Studies on the Effect of Pole Piece Shape for Saturated Single Pole Magnetic Lens

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Received November 13, 2013; Revised November 14, 2013; Accepted November 15, 2013

Abstract: *Magnetic electron objective lens is of a great importance for electron microscope intended for high resolution. The present work investigates the objective properties of a single pole piece magnetic lens with different pole piece shapes. The results indicate that the lens with a spherical pole – face has the best resolution.*

Keywords: *Finite element method; objective magnetic lenses; aberration PACS: 41.85*

Introduction

A single pole piece magnetic electron lens has a unique design and performance. This form of lens was designed by Mulvey [1] It has an open construction so that the flux lines concentrated at the pole face diverge widely before re-entering the iron circuit. Thus the axial magnetic field has a maximum value in the vicinity of the pole face but decays outside the lens structure [2] . The factors that affect its axial flux distribution and the electron optical properties the shape, size and axial bore diameter of its pole [3], [4]. The size of the axial bore in the pole piece plays an important role in determining the best focal properties [5]. However, in single pole-piece lenses the axial bore not always necessary. The absence of the axial bore makes fabrication of the lens easier; in addition, it may be employed as an objective lens in the scanning electron microscope (SEM) [6], [7]. In the present work attention has been concentrated on a lens of a zero bore and varied pole piece shape. The axial flux density distribution has been computed by means of the finite element method which was first introduced in electron optics by Munro [8] who applied it to computation of the magnetic field in round lens [9]. The axial flux density distribution was computed using the computer programs set up by Munro [10], Munro programs written with FORTRAN language.

EOD program [11], its packages software for computing saturated magnetic field of electron lenses of complicated geometry and Optical properties including aberration coefficients with high accuracy. The present work is mainly concerned with the design magnetic saturation lens to produce a high flux density with different pole shape by Munro program and EOD program.

Design of saturation single pole-piece objective lens

In objective lens, aberration coefficients must be small to achieve high resolution. And if possible a large space should be available at the pole to put the specimen at the maximum value of the magnetic field distribution; this must have reduced spherical (C_S) and chromatic (C_c) aberration coefficients.

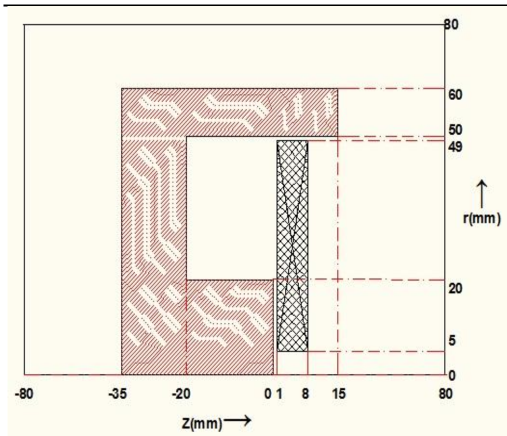
The resolution power ∂ of such an objective is given by [12] $\partial = 0.7\left(c_s\lambda^3\right)^{\frac{1}{4}}$ Where λ is the wavelength. Although, for a given lens shape, c_s increases with decreasing wavelength (High acceleration voltage) good resolution is Best achieved by operating at the highest practical acceleration voltage and the lowest possible c_s value.

Test lens

One of The factors involved in controlling the electron –optical parameters of the single pole piece lens is the pole piece shape. The following three shapes of pole pieces were studied:

1- flat-face cylindrical pole-piece.
2- flat- face truncated- cone pole-piece.
3-spherical-face pole-piece
(The spherical face is a more practical design for an electron microscope and it has an analytical treatment [13]).

