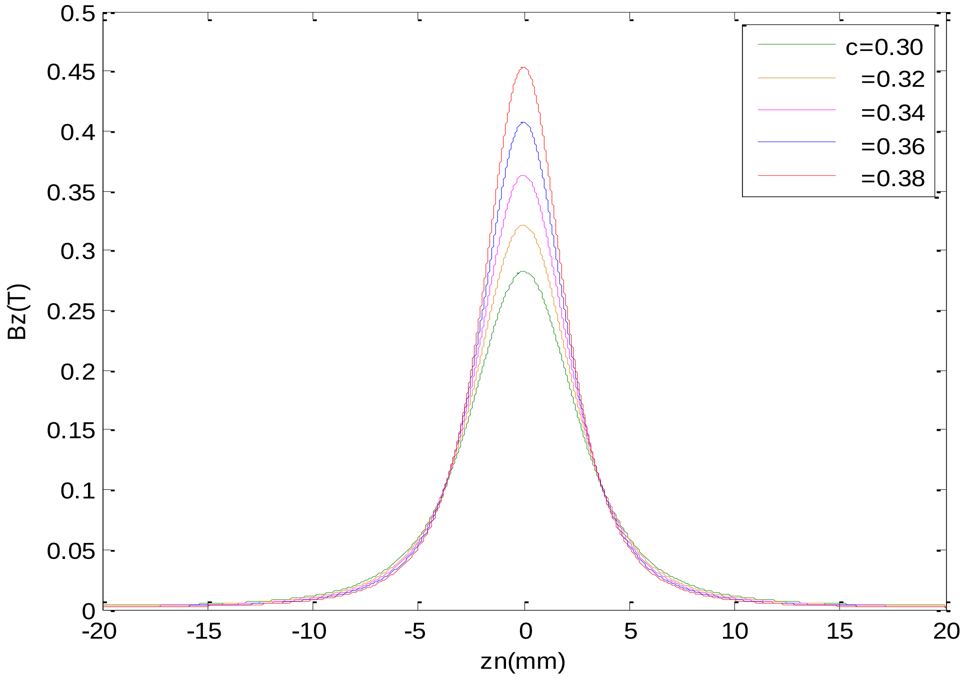
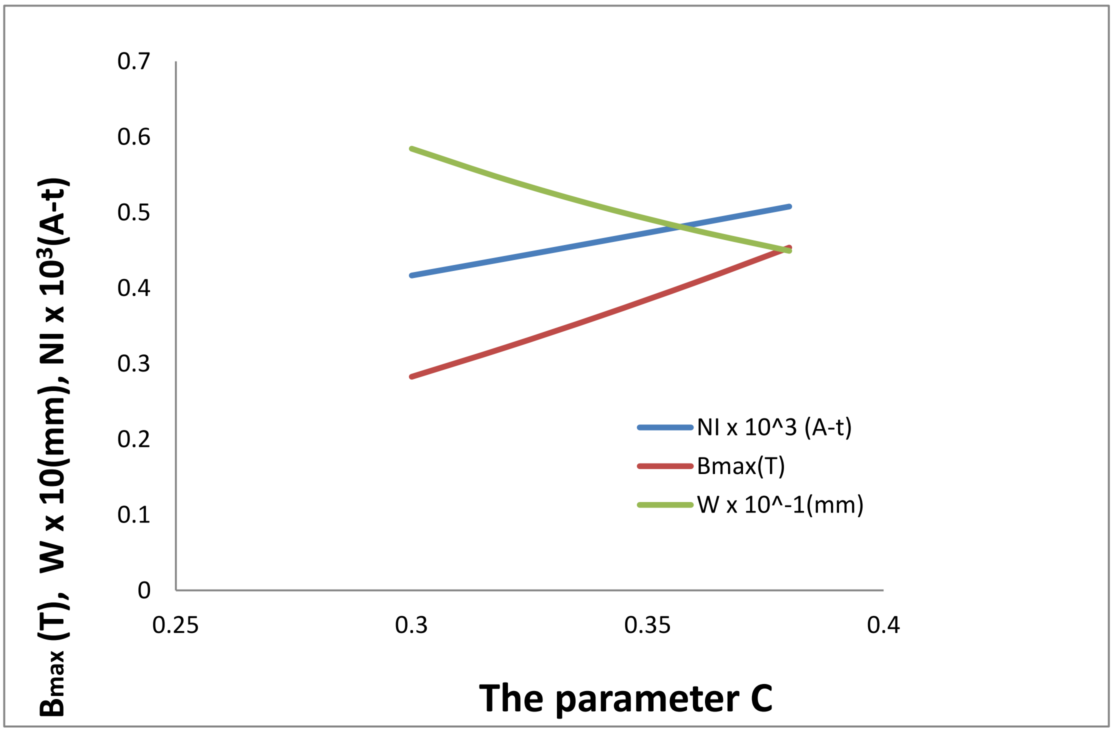
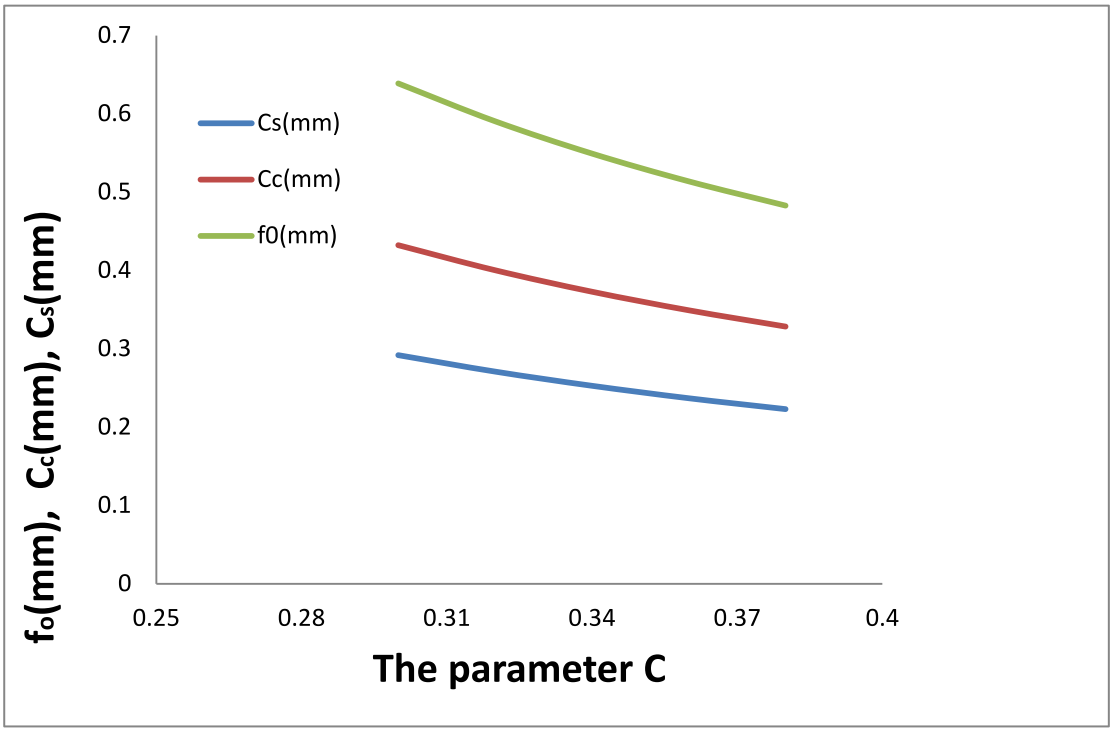


Figure (10): The axial magnetic field distribution $B_Z(z)$ for different c values.



Figure(11): Variation of B_{max}, W, and NI with the parameter c.



Figure(12):Variation of f_o, c_c and c_c with the parameter c at constant a and b parameters when NI/v_r=20.

7. Conclusions

The results have shown clearly that the followed optimization procedure with the Simulation environment in Matlab can be widely used in the charged particle optics to determine the design of the double polepiece magnetic lens and other types of electron lenses. Also, the results have shown that the most important geometrical aberrations in the images of the magnetic lens are very small compared with other investigations.

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