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## ► To cite this version:

A. Alshwaikh. CHROMATIC CHANGE IN MAGNIFICATION AND IN ROTATION FOR MAGNETIC LENSES. Journal de Physique Colloques, 1984, 45 (C2), pp.C2-165-C2-168. 10.1051/jphyscol:1984237 . jpa-00223950

**HAL Id: jpa-00223950**

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Submitted on 4 Feb 2008

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## CHROMATIC CHANGE IN MAGNIFICATION AND IN ROTATION FOR MAGNETIC LENSES

A.A. Alshwaikh

*Department of Physics, King Saud University, Riyadh, Saudi Arabia*

**Résumé** La variation chromatique de l'agrandissement et de la rotation, pour les lentilles conventionnelles et les lentilles magnétiques monopolaires a été étudiée en utilisant des distributions de champ réelles et des modèles mathématiques.

**Abstract** Chromatic change in magnification and in rotation for conventional and single-pole magnetic lenses were studied, using realistic field distributions and mathematical models.

1. INTRODUCTION

There are two chromatic defects in the image of the high resolution electron microscopes. The first defect is known as chromatic change in magnification, which results in loss of image in the marginal zone. This is due to a number of images of different sizes which are superimposed over one another, resulting in blurring. The effect then gets worse towards the outer regions as the field of view is increased. This image blurring is due to the electron energy spread in the beam, arising from fluctuations in lens excitation (NI) and relativistically corrected accelerating voltage ( $V_r$ ), or due to energy losses in the specimen. The second defects is called chromatic change in rotation. This produces a circumferential blurring in the image.

For convenience, the terms  $C_m$  and  $C_r$  are to present aberration coefficient of chromatic change in magnification and in rotation respectively. The subscripts o and p are represented for the objective and projector lens respectively.

Expressions have been derived using electron path method [1], and used by many authors [2,3] to calculate the coefficients identified earlier, for conventional (i.e. double-polepiece) objective lenses. Similar expressions have been derived for conventional projector lens [4,5]. The results obtained from these works is a basis to verify the numerical investigation presented in this paper, for aberration coefficients for single-polepiece magnetic lenses.

In this paper, analytical results are presented using mathematical models to find universal curves for the mentioned aberration coefficients.

2. COEFFICIENTS FOR CONVENTIONAL LENSES

The coefficients can be derived for conventional (i.e. double-polepiece) magnetic lenses by using Glaser-Bell shaped model [2,3] as follow

$$C_m^p = [(w^2 - 1)/2w^2](1 - w\pi \cot w\pi) \quad \dots \quad (1)$$

$$C_r^p = -(\pi/2)w^2 - 1)^{1/2} \quad \dots \quad (2)$$

$$C_m^o = \pi(w^2 - 1)\cos(\pi/w)/2w^3 \sin(\pi/w) \quad \dots \quad (3)$$

$$C_r^o = \pi(w^2 - 1)^{1/2}/2w \quad \dots \quad (4)$$

where  $w = (1 + K^2)^{\frac{1}{2}} = [1 + (\frac{e}{m} \cdot \frac{B_0^2 d^2}{8V_r})]^{\frac{1}{2}}$ ,

$B_0$  is the maximum value of the axial magnetic field distribution,  $d$  is the half-width of the field, and  $e/m$  is the specific charge of electron.

Equations different in values, or in form, are derived by other authors [5,6,7].

The results obtained from these equations were used to verify the accuracy of the numerical analysis which is done by relevant computer program. The results for the analytical (dotted lines) shown in Fig.1 are in excellent agreement with the numerical calculations (solid lines) for Glaser-Bell shaped model. Therefore, it is possible to use the program to find coefficients for single-polepiece magnetic lenses for which the similar formulae to calculate them does not exist.