Figure 1 shows a diagram and geometrical dimension for the test lens suggested in the present work with different pole shape. The outermost diameter of each pole was fixed at 40 mm .the axial protrusion of the pole piece from the lens flat plate was also fixed at 20 mm .this means that the radius of the spherical pole face is 20 mm. The axial flux density distributions in zero-bore single pole-piece lens with a soft iron computed at constant lens excitation ($NI = 60000\ A - t$) ,where N being the total number of turns of the energizing coil and I the d.c. current passing through it and current density ($\sigma = 19480.6\ A - t/cm^2$). The coil is of 98 mm outer diameter, 10 mm inner diameter and 7 mm axial thickness. The dimension of the energizing coil is chosen such that the value of the ratio of its axial thickness **s** to the mean diameter d_m was maintained at about(s/dm) 0.13. Figure 2 shows the mesh on the upper half of the three test lenses, from this figures it is noticed that the mesh lines are very few at the edges of the lens due to the unimportance of the magnetic field distribution in this region. the distribution of these lines increase near to the poles and the region between them due to the importance of this region in determining the optical properties for these lenses.



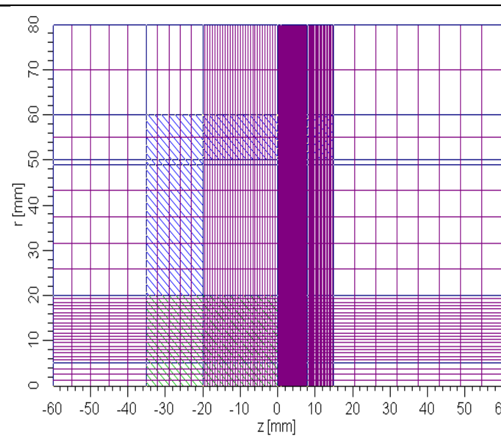


Fig.1a: diagram and geometrical dimension for rectangular pole-face

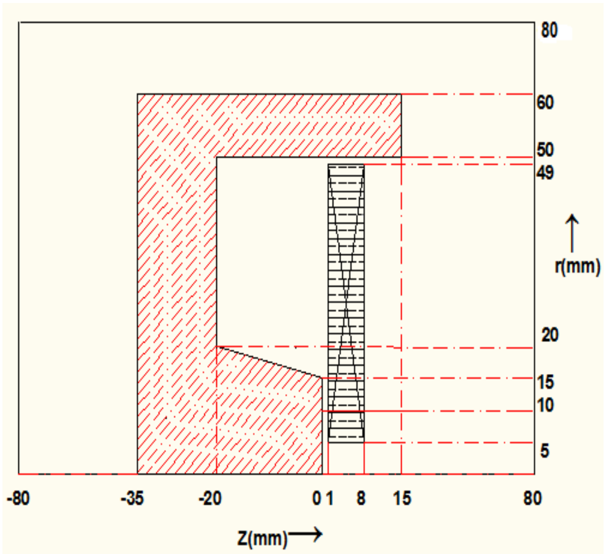


Fig.2a: The line distribution of the mesh on the upper half of the Single pole piece with flat-face rectangular pole

