Coplanar Multiple-Ring Electrostatic Particle-Beam Lenses

Michael J. Moran

Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94550

ABSTRACT

Electrostatic particle-beam lenses using a concentric co-planar array of independently biased rings can be advantageous for some applications. Traditional electrostatic lenses often consist of axial series of biased rings, apertures, or tubes. The science of lens design has devoted much attention to finding axial arrangements that compensate for the substantial optical aberrations of the individual elements. Thus, as with multi-element lenses for light, a multi-element charged-particle lens can have optical behavior that is far superior to that of the individual elements. This paper discusses the possibility that transverse multiple-concentric-ring lenses can achieve high performance, while also having advantages in terms of compactness and optical versatility.

I. Introduction

Electrostatic lenses use electric fields to focus charged particle beams, but the basic nature of the field distributions results in complicated optical behavior. The electric fields are associated with charge distributions that reside on biased electrodes having specific geometries. Because of the nature of electric fields, a charged particle beam experiences both focusing and defocusing forces as it passes through an electrostatic lens. Thus, the desired focusing effect must be the net difference between the two forces. Furthermore, since the 1/r nature of the Coulomb field has infinite extent, electrostatic lenses tend to be "thick". This means that particle trajectories change substantially while they are passing through a lens.

These complications mean not only that theoretical analysis of electrostatic lenses is complex, but also that electrostatic lenses tend to have substantial aberrations that degrade their performance. The traditional approach to compensating for aberrations has been to use a linear sequence of simple lens elements, such as biased rings, apertures, or tubes, whose individual aberrations compensate for each other. Such a lens system can have an overall performance that is far superior to that of a single lens element. More recently, the advent of software for numerical modeling of lens performance on personal computers has helped to improve the design of high-performance lens systems. These newer designs often use fewer lens elements, but with rather sophisticated three-dimensional geometries.[1]

The present lens system, an array of biased co-planar rings (shown in Fig. 1), has a simple geometry that makes possible high performance from a single lens element. The geometry of this design is conveient for numerical and theoretical analysis, and some simple considerations suggest that the multiple-ring design might be superior to conventional lenses for some applications.. This design has inherently a large number of independent parameters: the number, radii and widths of the rings, and their bias voltages (In the discussion that follows, bias voltage and charge on the rings will be used interchangeably, even though converting from one to the other may not always be easy to accomplish.). For the moment, it is interesting to consider the versatility that is available from a single choice of rings (i.e., number, radii and widths), allowing only for variation of the bias potentials that are imposed on the rings.

Consider then, a multiple-ring lens which, although with zero net charge, exerts net focusing forces for particles passing near the center of the lens. Since the total charge is zero, as the particle leaves the vicinity of the lens, it will experience fields that decay to zero much more quickly than $1/z$. Thus, we expect that multiple-ring lenses can approach the "thin lens" limit much more effectively than single biased elements. Furthermore, within the constraint of zero total charge, it is possible to vary the radial profile of the electrostatic potential distribution by varying the allocation of charges among the rings of the lens. This means that variation of the potentials on the lens rings can be used to control both the radial and longitudinal profiles of the electrostatic fields. While this certainly does not demonstrate superior performance, the argument here suggests that variation of the potentials on the individual rings can be used to control precisely those aspects of the electrostatic field that are important for designing low-aberration systems.

The purpose of this paper is to discuss some basic ideas associated with a multiple-ring electrostatic lens and to describe a prototype lens that is designed to aid in the transport of ions from an ion source to an ion trap. Some simple calculations will demonstrate the degree of flexibility that might be expected from these lenses. Further numerical calculations, using a charged-particle transport code,[2] will demonstrate the performance that might be expected from the prototype lens.

II. Theory

A full description of the motion of charged particles in electrostatic fields requires the solution of higher-order nonlinear differential equations that are derived from Newton's Law and Laplace's equation. Early theoretical work used mathematical simplifications that made analytical solutions possible. Thus, the first-order linear "paraxial" ray equation for axially-symmetric fields leads to so-called "Gaussian" optics for charged-particle that are very similar to their analogs for light-focusing systems. One key aspect of this approach is that the optics of a system can be calculated, given only the on-axis potential distribution of the system.

