The effective of the inner radius of the iron free coil on the paraxial ray for magnetic lenses

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Abstract. In this paper, the magnetic flux density was studied using a mathematical model and different inner radius has been used for the iron free coil. The maximum value of magnetic field and the magnetic scalar potential was calculated. The paraxial ray can be studied using rung Kutta to solve the differential equation in the infinite and zero magnification condition, all results are determined using MATLAB program.

Keywords: electron optics, ions optics, iron free magnetic lenses, the potential of the electron lenses, electron microscopy

1. Introduction:
Electron optics is image formation by means of Deblorgle principle which can change the resolution by changing some parameters as electrons potential or the excitation of the lens\cite{1, 2}. The magnetic field can be stimulated using a mathematical model which has parameters and change the foundation of the lens \cite{2, 3}. The effect of the geometry parameters on the results, the beam throw and emerge beams are studied\cite{4}.
There are many mathematical models which represent the magnetic field, and many models can represent the magnetic scalar potential. Using the inverse design procedure and the optimization to receive the optimal lenses, the non-dominated sorting genetic algorithm (2) and the electron optics simulations were combined and make a multi-objective optimization design tool for electron optics. To determine the function of the objective that varies with the parameters of the macroscopic electrical to need that optimize the electron optics system\cite{5}.
In general, the solution of the inverse design problems can be found by using mathematical models can control to the properties of the lens inside the scanning electron microscopy and transmission electron microscopy and determine analytically the first derivative and the second derivative for the model to design and simulate the lenses\cite{6-8}.

2. The Theoretical Treatment
Many mathematical models can represent the axial magnetic field. The axial distribution of the magnetic field for iron free magnetic lens can be represented by\cite{9}
\[ B(z) = \frac{\mu_0 NI}{2lS} \left[ \ln \left( \frac{R_2 + \left( \frac{S}{2} + z \right)^2}{R_1 + \left( \frac{S}{2} - z \right)^2} \right)^{1/2} + \ln \left( \frac{R_2 + \left( \frac{S}{2} + z \right)^2}{R_1 + \left( \frac{S}{2} - z \right)^2} \right)^{1/2} \right] \] ...

Where \( \mu_0 = 4\pi \times 10^{-7} \text{H/m} \) and \( l = R_2 - R_1 \), \( R_2, R_1, S \) and \( z \) are in meters, \( NI \) in ampere turns and \( B(z) \) in teslas [9].

\( \sigma A = NI \) ……………………………(2)

Where \( \sigma \) the density of the current, \( A \) the area of the cross-section of the energizing (N the turn numbers) \( I \) the electrical current coil [9],

\[ A = \gamma (R_2 - R_1)s = \gamma lS \] ………………(3)

Where \( \gamma \) the packing factor (0.9) for the copper tape winding (s is coil thickness), one can imagine the system is [9].

In the present work, the equation (1) can be modified as [modified from the researcher]:-
The inner diameter of the coil is \([9]\)

\[D_1=2R_1 \ldots \ldots \text{(5)}\]

This paper was to study the axial flux density and the paraxial ray by using the paraxial ray equation\([10]\):

\[r'' + \frac{\eta}{8V_r} B_z^2(z)r = 0 \ldots \ldots \text{(6)}\]

Where \(r\) is the trajectory and \(V_r\) is the relativistically corrected accelerating voltage, \(\eta\) is the charge-to-mass quotient. by using the fourth order Runge-Kutta numerical method to solve differential equation (6).

The magnetic scalar potential can be calculated by using the equation\([10]\):

\[B_x(z) = -\mu_0 \frac{dV_z}{dz} \ldots \ldots \text{(7)}\]

Where \(V_z\) is the magnetic scalar potential, \(\mu_0\) the magnetic permeability.

The inner diameter for the coil took (3, 5, 10, 15, 20) mm

Results and discussion:

The magnetic lenses play important role in the scanning electron microscopy and transmission electron microscopy then the inverse design and the optimization draw the complete image for the lens properties which many researchers works in this line to receive for the perfect study to the samples \([2, 11]\).

According to the equation (1), the distribution of the asymmetric magnetic field of the lens as a function of the optical axis as shown in the figure (1) with different inner radius (3,5,10,15,20), one can see the increasing the inner radius for the coil this causes decreasing the half width of the curve in addition to that the maximum value for the magnetic field distribution will be reduced as shown in the table (1)
Figure 1. The axial flux density for different diameters.

Table 1. Value for magnetic field distribution maximum for different value inner diameter

| D1 (mm) | B_{max} (T) |
|--------|-------------|
| 3      | 1.9658      |
| 5      | 1.7028      |
| 10     | 1.3333      |
| 15     | 1.1145      |
| 20     | 0.9617      |

The decreasing in the inner diameter may make the dissipation the magnetic line in the wide area in the space and this causes the weakness for the lens, this can be shown in the global papers [12, 13], which support this results. The paraxial ray under zero magnification for different inner diameters for the iron free coil can be shown in figure (2). One can show that the decreasing in the diameters causes arising the curve coming from a weakness interaction the ray with lines of the magnetic field, but in the general, the behaviour of the curve is normal focusing with the magnetic field to make the discover imagine the samples. The same speech for the figure (3) which shows the paraxial ray under infinite magnification figures (2) and (3) are deduced by using mathematical models in the magnetic field with assisted numerical determinations in the inverse design optimization with different values inner diameters [14, 15], these figures show the effects of interaction between the current and the magnetic fields which produces and the electron beam with different inner diameters. The magnetic scalar potential distributions as a function of the optical axis with variable inner diameters can be shown in the figure (4) which produced from equation (7), by this figure, one can show the decreasing the magnetic scalar potential with increasing the inner diameter this may decrease the maximum value for magnetic field distributions which effective to the magnetic scalar potential distribution because decreasing the area under the curve for the magnetic field distributions.
Figure 2. the paraxial ray for different inner diameters.

Figure 3. the paraxial ray under infinite magnification for different inner diameters.
3. Conclusion:
In this work, the effects of different inner diameter for the iron free lenses on the magnetic field distributions and the paraxial ray along the optical axis were studied. The increasing in the inner diameter causes a complication in the interaction between the electron beam and the magnetic field and makes the lens weaker. The increased diameter makes the effect and change in the magnetic scalar potential this may be due to the shape of asymmetric magnetic field distribution determined from variable inner diameter.

4. References
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