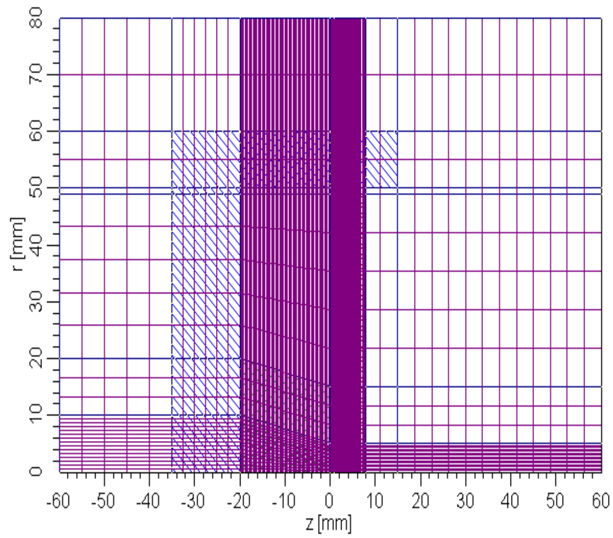


Fig.1b: diagram and geometrical dimension for truncated-cone pole-face

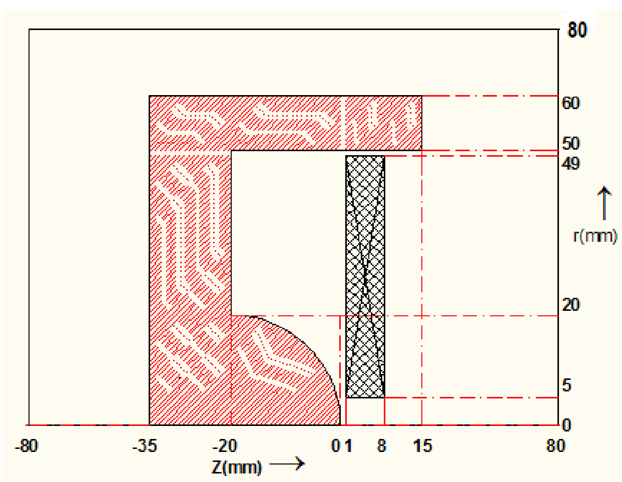


Fig.2b: The line distribution of the mesh on the upper half of the Single pole piece with flat-face truncated-cone pole

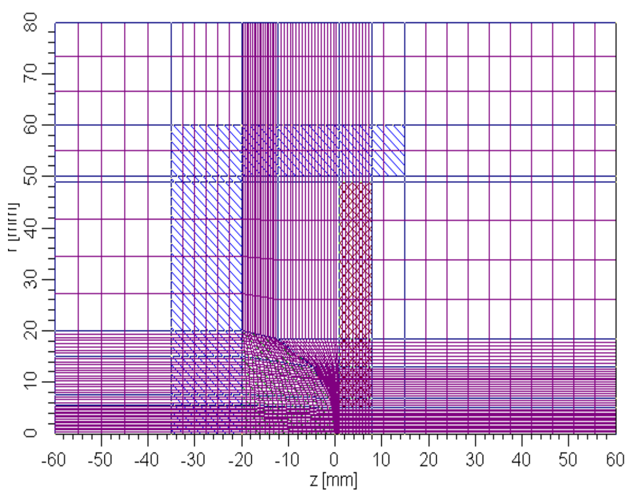


Fig.1c: diagram and geometrical dimension for spherical pole- face

Fig.2c: The line distribution of the mesh on the upper half of the Single pole piece with spherical pole- face

The distribution of the axially magnetic field (Bz)

Computations of axial field distribution of magnetic field and optical focal properties were carried out by using EOD program and M21 program of Munro. Consider the test lenses shown in figures 1, with single pole pieces of flat-face (rectangular, truncated cone) and spherical – face. Figure 3 presents the distribution of the axially magnetic field (B_z) for different pole-faces.

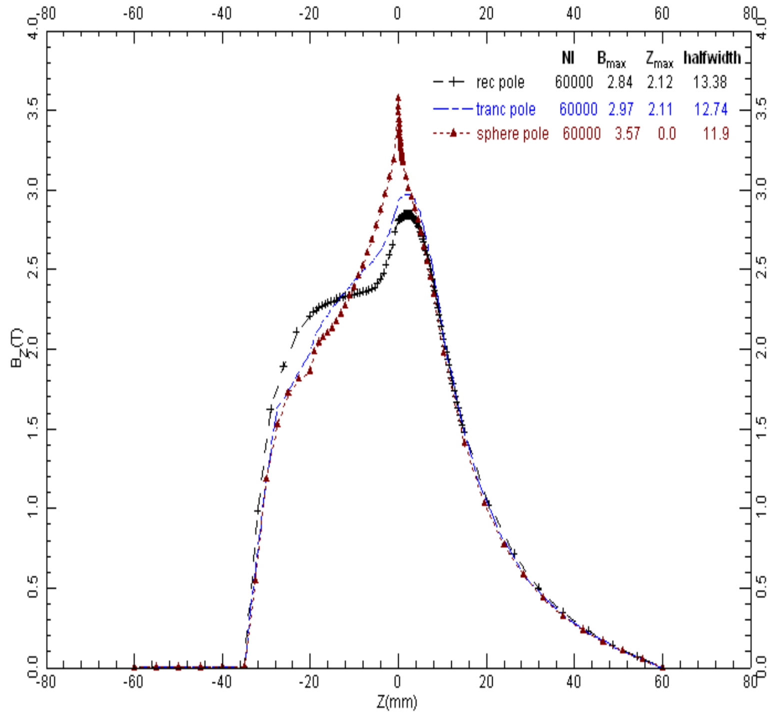


Fig.3:The axially magnetic field flux (Bz) for test lens for different pole-faces