This work was extended in 1936 by Scherzer[3], who determined the lowest-order spherical aberration of such a system. Scherzer found further that the spherical aberration of an axially symmetric potential was minimized for a potential distribution having a "Gaussian" form along the axis.[4] Subsequent studies operating under a variety of assumptions, and using direct numerical integration of the equations of motion, have identified other symmetric potential distributions having somewhat smaller spherical aberration coefficients.[5]

In order to get a preliminary indication of the possible usefulness of the multiple-ring lens, it is useful to study the axial potentials that can be generated by a particular choice of lens design. Consider then, a lens with three concentric rings having radii of 7, 12 and 16 mm. This choi ce of radii, which is arbitrary, was chosen to be similar to the radii of Airy diffraction rings. This lens, which is used below for ray-tracing calculations, also is centered in a shielding "can" 50 mm in diameter and 40 mm long. The can is needed to shield the lens from the fields of nearby structures. Figure 2 shows plots of the axial potential distribution associated with each lens ring, as well as the overall potential for two different combinations of biases on all three rings. In all cases, the can is at ground potential.

The potential distributions in Fig. 2 were calculated using a second-order finite-element method. V1 represents the potential on the 7-mm ring, V2 the potential on the 12-mm ring, and V3 the potential on the 16-mm ring. The corresponding axial potential distributions also are linearly independent functions. As such, they can be added together to generate a wide variety of axial potential distribution functions.

Figure 2 shows two different combinations of potentials that approximate Gaussian distributions. An iterative search found that the potentials V1 through V3 could be combined to give good fits to Gaussian potentials having widths σ from 4.5 through 10 mm. Attempts to fit narrower or broader σ's than this range gave progressively poorer fits. Similarly, the potential functions also were able to provide good fits to a variety of polynomial functions and other kinds of symmetric distributions.

III. A Prototype Lens

The design of a concentric-ring structure that allows for independent biasing of the rings presents certain physical difficulties. The solutions to these difficulties depend on the size scale of the particular lens. In the present case, the lens is being used to focus a relatively large (diameter ≈ 4 mm) ion beam with a relatively long focal length of abut 30 cm. Figure 3 shows the design of the prototype lens.

The lens structure is based on copper rings and a thin sandwich of ceramic wafers. The 7-mm radius ring forms a hole through the center and pairs of the 12- and 16-mm rings are attached to opposing surfaces of the sandwich. The rings have 1-mm toroidal radii. Electrical connection to the rings is accomplished by bias leads consisting of thin ribbons of copper conductor that pass between the ceramic sandwich. Sheets of Kapton™ provide additional insulation between the rings and the bias leads. This design results in rings that have a total thickness in the axial direction of about 4.5 mm.

IV. Ray-tracing calculations

Figure 4 shows the basic system that is used to characterize the performance of the lens. A 4-mm diameter beam of 10 keV ions is incident from the left on the canister which houses the multiple-ring lens. The canister always is set to ground potential, and the lens rings then are set to the desired potentials.

The lens properties are calculated with a version of Munro's particle-beam programs,[2] using a cylindrically symmetric second-order finite element to calculate the electrostatic fields. The calculation can accommodate multiple electrodes and accounts for the dielectric constants of insulating materials. A Runge-Kutta integration method is used to perform the particle trajectory ray tracing. The aberration coefficients are determined from the ray-tracing results.

Figure 5 shows the ray-tracing result for focusing a monoenergetic 10-keV ion beam with electrode potentials of 5000, 8000 and -12000 volts. The results show that the initial 4-mm beam is focused to a 50-μm spot diameter. Figure 5 shows the overall system, including the equipotential contours in the vicinity of the lens. The inset in Fig. 5 shows an expanded view of the focal region 160 mm from the lens.

The ray-tracing solution also serves as the basis of calculations of spherical and chromatic aberration coefficients. For the present example with a focal length of 160 mm the spherical aberration coefficient, C_s, is about $2.3x10^4$ mm and the chromatic aberration, C_c, is about 430 mm. These coefficients admittedly are rather large, but this is due partly to the long focal length of the system. A preliminary survey of focal characteristics with different bias voltages for the present lens indicates that for focal lengths of about 150 mm C_s increases roughly in proportion to the focal length. Additional calculations indicate that the optics of the prototype lens scale in a predictable way: smaller input beams produce smaller focal spots, and a system whose size, potentials and beam energy are scaled down by a factor of ten, for example, produce correspondingly smaller focal spots.

V. Conclusions

This paper has described a new geometry that can be used in the design of electrostatic lenses. The prototype lens that has been discussed has rather large aberration coefficients, but it is perfectly adequate for our current applications. Further and more detailed studies will be required to determine whether multiple ring lenses by themselves could function as low-aberrations optical elements.

