Simulation and Optimization of the Optical Properties of an Einzel lens

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Abstract
The simulation and optimization calculations were carried out for an einzell lens consists of three overlap cylindrical electrodes with the same length but with different electrode diameters under point-to-point focusing condition. The effects of the overlap distance (d) between the central and the outer cylindrical electrodes on the optical properties of an einzell lens were investigated. The results showed that the increasing of the overlap distance (d) will improve the aberration figures of the images, where by increasing the overlap distance (d) from 2 mm to 6 mm the dimensions of the image were reduced by about 50% for both y and z-directions. The results appeared that both the dimensions of the lens, and the aberrations can be reduced at the same time without affecting the homogeneous distribution of an electron-beam kinetic energy of at the image plane.

Keywords: electrostatic Einzel lens, charged particles optics, electron optics, aberration figures

1. Introduction
One of the important parts in the electron and ion optical system is the electrostatic lens [1, 2]. The einzell lens is one of the most used types of this lens in a widely range of applications, where it is used, for example, in the electron microscopy, ion-mass spectroscopy systems [3], and ion beam extraction system [4], electron energy analyzer [5], finely ion-beam focusing system [6], digital accelerator [7].

The importance of einzell lens is appearing when the ratio of the initial to final energy of the charged particles is required without changing the position of the image [2], where this property cannot be achieved with two-element lenses, i.e. the einzell lens is the best choice for the systems which need to the focusing without changing the energy of the both sides of the lens.

The simplest design of the round einzell lens is consist of three cylindrical electrodes. The outer electrodes of the einzell lens with constant voltage, while the middle electrode with different value of voltage, and this voltage distribution on the three electrodes will lead to the same value of the energy at the object and image sides of the lens [1, 8].

The einzell lens can be used to accelerate or decelerated the electron-beam kinetic energy; therefore, the einzell lens can be designate as accelerating or decelerating lens according to this property. The einzell lens can be classified to a symmetric and antisymmetry lens, where if the all cylindrical electrodes have the same geometrical dimensions, then the lens is denoted as a symmetric lens; otherwise, the lens is antisymmetry lens [1, 8]. Due to the importance of the einzell lens in many applications, its characteristics and designs have been studied by many researchers (see [9, 10, 11, and 12]).
The present work aims to study the properties of the einzel lens of the same electrode lengths, but with a different diameter between the outer and central cylindrical electrodes. The present work concentrated upon the study the optical properties of the lens in the case of the design with overlap distance between the outer electrodes and central electrode as is shown in figure 1. The effects of this overlap distance (d) on the optical properties, especially the aberration of the image will be investigated. These effects and properties will be studied with the aid of SIMION 8.1, the simulation software in the field of the charged particles optics.

2. Geometry and Calculation Procedure

The calculations were carried out of the einzel lens consist of three cylindrical electrodes of the length 25 mm. The diameters of the outer cylindrical electrode are 30 mm, and the diameter of the central cylindrical electrode is 24 mm. This design has an overlap distance (d) at the edges of the central electrode with both outer electrodes. The two outer electrodes were hold at the same voltages V1 and this voltage is V1= 0, while the central electrode was hold at different voltage V2.

The reference point of the lens (R) is selected to be at the middle of the central electrode (x=0). Both distances to the left and right of the reference point (R) were denoted by P and Q, respectively, where P and Q are the object and the image distance, respectively.

The simulation in the field of the charged particle optics SIMION [13] gives a good understanding to the physical principles of this branch of the physics and provides clear imagine to the designer to understanding the behavior of the charged particle beam inside the focusing systems (see, for example: [14, 15]).

In the present work, the results were determined for an electron-beam with 100 eV. The effects of increasing the overlap distance (d) on the optical properties were studied to found best operation condition and the suitable geometrical design which leads to the optimum properties. The criterion of the present work was finding the minimum aberration in the image, and the maximum image radius is less than 0.1 mm.

![Figure 1 Three-dimensional view of the einzel lens.](image-url)
3. Results and Discussion

One of the important aims of the present work is to show the effects of the overlap distance (d) on the optical properties of the einzel lens, where the increasing this parameter will reduce the geometrical dimensions of the charged particle systems and devices. To show these effects the determinations carried out for point-to-point operation condition to the electron-beam of the initial energy 100 eV with object and image distance P/D_{out} = 4 and Q/D_{out} = 4 for a number of values of the overlap distance d = 2, 4 and 6 mm.