### 3. UNIVERSAL CURVE FOR ABERRATION COEFFICIENTS

For a rectangular model which represents conventional lenses, an electron passing the specimen, loses energy, and its trajectory (dotted line) is different from that of an electron which has not lost its energy (solid line) as shown in Fig.2. The heights for the trajectory at points  $Z_0$  and  $S/2$ , are as follows:

$$\text{at } Z = Z_0 \quad r_1 = r_0 \cos K (Z_0 + S/2) \quad \dots (5)$$

$$\text{at } Z = S/2 \quad r_2 = r_0 \cos K S \quad \dots (6)$$

By ignoring the small contribution of  $r_2$ , it is possible to prove from the equations that

$$dr/dk = r [1/K + S \cot KS + (Z + S/2) \tan K(Z_0 + S/2)] \quad \dots (7)$$

$$C_m = (dr/r)(dV/V) = (dr/r)/(K/2dK) = 0.5[1 + KS \cot KS + K(Z_0 + S/2) \tan K(Z_0 + S/2)] \quad \dots (8)$$

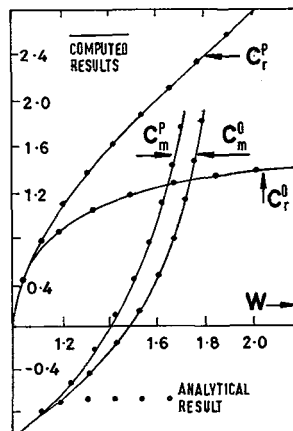


Fig.1 Calculated coefficients of chromatic change in magnification and in rotation for Glaser-Bell shaped field (solid lines), compared with the analytical solution (dotted lines).

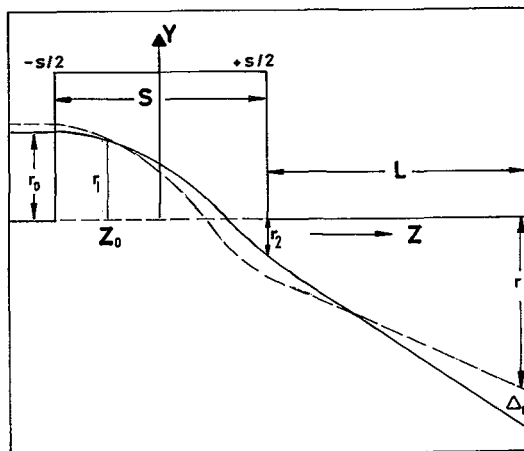


Fig.2 Paraxial rays through square top magnetic field.  
Solid line (no energy loss)  
Dotted line (with energy loss)  
 $L$  = Image distance.  
 $Z_0$  = Object position.  
 $S$  = The field width.

$$C_m^0 = -0.5 [1 + (\pi/2) \cot(2.03 \text{ NI}/\text{NI}_0)] \quad \dots (9)$$

Where  $\text{NI}_0$  is the excitation required to produce the minimum projector focal length and  $\text{NI}_0/\sqrt{2} = 10.9$  for rectangular field [8]. It is evident that  $C_m^0$  takes the value zero at  $\text{NI}/\text{NI}_0 = 1.06$ .

When we consider energy losses in the specimen the electron will start to deviate from the ordinary electron path at  $Z$ , although it starts with the same value of slope. So it is possible to derive equation (9) again. Thus  $C_m^0$  is similar to both the fluctuations in  $V_r$  and the energy losses in the specimen.

It should be noticed that the coefficients have been evaluated for the case of the incident electron beam, on the lens parallel to the axis, which is a good approximation to the normal usage of an electron microscope for lower magnification where the illumination is spread out by the condenser.

The coefficient  $C_r^0$  takes the values:

$$C_r^0 = -\pi/4 \text{ for } KS \geq \pi/2 \text{ and } C_r^0 = 0.5KS = \text{NI}/\text{NI}_0 \text{ for } KS < \pi/2 \quad \dots (10)$$

The projector focal length ( $f_p$ ) obeys the relation  $[S/f_p = KS \sin KS]$ . By differentiating  $f_p$  with respect to  $K$ , the universal curve can be found as

$$C_m^p = -0.5 [1 + 2.03 (\text{NI}/\text{NI}_0) \cot(2.03 \text{ NI}/\text{NI}_0)] \quad \dots (11)$$

This expression was used in the range  $KS \geq \pi/2$ ; while  $C_m$  in the range  $KS < \pi/2$  is equal to  $C_m^0$ . By using Ampers law, it is possible to show

$$C_r^p = -0.5 KS = -(\text{NI}/\text{NI}_0) \quad \dots (12)$$

The universal curves for  $C_m^0$ ,  $C_r^0$ ,  $C_m^p$  and  $C_r^p$  verses  $\text{NI}/\text{NI}_0$ , which are represented analytically for rectangular field model, are in close conformity with the Glaser-Bell shaped and Grivet-Lenz [9] models.

