Large-aperture, axially symmetric ion-optical lens systems using new types of electrostatic and magnetic elements

W. Z. Liu and F. D. Becchetti

Department of Physics, Randall Laboratory, The University of Michigan, Ann Arbor, Michigan 48109

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We have developed new types of ion-optical systems having larger solid angles (i.e., collecting power) and flexibility than many existing designs. They use relatively simple axially symmetric elements, namely solenoids, axial magnetic dipoles, and radial electric field lenses. The systems can focus, with good optical properties, energetic ions in the range of tens of keV up to tens of MeV kinetic energy and are capable of operating in nondispersive, achromatic modes. The key elements for the latter are new types of *defocusing* magnetic and electrostatic correction lenses. The lens systems have applications in any existing devices used to collect and focus energetic ions (including electrons). Typical devices are: mass spectrometers, leak detectors and gas analyzers, ion sources, accelerators and ion implantation systems, nuclear particle spectrometers, electron microscopes, ion microprobes, and ion-beam lenses for cancer therapy.

INTRODUCTION

Most ion-optical systems have used magnetic or electric quadrupoles, magnetic or electric dipoles, or electrostatic grids to achieve ion focusing. The former (quadrupoles and conventional dipoles) do not have azimuthal symmetry and thus have a poor aspect ratio (opening aperture/length). Hence, these elements often severely constrain the angular acceptance ($f/\#$) of the optical system. Also, their mechanical construction and alignment can be difficult and they do not possess simple optical properties, viz. simple ion orbits, ion focusing, and aberrations. Alternate grid type lenses often introduce unwanted background since some ions will hit the grids. This is not acceptable for many applications.

We have devised an ion-optical lens design consisting of simple magnetic and electrostatic focusing and defocusing elements, each having azimuthal symmetry and hence simple ion-optical properties. Mechanical construction and alignment are relatively uncomplicated. The system consists of (i) solenoidal or axial dipole magnetic focusing (F_M) and defocusing (D_M) elements combined with (ii) radial-field electrostatic elements [focusing (F_E) or defocusing (D_E)]. Key elements in the design are the use of new types of defocusing elements based on solenoids, or axially aligned magnetic or electrostatic dipoles.

I. DESIGN

A magnetic solenoid provides an axial magnetic field which can be shown to provide ion focusing. The magnet may be a conventional coil/yoke/solenoid, a dipole magnet or a superconducting solenoid. (The latter is appropriate for very energetic ions such as nuclear reaction products). Solenoids have been used extensively for focusing electrons and, recently, for heavier ions.[1,2] They can have a large aperture/focal length ratio, hence high collecting power (i.e., fast $f/\#$), and they have full $\phi = 2\pi$ symmetry around the optical axis. Both positive and negative ions can be focused—simultaneously if desirable. Previously, solenoid lenses were always considered to be focusing (F_M): hence one could not easily correct for aberrations or make an achromatic system using another solenoid since this requires a defocusing (D) element, e.g., in a FD, DFD, FDF, etc. combination. We have recently developed a lens system[3] which uses radial electric field lenses (for D_E) combined with magnetic solenoid lenses (F_M) to yield a large-aperture ion lens that can be corrected for spherical aberrations and, in some cases, chromatic aberrations. While this design is an improvement over many existing ion-optical systems, the need for high voltages on the electrostatic radial-field lens can be a major limitation.

II. DEFOCUSING ELEMENTS

Ideally one should use, instead, an axially symmetric, *defocusing* magnetic element (e.g., solenoid) which until now has not been considered feasible. However, one notes that solenoidal fields are always focusing only if the ions pass *inside* the solenoid. Ions which pass on the outside of the solenoid are defocused (D_M) with a definable focal length, albeit large aberrations. (A similar effect can be achieved with a magnetic dipole oriented on axis.) Typical ion orbits for such a lens are shown in Fig. 1 and, as noted, exhibit both spherical and chromatic aberrations (SA and CA). In first order the CA (i.e., momentum dispersion), like that for a conventional solenoid lens[1,3] is proportional to the square of the ions' magnetic rigidity, but of opposite sign (see Appendix). Hence, by proper choice of its location and strength, one can use this element to cancel, in first order at least, the momentum dispersion (CA) of the primary focusing element (F_M or F_E). However, as is the case for most optical systems, due to SA and higher-order chromatic dispersion terms, only partial compensation may be achieved in a practical design.