The first important step of the calculations is finding the suitable voltage of the central electrode V_2 which gives the image at the certain focal point according to the criteria of the present work. Therefore, the relation between the voltage of the central electrode (V_2) and the focal length of the lens were investigated for a number of values of d, and the results are shown in figure 2 and the values are listed in table 1. Figure 2 and table 1 show that the values of the central electrode voltage (V_2) decrease with increasing the focal length, while this electrode voltage decreases with decreasing the value of the overlap distance (d).

![Figure 2](image.png)

The relation between the central electrode voltage (V_2) and the focal length for a number of values of the overlap distance (d); d = 2, 4 and 6 mm.

| Focal length (mm) | d = 2 mm | d = 4 mm | d = 6 mm |
|-------------------|----------|----------|----------|
| V_2 (volts)       | V_2 (volts) | V_2 (volts) |
| 120               | 259.3    | 267.5    | 273.5    |
| 130               | 250.3    | 257      | 262.4    |
| 140               | 241.8    | 247.5    | 254      |
| 150               | 234      | 239.2    | 244.3    |
| 160               | 226      | 232      | 236.8    |

The distribution of the equipotential surface of the lens was shown in figure 3, and in this figure, one can notice the difference between the distributions of these equipotential surfaces inside the...
lens. This difference will lead to different behavior of the electron-beam inside the lens, and this behavior will affect the optical properties of the lens.

One of the sequential equipotential surface distributions is the electron-beam trajectories, where this distribution forces electron-beams to take specific paths or trajectories. The electron-beam trajectories were shown in figure 4 for P = Q = 4 D_{out} and the initial angle of the electron-beam α = 0.3°, this figure appears that the width of the electron-beam inside the lens decreases with increasing of the overlap distance (d), and that means the focusing of the electron-beam will be greater when the values of the overlap distance (d) is increasing. This behavior will be an important parameter to specify the other optical properties of the system, especially on the image aberration figures.

Figure 3 Equipotential surface distribution of an einzel lens for a number of the values of the overlap distance (d); d = 2, 4 and 6 mm.
Figure 4 The electron-beam trajectories for \( P=Q=4D_{\text{out}} \). The values of the central electrode voltages (\( V_2 \)) were taken from table 1. The initial energy and angles are 100 eV and 0.3°, respectively.

To know the importance of the role that the overlap distance (\( d \)) can play in optimization calculations, the effect of the overlap distance (\( d \)) on the aberration figures of the image was studied for several values of \( d \). The calculations were carried out for \( d=2 \), 4 and 6 mm, also the effects of the starting angles of the electron-beam were taken into account where \( \alpha=0.1°, 0.3° \) and \( 0.5° \) in the calculations and the results are shown in the figure 5. From this figure, one can notice the important role that the overlap distance (\( d \)) can play in the reduction of the aberration, where the results show that the increasing of the overlap distance will improve the aberration figures. Both \( \Delta y \) and \( \Delta z \) were minimized by increasing \( d \) values, where the minimum values of \( \Delta y \) and \( \Delta z \) were found at \( d = 6 \) mm, i.e. the electron-beam spot at the image plane at \( d = 6 \) mm is smaller than at \( d = 2 \) and 4 mm, and these results are true for all values of starting angles of the electron-beam. Also, the results appear that the small angles of the electron-beam give the images with low distortion at the image plane. Table 2 gives exact values of \( \Delta y \) and \( \Delta z \) for a number of values of the overlap distance (\( d \)) and initial electron-beams angles (\( \alpha \)).

