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Low-aberration optics for large-angle beam with unit core lenses

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ABSTRACT

The characteristics of core lenses are numerically examined for a large-angle beam whose aberration is huge for a circular-lens system. The unit core lens, which both, focuses and deflects, is defined by ring charges. The geometric and energy aberrations are analyzed using the diagrams of axis-intercept. For a single unit core lens or two cascaded unit core lenses, the aberrations cannot be commonly reduced over a wide range of initial beam conditions. By cascading three unit core lenses, both geometric and energy aberrations are small for a symmetric-trajectory beam over a wider range of initial beam conditions. In addition, a procedure for searching suitable conditions is explained because the number of setting parameters is 12. An example shows that taking diffraction aberration into account, the resulting beam diameter is 4.7 nm for 10 keV beam energy.

1. Introduction

Electron optics with electrodes on a rotationally symmetric axis was proposed by Gabor, who proposed a way to correct for spherical aberration from a circular objective lens [1]. This idea was then expanded by Hoppe, Plies, and Typke in the 1970s and applied to the large-angle beams of three-dimensional (3D) electron microscopes [2–4]. They called the center electrode the “core.”

In this article, we focus our discussion on low-aberration optics with core lenses for stereoscopic beams with a large angle of more than 5° with respect to the rotationally symmetric axis. In our previous work, we proposed using the diagrams of axis intercept to analyze such large-angle beams in an electrostatic core-lens system [5,6]. For core lenses, it is easy to find operational conditions that minimize either the geometric or energy aberration. Both the aberrations strongly depend on the center trajectory of the beam flux, which shifts as a function of the selection of parameters with respect to the field arrangement and the initial beam conditions. Therefore, it is usually difficult to simultaneously minimize both aberrations.

Here, we define a unit core lens that has the combined properties of a unipotential lens and a deflector. By combining unit core lenses, we examine the operational conditions that minimize both aberrations. To simplify the calculation of electrostatic field, the field near the electrodes is approximated using ring charges. We examine the conditions that minimize the beam diameter when several unit core lenses are combined.

2. Unit core lens

It is known that the electrostatic field for a rotationally symmetrical electrode system can be calculated by superimposing the electrostatic field of ring charges [7]. Here, we apply one ring charge to each electrode to simplify the field calculation because our purpose is to examine the basic properties of core-lens systems. We define a unit core lens as shown in Fig. 1. Three ring charges Q_l, Q_c, and Q_r are aligned on the same axis and have the same radius r_c and same interval z_{gap}, where $Q_l = Q_r = -Q_c/2$. Furthermore, a ring charge Q_o at the position (z_c, r_c) is paired with a coaxial ring charge Q_i with radius r_i, where $r_i < r_c$ or $r_i > r_c$. The charges Q_c and Q_o are at the same position, so that the charges can be summed. We call this charge arrangement a unit core lens. The total charge of Q_l, Q_c, and Q_r is zero and these charges create an electrostatic field similar to that of a unipotential lens. The pair charges Q_o and Q_i have opposite signs and create a deflection field. Similar to the electrostatic field in a shielding tube, the field of a unit core lens quickly decays by moving away from the lens center because the total charge is zero. A unit core lens has six parameters: Q_c, Q_o, r_c, r_i, z_c, and z_{gap}. The position z_c can be replaced by the distance between the object at z_o and the lens center at z_c.

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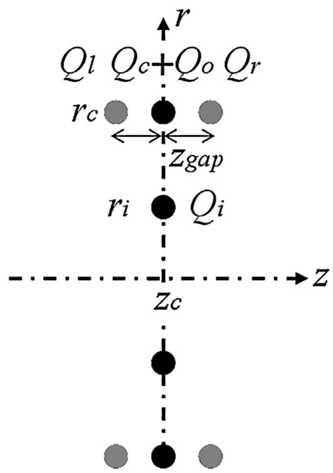

Fig. 1. Arrangement of ring charges in unit core lens with six parameters. Gray and black solid circles indicate the positive and negative charges, respectively. Here, $Q_l = Q_r = -Q_c/2$ and $Q_o = -Q_i$.