The plots based on Bell shaped model, are represented by solid lines in Fig. 3 while the crosses represents values for two realistic conventional magnetic fields in order to verify the applicability of the universal curves.

#### 4. COEFFICIENTS OF SINGLE-POLEPIECE LENS

The computation of the four coefficients was carried out for single-polepiece lens using the numerical method, in the same way as for the conventional lens. The same procedure is used for  $C_r^p$  which its analytical solution exist for any field distribution to verify the numerical procedure. This procedure is based on realistic mathematical model, namely spherical field [10]. For this type of field there are two modes of operation. The first mode is based on incident ray for a slow decaying edge of the field, while the second mode for the incident ray for the high raising edge of the field.

The solid lines in Fig. 4 represent the universal curves for projector single-polepiece lens, for both modes using the spherical model. The crosses indicate

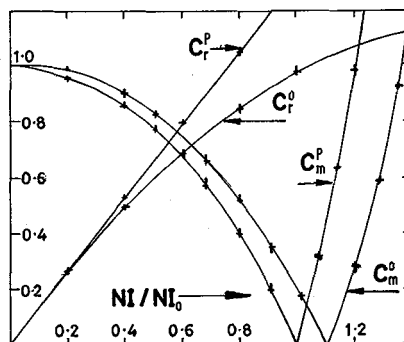


Fig.3 The coefficients of chromatic changes in magnification ( $C_m$ ) and in rotation ( $C_r$ ) for conventional projector and objective lenses (crosses) compared with the universal curves (solid lines) based on Bell shaped model.

same coefficients calculated for a 100 KV single-polepiece lens [11], to confirm the applicability of the universal curves.

The chromatic change coefficients of the objective lens obtained by numerical calculations, for both modes of operation are represented by the universal curves in Fig.5 using the spherical field, exponential field model and a 100 KV single-polepiece lens.

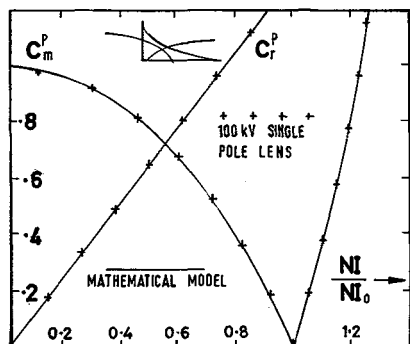


Fig.4 Universal curve of the coefficients of chromatic changes in magnification and in rotation for a single-polepiece project lens for both modes of operation, using the mathematical model (solid line) and experimental 100 KV lens.

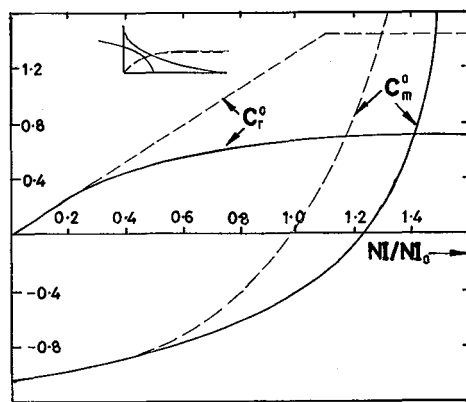


Fig.5 The coefficients of chromatic changes in magnification and in rotation for the single-polepiece objective lens in two modes of operation, using spherical field model, exponential field model and 100 KV single-pole lens.

## 5. CONCLUSION

Results obtained for chromatic change in magnification and in rotation, for single-polepiece projector lens, are approximately the same as of the conventional projector lens.

For objective lens, the coefficients  $C_m^o$  and  $C_r^o$  due to incident ray of the high raising edge of the field are lower in values than that obtained for the other direction. It seems that in its preferred direction (i.e. first mode), both coefficients values are lower than those for conventional lenses.

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