This new D_M element, together with the previously described[3] F_M, F_E, and D_E lenses, can be combined with suit-

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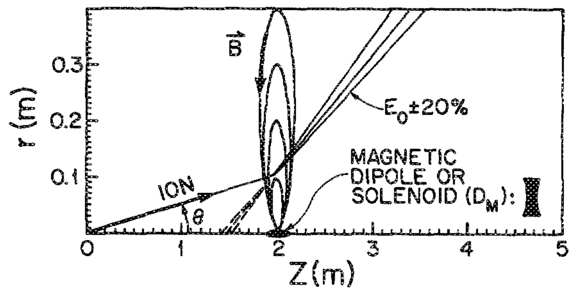

FIG. 1. Optical properties of a defocusing, axially symmetric magnetic element (solenoid or, as shown, axial magnetic dipole). Typical ray orbits are shown ($^{8}Li^{3+}$ ions, $E_0 = 120$ MeV, $\theta = 3°$). The quantity "r" is the ion's distance from the axis.

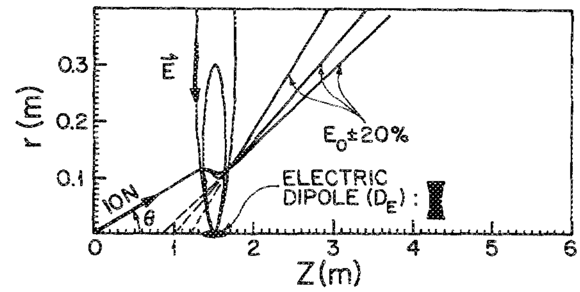

FIG. 3. Optical properties of a defocusing, axially symmetric electric dipole. Typical ray orbits are shown ($^{8}Li^{3+}$, $E_0 = 120$ MeV, $\theta = 5°$).

able field profiles and lens separations to produce axially symmetric, compact, large-aperture, well-corrected, and even semiachromatic ion-optical lens systems. While the axial components (D_M, F_E, and D_E) are intrusive for central, $\theta = 0°$, i.e., paraxial rays they can be located to minimize background scattering, etc. In many transmission devices they may serve as the incident beam-blocking aperture and hence their effect can be minimal. The other intrusive elements are the lens support structures and power/current leads. Since the intrusive lenses are generally used as correction elements, they can be much smaller and lighter than the main focusing element (e.g., solenoid F_M). Also the D_M element can serve as the grounded electrode for a radial electric field lens and hence serve a dual function ($D_M D_E$ or $D_M F_E$), of course, mechanical forces between the magnetic elements can be large and must be considered.

As an example, very compact systems can be formed by a solenoid (F_M) with a radial electric-field lens (D_E or F_E) and defocusing (D_M) solenoid (or magnetic dipole) located at the lens exit. We have done ion-orbit ray tracing and demonstrated that a suitably designed lens system can be corrected for spherical aberrations and, if a sufficiently high field for D_M is used, can be combined (Fig. 2) to form an achromat. The latter is rather unique since this device also has a very large collecting power owing to the $\phi = 2\pi$ symmetry.

The same concept as the magnetic defocusing lens can be applied to an axially aligned electric dipole. One again notes that ions passing on the outside of the lens element are defocused (D_E). This is shown in Fig. 3. While this can also be achieved with a defocusing radial-electric field lens,[3] the SA and CA terms are different since the $\mathbf{E}(r)$ gradients are different. This allows more flexibility in compensating the SA or CA from the primary focusing element. We display in Fig. 4 an achromat ($E_0 \pm 20\%$) designed using an electric dipole. It has optical properties similar to that obtained using the magnetic defocusing element (Fig. 2). In a practical design the size and shape of the electrodes would need to be optimized to accommodate reasonable field gradients viz. 50–100 kV/cm.

Although we are using dc fields for the devices described, an air-core solenoid and electrostatic lens can also be run in a pulsed mode. The frequency of operation, of course, depends on the particular design, but electric lenses, such as electric quadrupoles, can run at rf frequencies (MHz). Also, large slow-pulsed air-core solenoids can achieve very high fields (>5 T) if one can tolerate a low duty factor. However, this may be appropriate for certain applications in order to avoid the cost of a superconducting magnet.

