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Optimization of an electrostatic quadrupole doublet focusing systems

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ABSTRACT

The imaging properties of an electrostatic quadrupole doublet lens were analyzed with the aid of computer simulation. The optimal electrode voltages which lead to stigmatic image in both planes of the quadrupole doublet lens with minimum spot size at position sensitive detector (PSD) were found for two operation modes: point-to-point focusing and parallel-to-point focusing. The optical properties as: Magnifications, spot sizes in the image plane and aberration figures were discussed. The results showed that the focusing of the lens was strong in the *xy*-plane in comparison with the focusing in the *xz*-plane. The distortion of the image was greater when the image position will be close to the lens in comparison with object position. Also, the imaging properties were very sensitive to the lunching angle of the electron-beam.

1. Introduction

In quadrupole lens, the field has two perpendicular planes of symmetry and two planes of antisymmetry. Such a field can be made by four identical electrodes located symmetrically relative to the axis, to which alternating potentials and the potentials are applied. The quadrupole lens has zero axial potential. Note that the potentials are measured from the axial potential as the reference point [1,2]. Because of the wide range of using of quadrupole lenses in different fields of science and technology, many researchers studied briefly the theory and application of quadrupole lenses (see [3–6]).

The stigmatic imaging is the property of axially symmetric fields in the first-order approximation. This property is absolutely important for the purposes of electron microscopy. While, there are many applications (as: mass spectrometers, particle accelerators, vacuum tubes, and also, even electron and ion probes) where stigmatic imaging is not required. In fact, in particle accelerators the role of beam optics is only to keep the beam together, analyze its parameters, and guide it to the experiments. In this case, no image has to be created [7].

It is necessary in some applications the departure from axial symmetry, particularly, when the strong focusing action is required. Quadrupole lenses are mostly used in high-energy beams because they are stronger focusing than rotationally symmetric lenses [8]. Subsequently, it is greatly improved to employ quadrupoles, whose fields are nearly perpendicular to the optical axis. Furthermore, a system of quadrupole can produce a stigmatic image [7].

One of the important applications of electrostatic quadrupole doublet lenses is in the focusing MeV heavy ions. In the case of MeV heavy ion beam there are two methods of lenses for focusing. The first is by using the magnetic quadrupole lens and the second via the electrostatic quadrupole lens. To select the lens type, the energy and mass of the primary ion should be considered. The most important parameter for MeV imaging is the secondary molecular ion yield [9].

The energy, mass and charge of the ion are the limits of quality of a magnetic quadrupole lens, and it is not easy to focus ion beams of high-energy and heavy mass. By difference; an electrostatic quadrupole lens is mass independent in the focusing process; therefore, it can be used to focus heavy ions with more efficiency in comparison [10]. Moreover, the selection of the electrostatic quadrupole lens to focus the heavy-ion beams of high energy because it is compact and light with respect to the magnetic quadrupole lens [9].

With the aid of magnetic storage rings and at rest in electrostatic traps, the high energies ions play a greater role in experiments to understand the complex nature of many particle systems. With these storage rings of high repetition rates and with the aid of new ability of imaging, the single particles could be analyzed with high-accuracy [11]. Despite these possibilities of magnetic storage rings,

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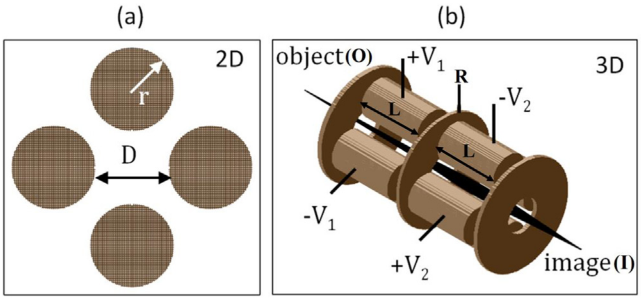

Fig. 1. 2D and 3D views of an electrostatic quadrupole doublet lens. Here, $r = 1.14511R$, $R = D/2$ [2].

its energy ranges not enough to cover many fields like selective fragmentation of heavy biomolecules. Therefore, electrostatic storage rings are developed to this role and became important part of new facilities [12–15]. The growth of the beam size is one of the important problems in storage rings due to initial divergence of an ion beam. Therefore, the electrostatic quadrupole lenses are used as counteracting force to prevent the particles hit the walls. Therefore, to produce overall focusing effects in both planes the combination of at least two quadrupole lenses must be used [11].

The aberration correctors are another application of the electrostatic quadrupole lenses where the electrostatic lenses were used to correct both spherical and chromatic aberration for scanning electron microscope (SEM) [16] and then the spherical aberration correction was achieved for TEM or scanning TEM (STEM) [17]. The electrostatic quadrupole lenses can be used into two methods in correcting both spherical and chromatic aberrations at low accelerating voltages for SEM, low-energy electron microscope (LEEM), photoelectron emission microscope (PEEM) and focused ion beam systems (FIB) [8]. The first, by creating negative chromatic aberration by combined magnetic and electrostatic quadrupoles and octupoles generate aperture [16]. The second, by producing the chromatic aberration via electrostatic quadrupoles and octupoles combined with retarding potential and negative spherical aberration is generated by using octupoles [18].