From the figure, it is noticed that the axial flux density distribution of the lens with a spherical –face pole piece is better than that with a flat ended pole piece due to its higher peak and smaller half width. The maximum value of the axial magnetic flux of single pole piece lens with a spherical face is of 20.5 % higher than that with rectangular pole – face and of 16.5 % higher than that with a truncated cone pole – face EOD program allowed viewing the distribution of the magnetic field lines around the lens and 3D view. Figure 4 presents axial field of saturated single pole-piece lens and 3D viewing.

ISSN 1857-8179 (paper). ISSN 1857-8187 (online). http://www.anglisticum.mk
Proceedings of the 1st International Conference on New Horizons in Basic and Applied Science, Hurghada – Egypt, Vol 1(1), 2013.

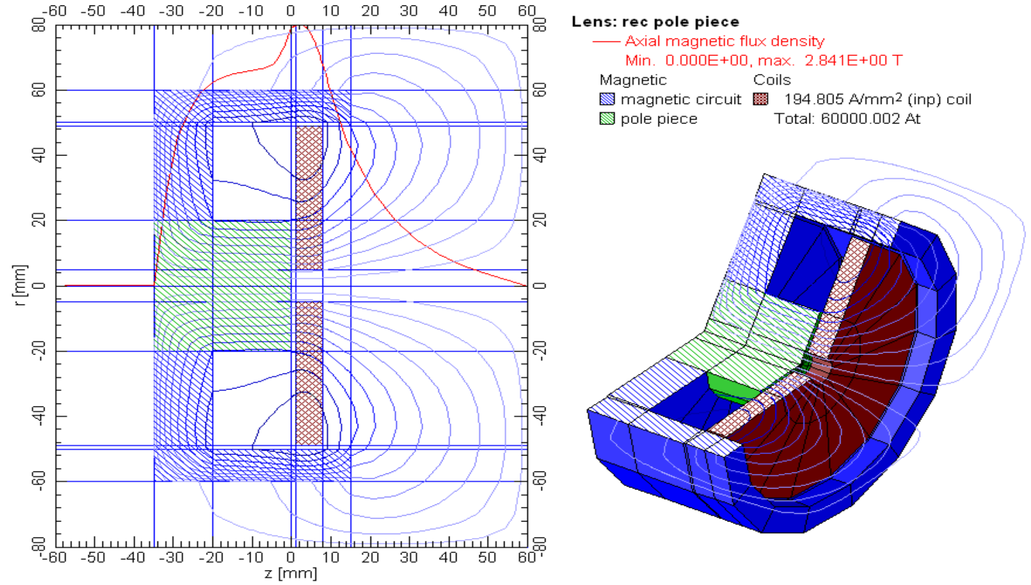


Fig 4a: axial field of saturated rectangular single pole-piece lens and 3D view.