3. Ray-tracing analysis

We use the MKSQ system of units from electromagnetics. For the analysis, there are four physical quantities: (1) the position of (r, z) is given by the distance L [m], (2) the charge Q [C] related to the field intensity, (3) the initial electron energy $W_0 = e\phi_0$ [eV] that determines the initial velocity v_0, and (4) the time t [s] in the differential equation. Here, the amount of charge is replaced by $Q^* = (1/2\pi^2\varepsilon_0)\,Q$. The potential and electric field produced by a ring charge are given by

$$V(r, z) = Q^* K(r, z)/l(r, z)\,[V] \text{ and } E(r, z) = -\text{grad}\,V(r, z)\,[V/m] \quad (1)$$

where, $K(r,z)$ is the complete elliptic integral of the first kind and $l(r, z) = \sqrt{(r + r_c)^2 + (z - z_c)^2}$ is the length. The electrostatic field of the unit core lens is given by superimposing the electrostatic ring-charge fields. Time is replaced by $t^* = \sqrt{2e/m}\,t$ to prevent the value of time steps from becoming extremely small in the differential equation. With this substitution, the equation of motion and the reduced initial velocity $\boldsymbol{v}_0{}^*$ simplify to

$$\mathrm{d}v^*/\mathrm{d}t^* = E/2 \text{ and } v_0{}^* = \sqrt{\phi_0} \quad (2)$$

where, $\boldsymbol{v}_0{}^*$ is the reduced velocity.

When we modify the distance L by the factor M_L and the initial energy W_0 by the factor M_W, the charge Q^* and the time t^* have to be multiplied by the factors M_Q and M_T to keep the same trajectory shapes:

$$M_Q = M_L \times M_W \text{ and } M_T = M_L/\sqrt{M_W} \quad (3)$$

The first equation implies that the trajectories maintain the same shape when the field strength and initial energy are proportionally varied. The second equation implies that the required time does not change if the length of electron-optical system and the initial velocity are proportionally varied. Here, t^* is the reduced value but it is simply rewritten as t from here on. We use Mathematica ver.7 for the numerical analysis of field and for ray tracing.

4. Diagram of axis intercept and beam emittance

In rotationally symmetrical optical systems, trajectories that start on the z axis always cross the z axis again. To analyze the geometric and energy aberrations[2] of core lenses, the intercept positions on the z axis are examined for trajectories with different initial angle and energy. Fig. 2 shows the intercept positions and angles. We call this figure the "diagram of axis intercept" [5,6]. When the points horizontally align in a diagram of axis intercept for shifted initial parameters, both geometric and energy aberrations are minimized. Usually, the emittance of beam flux is shown in a diagram where the abscissa and the ordinate are the beam position and the beam angle, respectively. Here, we interchange the coordinates of emittance such that they correspond to the diagram of axis intercept.

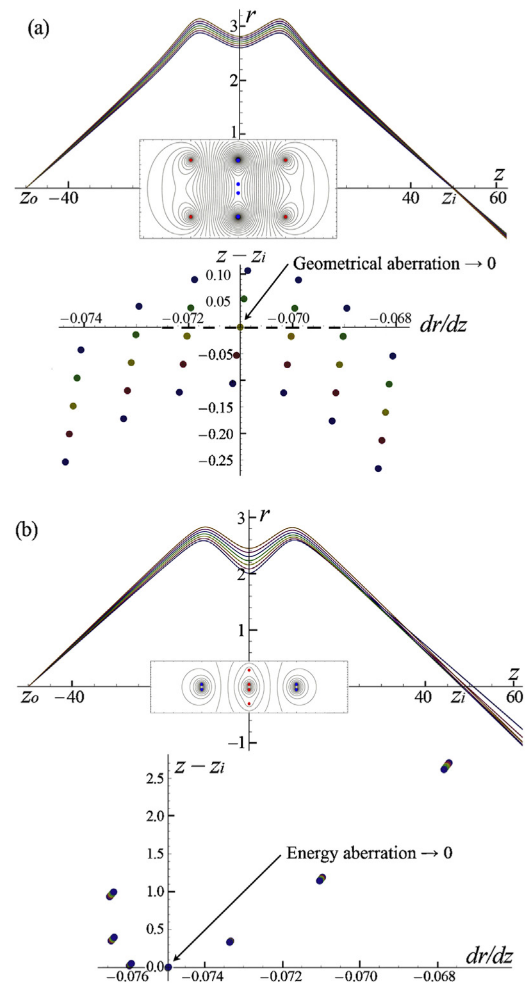

Fig. 2. Typical trajectories and diagram of axis intercept for single unit core lens. Seven points of the same color represent trajectories with the same initial energy, and the five points of different color that are aligned represent the trajectories with same initial angle.

5. Feature of single unit core lens

Typical results for trajectories and the diagram of axis intercept for a single unit core lens are shown in Fig. 2 when either geometric or energy aberration is minimal. The insets below the trajectories show the equipotential lines for ring charges. In the

[2] The axis of beam flux in a core-lens system is curved and the aperture angle related to the geometric aberration is measured from the central trajectory. Here, the geometric aberration corresponds to spherical aberration in axially symmetric optical systems. The energy aberration is the beam spread when the initial energy shifts and includes energy dispersion. The energy aberration here corresponds to chromatic aberration in axially symmetric systems.