There are several points to consider with respect to adapting multiple-ring lenses to low-aberration systems. First, these lenses almost never would constitute an isolated system, but would be part of a larger geometry. Since the entire geometry contributes to the optics of a system, one question to consider is whether multiple-ring lenses increase the versatility in a system, compared to the unipotential surfaces that the lenses would replace. This is particularly true in compact systems where there is limited space for multiple optical elements in the axial direction.

Another point is that the present lens uses only three rings. A lens that uses a larger number of rings can be expected to provide greater flexibility in varying ring potentials to produce a desired electrostatic potential contour. As the number of rings becomes large, the design problem will become very complex, but it is not clear whether there is an optimum with respect to complexity and the performance of the final lens. It is entirely possible that a modest number of rings, say five, would be able to produce a lens with aberration coefficients that are substantially superior to the example with three rings that has been discussed above.

In conclusion, a prototype lens for focusing an ion beam has been designed, using a concentric co-planar array of independently biased rings. The resulting lens is adequate for the proposed application, although it has rather large aberration coefficients. We would anticipate that further studies with lenses having a larger number of rings, for example, will produce higher-quality optical elements.

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VI References

1 See, for example, M. Gesley, J. Vac Sci Technol. B, **10**, 2451 (1992).

2 E. Munro, J. Vac Sci Technol. B, **8**, 1657 (1990).

3 A good summary of these and related results is given by A. Septier, *Optical and Electron Microscopy*, Vol. 1 (Academic Press, New York, 1966), p. 204.

4 See, for example, A.B. El-Kareh and J.C.J. El-Kareh, *Electron Beams, Lenses, and Optics*, Vol. 1 (Academic Press, New York, 1970), p. 9.

5 A.V. Crewe, Optik 88, 118 (1991).

FIGURE CAPTIONS

Figure 1 This figure illustrates the basic idea of the multiple-ring lens. Here, a radial sequence of independently biased co-planar and concentric rings provides a focusing field for a particle beam that passes through its center.

Figure 2 This figure illustrates the versatility that can be available even with a three-ring lens. The curves without data points show the axial potential distributions for unit potential on each of the electrodes, with the remainder of the system at ground potential. The remaining two curves show the net axial potential distributions for two different choices of potentials on the electrodes. These curves show a good match between the potentials and Gaussian distributions having σ of 4.5 and 10 mm. Thus, variation of the electrode potentials can result in Gaussian potentials whose widths vary by about a factor of two.

Figure 3 This figure shows the mechanical design of the prototype lens element. The structure is based on a ceramic wafer sandwich which supports the conducting rings. Electrical connection is accomplished by ribbon conductors that pass down the middle of the sandwich.

Figure 4 This figure shows the lens element mounted symmetrically inside a shielding can. For ray tracing, the beam enters from the left and focuses with relatively long focal lengths (>15 cm) downstream.

Figure 5 This figure shows one result from the ray-tracing calculations. For biases of 5000 V, 2000V and -2000V on the inner, middle and outer rings, respectively, the 4-mm beam focuses 160 mm from the lens element to a focal spot diameter of about 50 μm.

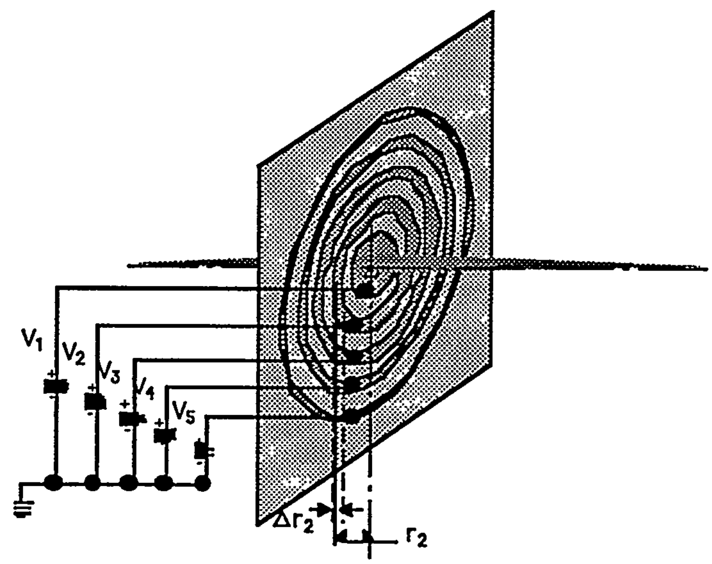
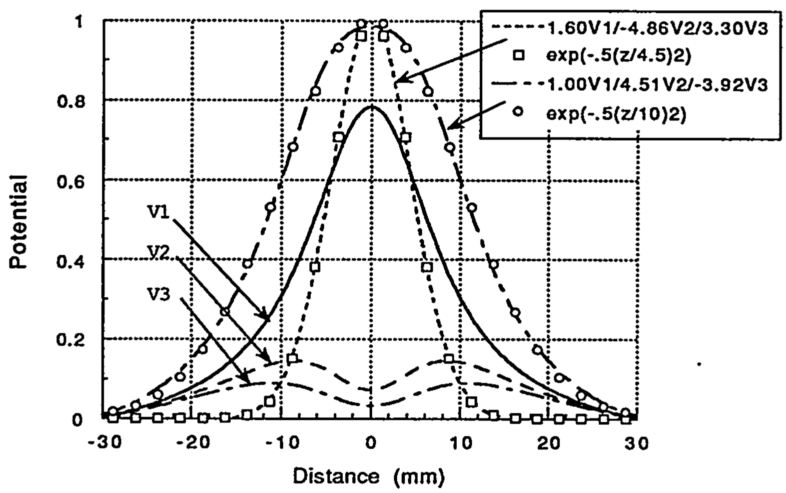


