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Multi-element cylindrical electrostatic lens systems for focusing and controlling charged particles

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Abstract

This paper describes theoretical modeling of electrostatic lenses based on three, four and five closely spaced cylindrical electrodes. In each case, modeling is carried out numerically using commercial packages SIMION and LENSYS, and a variety of performance parameters are obtained. Special cases such as a zoom lens (i.e., lenses whose magnification may be changed without losing focus) are considered. Results are obtained as a function of the ratios of the electrode lengths and gaps, and as a function of ratios of the controlling voltages. As a result, how a multi-element lens system can be operated with the whole focal properties in a useful mode for experimental studies is shown.

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Keywords: Multi-element lenses; Electron optics; Focal properties; Zoom lens; SIMION; LENSYS

1. Introduction

Electrostatic cylinder lenses are widely used to control beams of charged particles with various energies and directions in experiments covering many fields of applications including electron spectroscopy, surface science and mass spectroscopy. One of the fundamental goals in the design of electrostatic lenses is to keep lens parameters constant over a wide range of voltage ratio of final-to-initial energy. Lenses used in this way are often referred to as 'zoom' lenses. So far, there have been several attempts to determine the zoom-lens properties of multi-element electrostatic lenses with the whole focal properties.

In the 1960s, two-element electrostatic lenses have been used in low-energy electron spectrometers to increase sensitivity and resolution [1–3]. However, it is well known that a two-element lens cannot keep the image position constant while varying the ratio of final-to-initial energy. For that reason, it is necessary to add at least one further element to the system. The three-element lenses can be operated while keeping the image position constant. Details of the properties of two- and

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three-element lenses can be found in the literature [4–14]. The focal properties of three-element lenses with zoom type of optics have been obtained by Read and coworkers for various diameters and voltage ratios with special focusing characteristics [15–19]. Heddle and coworkers did a more extensive analytical calculation and generalized experimental results for three-element lenses [20–22]. One of the types of the three-element lens is as an "einzel" lens in which the outer electrode is held at the same potential and beam focusing is achieved by varying the potential of the center electrode. These lenses are necessary when a beam is to be focused without changing its energy [23–27].

Three-element lenses can be used to aid the design of lenses having a fixed image position, but the magnification is not constant. However, four-element lens systems can be operated with a constant magnification while keeping the image position also constant. Although multi-element lenses are both effective and flexible for controlling charged particles, two- and three-element lenses have been studied more often than four-element lenses due to the ease of operation. Several zoom lenses which consist of four elements have been used to ensure that focusing in the monochromator and analyzer optics would be independent of the electron kinetic energy [28,29]. The four-element lenses have been investigated experimentally [30] and theoretically [31,32], and it has been shown that the lens system with four elements is necessary to produce an image at a specific position with constant magnification. Martinez and Sancho [33] later did an extensive study including spherical aberration effects for a variety of configurations of four-element lens systems having $A/D = 0.5$ (where A is the length of the center electrodes including half the gap to each side). A four-element lens with zoom type described by Martinez et al. [34] has been used recently in the low-energy electron–molecule scattering experiments to provide a constant image position and magnification [35]. Böker et al. [36] have presented several different configurations of four-element lens systems operated in angular resolving mode, and showed that this lens configuration was compatible with applications involving photoemission spectroscopy. Apart from this dimension, it is also possible to operate these lens systems for $A/D = 1$. To our knowledge, this mode has only been mentioned in Milosavljevic et al. [37], but no detailed study has been published yet.

Based on the concerns described above, in an electrostatic lens system, quantitative information is required over a wide energy range and a zoom-type of optics is needed. If the magnification is to remain constant over a wide range of energies, quite complicated electrostatic lens systems are required, containing three, four, or even more lens elements. Electrostatic lens systems with more than four elements are generally used in experimental studies to maintain a truly zoom lens with constant magnification overall voltage ratios [38,39]. Additionally, five- and more element electrostatic lenses can be operated in the afocal mode in which rays incident parallel to the axis leave the lens system still parallel to the axis [40,41]. A five-element afocal case with a parallel beam and well-defined angles gives an excellent beam geometry which is especially useful for electron impact studies [42]. In this case, the lens system is operated with two lenses located such that the second focal point of the first lens coincides with the first focal point of the second lens. The focal properties of such multi-element afocal lenses are derived from calculated data of three and four element lenses. In the literature, an experimental study of a five-element lens was made by Heddle and Papadovassilakis [43] for an afocal lens described by Heddle [41] and for a true-zoom lens. Trager-Cowan et al. [44] described the behavior of two five-element lens systems by using standard matrix methods and calculated focal properties and spherical aberration coefficients. These two latter studies have concentrated on a five-element lens system having $A/D = 1.5$.

In the present work, the properties of multi-element electrostatic lens systems are investigated by using the electron ray-tracing simulation programs, SIMION [45] and LENSYS [46], for several configurations (the use of LENSYS and SIMION to numerically characterize these lens systems is novel). The objective of our modeling is to provide a guide for the design of any electrostatic lens system for controlling and focusing charged particles. With a long series of simulations, we present