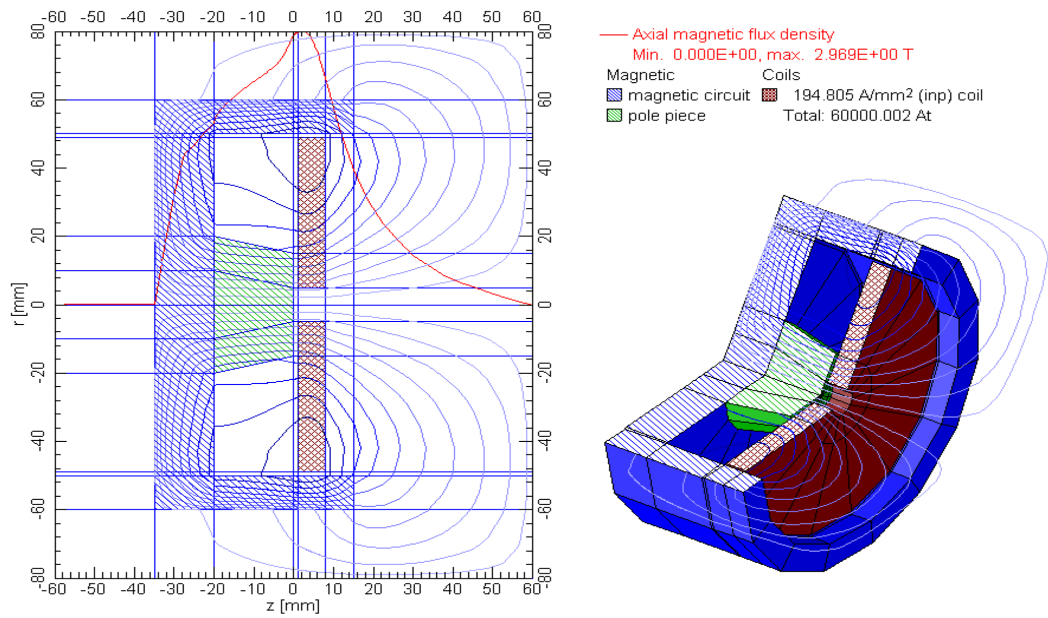


Fig 4b: axial field of saturated truncated cone single pole-piece lens and 3D view.

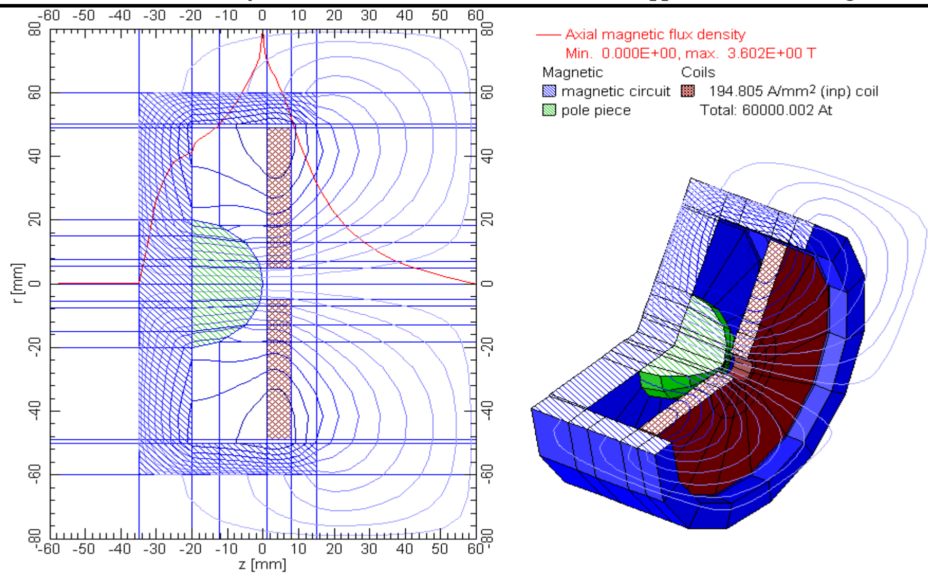


Fig 4c: axial field of saturated spherical single pole-piece lens and 3D view.

Objective optical properties

The objective lens with the highest possible axial flux density and smallest half width gives low chromatic and spherical aberration [14]. Figures 5 , 6 and 7 show respectively, the variation of the objective focal length (f_o), spherical aberration parameter (C_s) and chromatic aberration parameter (C_c) as functions of the excitation parameter ($\frac{NI}{\sqrt{V_r}}$) for different pole –face shapes. Figures 8, 9 and 10 show the variation of minimum aberration coefficients and minimum focal lens as functions of excitation parameter for different pole shapes.