III. DISCUSSION

The new ion lens systems have $\times 10$ to $\times 100$ larger collecting power (i.e., solid angle) than most existing ion-optical system designs based on dipoles or quadrupoles. Therefore a mass spectrometer using the new lenses would have greater sensitivity and an ion-beam implantation system would have higher intensity. These devices would possess unique optical properties since the lenses can be easily designed for variable dispersion and magnification, yet they can retain their simple optical properties. This is in contrast

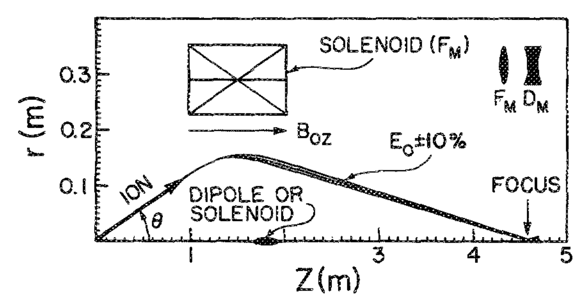

FIG. 2. An ion-optical lens configuration ($F_M D_M$) using the defocusing magnetic element (solenoid or axial magnetic dipole) to form a semiachromatic system for $\theta = 7°$, over an ion energy range of ca. $\pm 10\%$ (see Fig. 1).

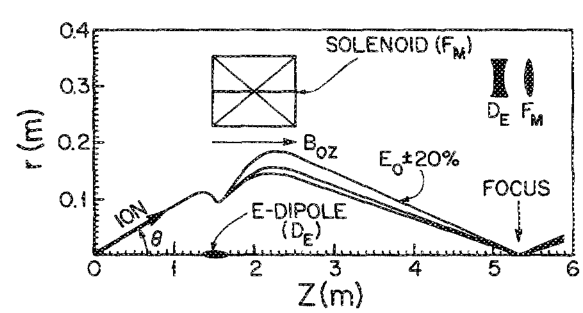

FIG. 4. An ion optical lens configuration ($D_E F_M$) using a defocusing axial electric dipole (Fig. 3) to form a semiachromatic system ($\theta = 5°$) over an ion energy range of ca. $\pm 20\%$.

to quadrupole lenses which do not have axially symmetric ion-optical orbits.

In a nuclear reaction–product spectrometer[1,2] the $\times 10$ to $\times 100$ increase in collecting power (solid angle) combined with the simple optical properties appear to offer a significant advance over present devices. Our research group has been using a superconducting solenoid (F_M) for this purpose for several years and a larger system (including a radial-electric field element and/or defocusing magnetic element) has been designed and is under construction.[4] References 2–4 describe some of our tests and previous design work and references to earlier work may be found there. However the combination of focusing and defocusing solenoidal, axial magnetic dipole, or axial electric dipole lenses together with radial-electric field lenses to our knowledge is new and unique and appears to be highly advantageous for many applications. The combination of the various axially symmetric electrostatic and magnetic elements gives one the necessary degrees of freedom to design large-aperture, corrected ion-optical systems with new and unique features.

ACKNOWLEDGMENT

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APPENDIX

Cosslett[5] gives a derivation of the focal length for a thin magnetic solenoid with the following result:

$$f = 4(B\rho)^2/\overline{B_z^2 L} = 4p^2/q^2\ \overline{B_z^2 L}\ , \qquad \text{(A1)}$$

where $\overline{B_z^2 L} = \int_{-\infty}^{\infty} B_z^2\, dz$, and $B\rho = p/q$ is the magnetic rigidity of the particle passing through the solenoid. Through similar procedures we are able to derive the focal length f_B (Fig. A1) for a magnetic dipole, oriented along the z axis:

$$f_B = \frac{-16}{9\pi}\frac{p^2}{q^2 M_B^2} r_m^5\ , \qquad \text{(A2)}$$

the spiral angle of the particle (Fig. A2):

$$\delta\phi = -2M_B q/r_m^2\, p, \qquad \text{(A3)}$$

and the change of slope of the trajectory:

$$\tan\theta(z = +\infty) - \tan\theta(z = -\infty) = r_m/-f_B\ , \qquad \text{(A4)}$$

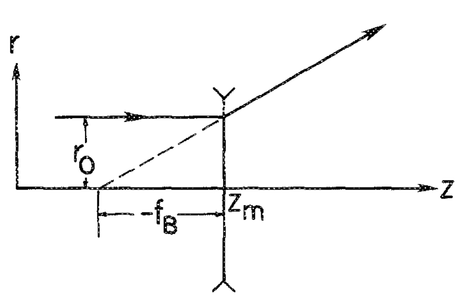

FIG. A1. Definition of ion-optical defocusing lens parameters.