The computer simulations can be used to quickly understanding to the new designers in the field of charged particles optics and its applications [19,20]. In the present work, the characteristics of an electrostatic quadrupole doublet lens were investigated for point-to-point focusing and parallel-to-point focusing operation modes by using SIMION 8.1 [21]. The important point in the focusing of the electrostatic quadrupole double lens to find stigmatic image is finding the electrode voltages combinations of the lens which give this image. Therefore, the calculations were carried out to find these electrode voltages combinations which give the stigmatic image with minimum spot size on the image plane. The effects of changing the positions of the object plane (the position of the electron-beam source) and the image plane with respect to the lens position on the imaging properties of the focusing system were studied, and the comparisons between the aberration figures in the image plane were made. Also, the effects the lunching angle of the electron-beam on the imaging properties were investigated.

2. Computational methods

2.1. Geometry

The charged particle optics simulation software 3D SIMION 8.1 [21] was used to study the characteristics of the symmetric electrostatic quadrupole doublet lens shown in Fig. 1. The system optically consists of two single quadrupole lenses with three apertures. The diameter of the lens (D) is 40 mm (the diameter of a circle with the edges of electrodes). The electrode length (L) of each single quadrupole lens is 80 mm ($L = 2D$). The radius of the electrode (r) is chosen according to the equation: $r = 1.14511R$, $R = D/2$ [2]. The gap between two lenses (d) is 30 mm, and an aperture is putted at the middle distance between the two lenses. The distance between the first aperture and the first lens (t) is equal to the distance between the second lens and the third aperture (t) and equal to 15 mm. The diameter of all apertures is equal, and it is equal to the diameter of the lens (D). The object (O) was assumed to be at the left hand end of the first aperture and the image (I) at the right hand end of the third aperture. The reference plane (R) was chosen to be at the center of the lens. Also, we will refer to the distance between the object position and the reference plane of the lens (R) by P, while the distance between the image position and the reference plane of the lens (R) by Q.

2.2. Optimization

The charged particles optics simulation package SIMION 8.1 [21] was used to study the behavior of the electrostatic quadrupole doublet lens. The geometry file was written to the lens system under investigation (Fig. 1). Code was written by using LUA language to search of the optimum electrode voltages which give the stigmatic image simultaneously in xy-plane and xz-plane, the computations were made for two operation modes: point-to-point focusing and for parallel-to-point focusing. The computations were achieved by variation the two lens voltages V_1 and V_2 to find the minimum spot size at position sensitive detector (PSD). In present calculations for the point-to-point focusing mode, the maximum radius of the stigmatic image (r_m) on PSD was considered to be $r_m = 0.1$ mm for initial electron-beam with the lunching angle $\alpha = 0.1^\circ$ and initial energy 100 eV. While, in the case of parallel-to-point focusing mode, the maximum radius of the stigmatic image (r_m) on PSD was considered to be $r_m = 0.1$ mm for initial circular electron-beam with radius 1 mm and initial energy 100 eV. Also, one must notice that the maximum radius of the stigmatic image (r_m) was considered on the assumption that the shape of the image is circular, but in the fact, because there is a distortion in the image, the shape will not be circularly. Therefore, $r_m = \Delta z/2$ for z-direction and $r_m = \Delta y/2$ for y-direction, where Δz and Δy are the widths of the image in yz-plane for z-direction and y-direction, respectively. Therefore, the conditions will be $\Delta z/2 < 1$ mm for z-direction $\Delta y/2 < 1$ mm for y-direction, for non-circularly image shape.

The electrons were used in this work for simulation, but one can use the positive ions by changing the signs of electrode voltages in Fig. 1.

3. Results and discussion

In an electrostatic quadrupole doublet lens, there are two adjustable voltages that should be optimized to fix image position and magnification. For point-to-point focusing mode, Fig. 2 shows the optimized voltages of the lens for the point-to-point focusing. In this figure, the calculations of optimized voltages combinations took into account the effects of changing the object position (electron-beam source position) and image position with respect to the lens position. These effects are important in some applications, especially; when one need to find addition distance to doing the experiment. These calculations were achieved by choosing unequal distance for object and image planes. Therefore, the search for optimum electrode voltages was made for different cases; $P/D = 4$ and $Q/D = 6$, $P/D = 5$ and $Q/D = 5$, and $P/D = 6$ and $Q/D = 4$; and the behavior through the lens was studied in each case with constant launching angle of an electron-beam ($\alpha = 0.1^\circ$) and the initial energy = 100 eV with maximum image radius at the PSD $r_m = 0.1$ mm. Fig. 2a, c and