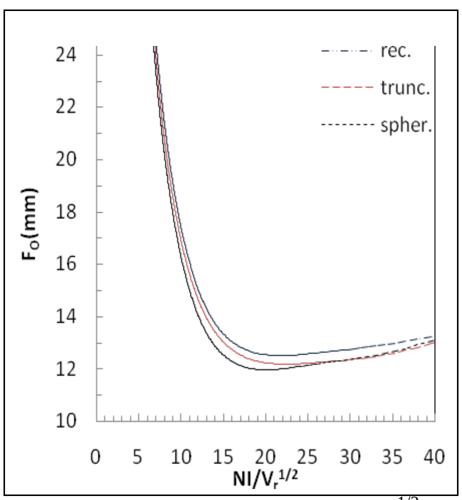


Fig.5: The variation of F_o with $NI/V_r^{1/2}$ for different pole –face shapes.

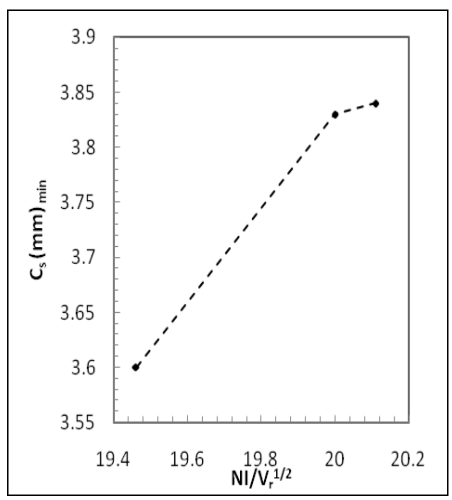


Fig.8: The variation of C_s (mm) $_{min}$ with $NI/V_r^{1/2}$for different pole –face shapes.

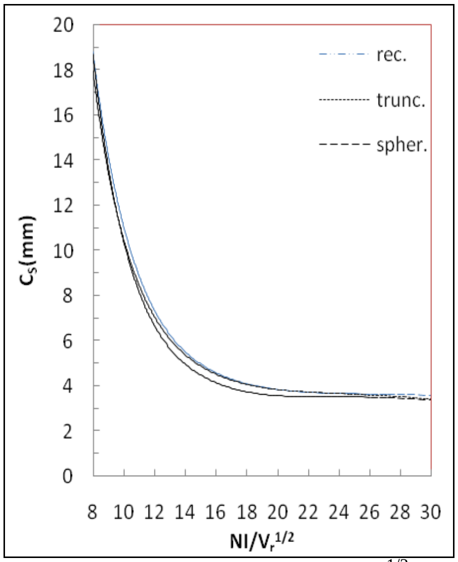


Fig.6: The variation (C_s) with $NI/V_r^{1/2}$ for different pole –face shapes.

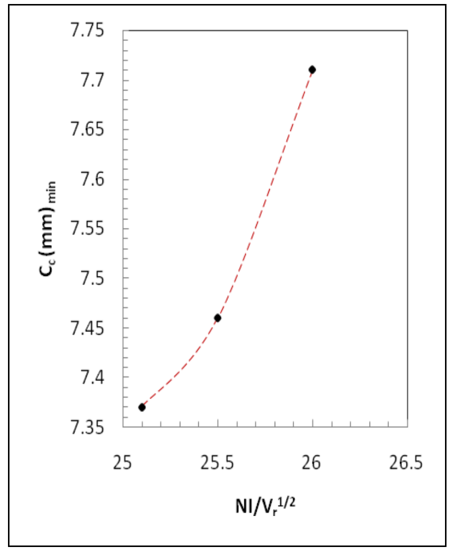


Fig.9: The variation of $C_c\,(mm)_{min}$ with $NI/V_r^{1/2}$ for different pole –face shapes.