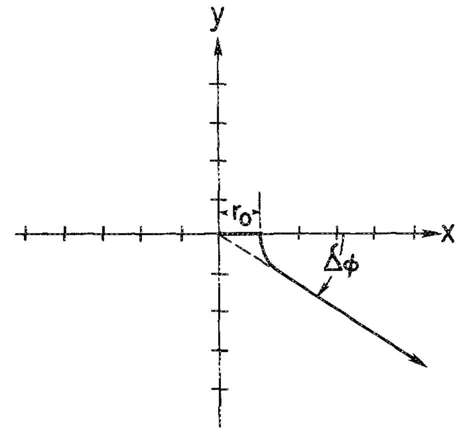

FIG. A2. Spiral angle, $\delta\phi$, as seen a long the optical (z) axis.

where m is the mass of particle, q is the change of the particle, p is the momentum of the particle, and M_B is the magnetic moment of the dipole where[6]

$$\mathbf{B} = [3\mathbf{n}(\mathbf{M}_B\cdot\mathbf{n}) - \mathbf{M}_B]/|\mathbf{x}|^3\ .$$

The radius

$$r_m \approx r_0\sqrt{1 + (\delta\phi/2)^2}$$

is the distance of the trajectory from the z axis at the position of the middle plane of the dipole lens. Equations (A1)–(A4) have been verified by numerical ray tracing. The first-order transfer matrices for the magnetic solenoid and dipole can be derived from these formulas.

The first-order transport equation, for a general focusing system, may be expressed as[7,8]

$$\begin{bmatrix} r \\ \phi \\ \alpha \\ \beta \\ \ell \\ \delta \end{bmatrix} = R \begin{bmatrix} r_0 \\ \phi_0 \\ \alpha_0 \\ \beta_0 \\ \ell_0 \\ \delta_0 \end{bmatrix}. \qquad \text{(A4)}$$

As illustrated in Fig. A3, the coordinates r and ϕ represent the position of the asymptotic line of the trajectory in

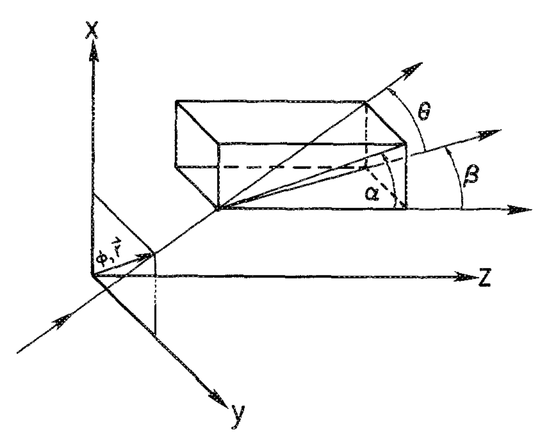

FIG. A3. Ion-optical ray coordinates for transfer matrix.

the x-y plane, and α and β represent the slopes of this line in the x-z plane and y-z plane, respectively. The quantity ℓ is the path-length difference between an arbitrary ray and the reference trajectory and $\delta = \delta p/p$ gives the fractional deviation of momentum of the ray from the reference momentum p. For a single trajectory, $\ell = \ell_0$, and $\delta = \delta_0$.

Since the coordinates, (r, ϕ, α, β) represent the position and orientation of the asymptotic line of the trajectory instead of the trajectory itself, we can ignore the detailed behavior of the interaction near the middle plane of the dipole.

To derive the first-order transfer matrix elements consider a parallel-incident beam with impact distance r_0, in the x-z plane. The beam will be deflected to make nonzero angles $\delta\alpha$ and $\delta\beta$ with (refer to Fig. A3)

$$\delta\alpha = \tan\theta \cos\delta\phi = (r_0/-f_B)\cos\delta\phi,$$

$$\delta\beta = \tan\theta \sin\delta\phi = (r_0/-f_B)\sin\delta\phi,$$

and its asymptotic line will intersect the lens middle plane at (r,ϕ) with

$$\phi = \delta\phi$$

and

$$r \approx r_0.$$

Therefore, for an arbitrary incident beam with coordinates $(r_0, \phi_0, \alpha_0, \beta_0)$ and momentum p, the deflected beam coordinates can be written as

$$r \approx r_0, \quad \text{(A5a)}$$

$$\phi = \phi_0 + \delta\phi, \quad \text{(A5b)}$$

$$\alpha = \alpha_0 + (r_m/-f_B)\cos\phi_1 \quad \text{(A5c)}$$

$$\beta = \beta_0 + (r_m/-f_B)\sin\phi_1 \quad \text{(A5d)}$$

where

$$\phi_1 = \phi_0 + \delta\phi.$$

The change of ϕ induced by an increase of momentum δp can be determined by differentiating Eq. (A5b), i.e.