Figure 1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1.00V1/4.51V2/-3.92V3
exp(-.5(z/10)2)
V1
V2
V3
Potential
Distance (mm)
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0.6
0.4
0.2
0
-30
-20
-10
0
10
20
30

Figure 2

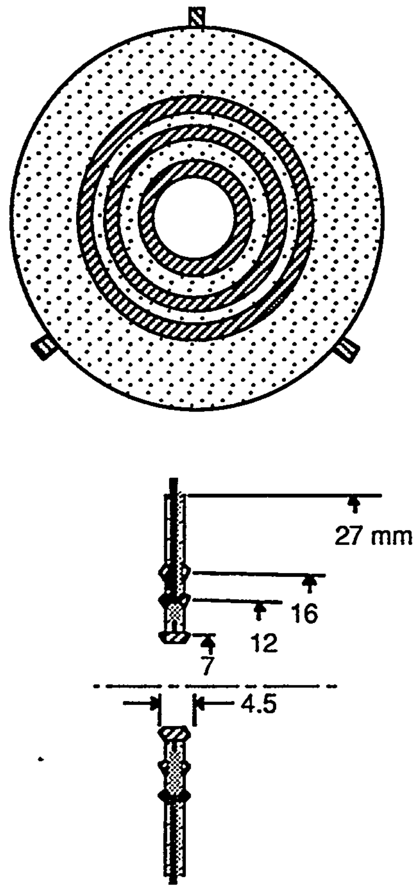

Figure 3

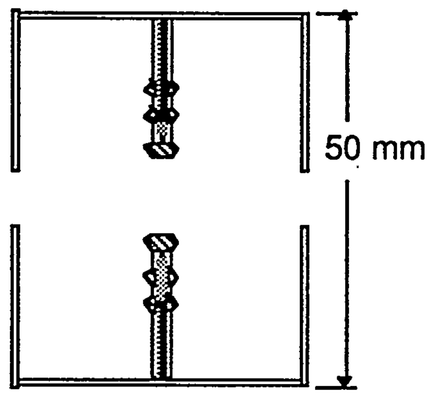

Figure 4

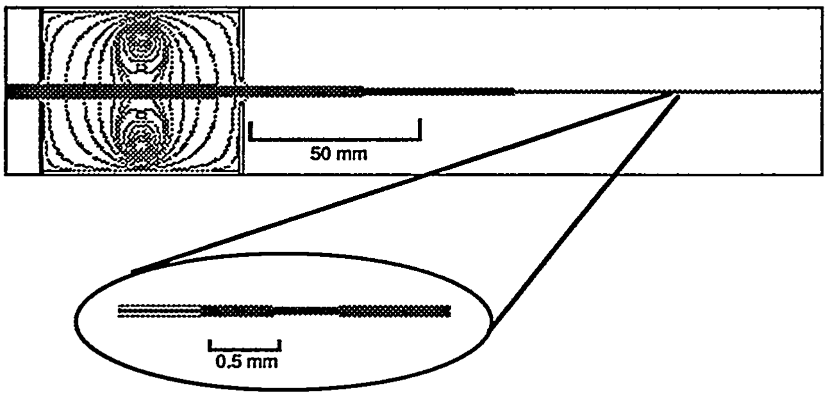

Figure 5