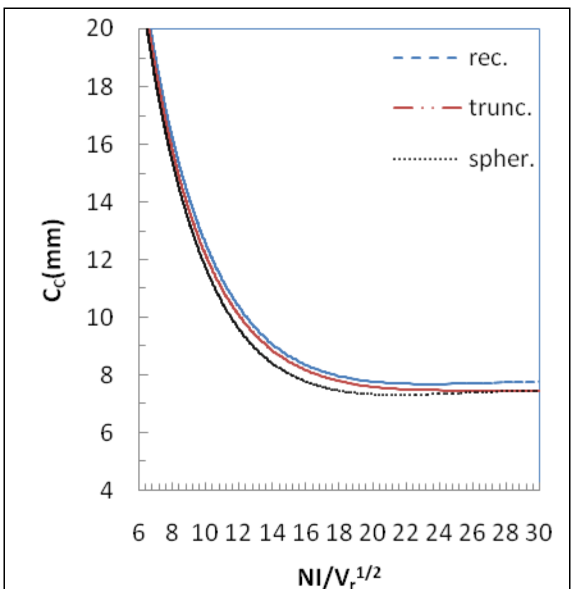


Fig.7: The variation of (C_c) with $NI/V_r^{1/2}$ for different pole –face shapes.

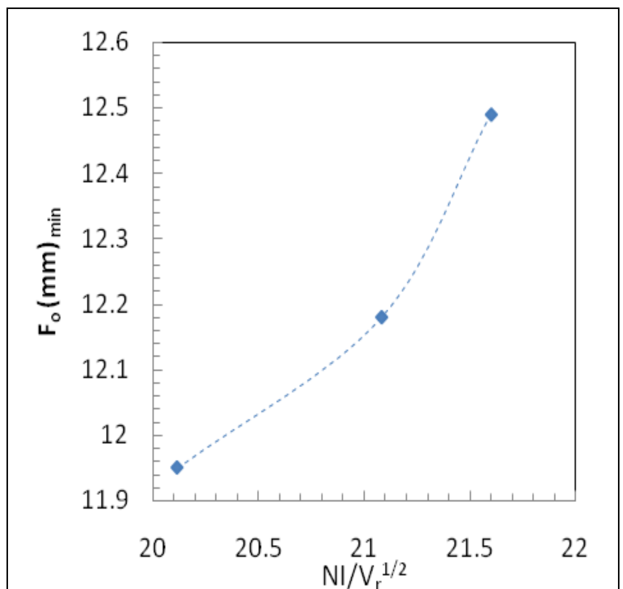


Fig.8: The variation of $F_o\,(mm)_{min}$ with $NI/V_r^{1/2}$ for different pole –face shapes.

From figures 5 to 8, rectangular single pole piece lens used as objective lens at an accelerating voltage of 8.9 MV for operation at 1MV ($v_r = 2MV$) it must be scaled down by a factor K is 0.15, namely with an overall diameter of 120 mm to 18.08 mm, an excitation of 9039.7 A-t and a current density 129870.6 A/cm^2 .Hence F_{obj}=1.87mm, C_c=1.15mm, C_s=0.576mm corresponding the resolution $\partial = 0.0976$ nm. The lens with truncated-cone pole used as objective lens at an accelerating voltage of 9 MV ($v_r = 90MV$) For operation at 1MV it must be scaled down by a factor K is 0.149 down from an overall diameter of 120 mm to 17.88 mm, an excitation of 8944.3 A-t and a current

ISSN 1857-8179 (paper). ISSN 1857-8187 (online). http://www.anglisticum.mk
Proceedings of the 1st International Conference on New Horizons in Basic and Applied Science, Hurghada – Egypt, Vol 1(1), 2013.

density 130679.8 A/cm^2 .Hence F_{obj}=1.81mm, C_c=1.11mm, C_s=0.57mm and $\partial = 0.0974$ nm. Further calculation show that spherical single pole-piece lens used as objective lens at an accelerating voltage of 9.5 MV for operation at 1MV it must be scaled down by a factor K is 0.14 down from an overall diameter of 120 mm to 17 mm, an excitation of 8496 A-t and a current density 137576.3 A/cm^2 .Hence F_{obj}=1.69mm, C_c=1.04mm, C_s=0.51mm and $\partial = 0.0947$ nm.

Conclusions

The pole piece shape has small effect on the electron optical parameters. Single pole piece lens with spherical face is a favorable pole shape. It has smallest optical properties and it can lead to better resolution in electron microscope .The minimum aberration parameters (spherical aberration and chromatic aberration) and focal lens occur at lowest excitation parameter $NI/V_r^{1/2}$ and high acceleration voltage.

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