$$\frac{d\phi}{dp} = \frac{-1}{p}\delta\phi$$

or

$$\delta\phi|_\delta = (\delta p/p)(-\delta\phi).$$

Similarly,

$$\delta\alpha|_\delta = (\delta p/p)(r_m/f_B)(2\cos\phi_1 - \delta\phi\sin\phi_1),$$

$$\delta\beta|_\delta = (\delta p/p)(r_m/f_B)(2\sin\phi_1 - \delta\phi\cos\phi_1).$$

Therefore, the complete expressions for the new coordinates, as a first-order approximation, are

$$r \approx r_0,$$

$$\phi = \phi_0 + \delta\phi + (\delta p/p)(-\delta\phi),$$

$$\alpha = \alpha_0 + r_0\left(\frac{-\cos\phi_1}{f_B}\right) + \left(\frac{\delta p}{p}\right)\left(\frac{r_m}{f_B}\right)(2\cos\phi_1 - \delta\phi\sin\phi_1),$$

$$\beta = \beta_0 + r_0\left(\frac{-\sin\phi_1}{f_B}\right) + \left(\frac{\delta p}{p}\right)\left(\frac{r_m}{f_B}\right)(2\sin\phi_1 + \delta\phi\cos\phi_1).$$

The last four equations, together with $\ell = \ell_0$ and $\delta = \delta_0$ form a 6×6 matrix equation, as follows

$$\begin{bmatrix} r \\ \phi \\ \alpha \\ \beta \\ \ell \\ \delta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \delta\phi/r_m & 1 & 0 & 0 & 0 & -\delta\phi \\ -\cos\delta\phi/f_B & 0 & 1 & 0 & 0 & c_\alpha r_m/f_B \\ -\sin\delta\phi/f_B & 0 & 0 & 1 & 0 & c_\beta r_m/f_B \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_0 \\ \phi_0 \\ \alpha_0 \\ \beta_0 \\ \ell_0 \\ \delta_0 \end{bmatrix},$$

where

$$c_\alpha = 2\cos\phi_1 - \delta\phi\sin\phi_1,$$

$$c_\beta = 2\sin\phi_1 + \delta\phi\cos\phi_1,$$

and r_0 and r_m are interchangeable in the 6×6 transfer matrix first-order approximation.

For the electric dipole, the transfer matrices for the x-z and y-z planes are identical, since particles do not spiral in electric fields and therefore have no azimuthal components. The matrix transfer equation therefore has a much simpler form and can be written as[7–9]

$$\begin{bmatrix} x \\ \alpha \\ \delta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -1/f_E & 1 & d' \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ \alpha_0 \\ \delta_0 \end{bmatrix},$$

where d' is the derivative of the momentum dispersion and f_E stands for the focal length of the electric dipole.

The field of the electric dipole with moment M_E is similar to that of the magnetic dipole. But the double twists of particle trajectories in the electric dipole field (Fig. 3) complicates the derivation of the focal length. At the moment, therefore, we only have derived numerical values for the matrix elements. For example, with ($m = 8$ amu, $q = 3|e|$, $E = 130$ MeV, $r_m = 0.12$ m, and $M_E = 245000$ N m^3/C), the focal length is

$$f_E = -0.311 \text{ m} \quad \text{(A6)}$$

and the derivative of momentum dispersion is

$$d' = -0.850.$$

The numerical form of the R matrix is therefore

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 3.22\, m^{-1} & 1 & -0.850 \\ 0 & 0 & 1 \end{bmatrix}.$$

Because the magnetic dipole and the electric dipole both have negative focal lengths [Eqs. (A2) and (A6)] while the solenoid has positive focal length [Eq. (A1)] proper solenoid-dipole combinations can cancel the momentum dispersions. The dipoles can often be treated as thin defocusing lenses because of the drastic drop of their fields with distance from the optical axis ($\propto 1/r^3$; Fig. A1). If the focusing solenoid element is located far away, and hence can be considered as a lens well separated from the dipoles, matrix multiplication methods can be employed. In our devices (Figs. 2

and 4) the dipoles are located inside the solenoid, partly to achieve large solid angles, and partly to achieve a short focal length and short overall length. Hence in most of our calculations we have used numerical ray tracing.[10,11] but have used the thin lens formulas to verify the latter in limiting cases, e.g., large lens separation.

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