Figure 5 Aberration figures of an einzel lens for a number of values of the different values of the overlap distance (\( d \)) and initial angles (\( \alpha \)).
Table 2 The parameters of an einzel lens for a number of values of the overlap distance (d) and initial angles (α).

| launching angle (α) | d = 2 mm | d = 4 mm | d = 6 mm |
|---------------------|----------|----------|----------|
| α = 0.1°            | 0.0047   | 0.0052   | 0.0037   |
| α = 0.3°            | 0.013    | 0.0083   | 0.01     |
| α = 0.5°            | 0.019    | 0.0185   | 0.013    |

The effects of the overlap distance (d) on the kinetic energy distribution of the electron-beam were studied, and this distribution is shown in figure 6 for the electron-beam spot at the image-plane. In his figure, the kinetic energy was determined for an electron-beam with initial energy 100 eV and initial angle α=0.3°. From this figure, the results show that the kinetic energy distribution homogeneous for all values of overlap distance (d), where the maximum difference between the kinetic energy is at about 0.01 eV, and this difference is very small and can be neglected. Therefore, the increasing of the overlap distance (d) gives a good enhancement to the aberration figures without changing the kinetic energy distribution of the electron-beam at the image plane.

Figure 6 The kinetic energy distribution of the electron-beam at the image plane for different values of overlap distance (d); d = 2, 4 and 6 mm.
4. Summary and Conclusion

The simulation calculations were carried out for an einzel lens with unequal diameters of the central and outer electrodes, to show the possibility of improving the lens properties by changing the overlap distance (d).

The results show that this parameter can play an effective role in improving the optical properties of the einzel lens, where by increasing this distance the distortion or aberration of the image can be reduced. By increasing the overlap distance (d) from 2 mm to 6 mm the dimensions of the image were reduced by about 50% (where both Δy and Δz were enhancement by about 50%).

The advantage of the present results is reducing the aberration of the image and minimizing the geometrical dimensions of the lens via increasing the overlap distance (d), simultaneously. Furthermore, the calculations appear that this improving unaffected the kinetic energy distribution of the electron-beam.

Also, this simulation method gives a good understanding to the charged particle optics principle of the einzel lens and that very important to understand the effective parameters to reach to optimum design.

References

[1] Yavor M 2009 Advances in Imaging and electron Physics vol 157: Optics of Charged Particles Analyzers, p 100.
[2] Szilagyi M 1988 Electron and Ion Optics, Plenum Press, New York, p 461.
[3] Orloff J 2009 Handbook of charged particle optics, CRC Press, Boca Raton, p 171.
[4] Toivanen I V, Kalvas T, Koivisto J, Komppula J and Tarvainen O 2013 Double einzel lens extraction for the JYFL 14GHz ECR ion source designed with IBSimu, J. Inst. 8 pp1-21.
[5] Maeda N 1982 Electron Energy Analysis Using an Einzel Lens, Japan. J. Appl. Phys. 24(2) p 671.
[6] Kurihara J 1985 Low-Aberration Einzel Lens for a Focused-Ion-Beam System, Jap. J. Appl. Phys. 21(4): pp 225-230.
[7] LeO K W, Adachi T, Arai T and Takayama K 2013 Einzel lens chopper and behavior of the chopped beam in the KEK digital accelerator, Phys. Rev. ST Accel. Beams 16: 043502.
[8] Helmut L 2008 Applied Charged Particle Optics, Springer-Verlag Berlin Heidelberg.
[9] Saito K, Okubo T and Takamoto K 1986 Design method for an electrostatic einzel lens having an asymmetric structure, J. Vac. Sci. Technol. A 4 (2): pp 226-229.
[10] EI-Kareh A B 1971 Analysis of the 3-Tube Asymmetrical Electrostatic Unipotential Lens, J. Appl. Phys. 42 (12).
[11] Gillespiea G H and Brown T A 1997 Optics elements for modeling electrostatic lenses and accelerator components i. einzel lenses, IEEE Xplore: Particle Accelerator Conference, Proceedings of the 1997, vol 2.
[12] Rempfer G F 1985 Unipotential electrostatic lenses: Paraxial properties and aberrations of focal length and focal point, J. Appl. Phys. 57 (7): pp 2385-2401.
[13] SIMION 3D v8.1, Scientific Instrument Services Inc. (www.simion.com).
[14] Hussein O A 2017 Comparison between the imaging properties of two different types of electrostatic quadrupole doublet lenses, Optik 140: pp 860–865.
[15] Sise O, Okumus N, Ulu M and Dogan M 2009 Computer simulation of electrostatic aperture lens systems for electron spectroscopy, J. Electron Spectroscopy and Related Phenomena 175: pp 76–86.