Focusing of multiply charged energetic ions using solenoidal B and radial E lenses

W. Z. Liu, R. Stern, and F. D. Becchetti

Department of Physics, University of Michigan, Ann Arbor, Michigan 48109

(Received 28 July 1986; accepted for publication 17 October 1986)

Several large-solid-angle devices for collecting, at a common focus, multiply charged heavy ions from nuclear reactions have been studied. These devices use axial magnetic fields (solenoids), radial electric fields (coaxial lenses), or a combination of these. Although each system has particular advantages and disadvantages, several designs appear promising for use as practical devices.

INTRODUCTION

Energetic heavy ions, i.e., those in the few MeV per nucleon range, are often detected as nuclear reaction[1] or fragmentation[2] products emitted in a range of charge states.[3] Typically the charge states span a distribution of 10%–30% of the equilibrium charge state $\bar{q}$. Thus, any simple magnetic or electric lens used to collect the reaction products will bring different charge states q_i, to different focal points depending on the mass and energy. Alternate devices, using $\mathbf{B} \times \mathbf{E}$, usually with dipole magnets and parallel-plate electrodes, have been built which can cancel the charge-state dispersion and are designed to act as velocity or mass filters.[4–6] However, these instruments have small solid angles, typically 0.1–5 msr. The study of rare events or the production of secondary, for example radioactive, beams requires a larger collection efficiency.[2]

A large-solid-angle device, suitable for work near 0°, is the superconducting solenoid spectrometer. Moderate size (~ 0.2 m diam by 0.4 m long, $B \geqslant 3$ T) solenoids, both with[7] and without[8] steel yokes, are in operation. These typically have solid angles of 10–60 msr. However, as normally run, they are charge dispersive.

In the first order[9,10] a solenoid can be treated as a lens with focal length

$$f = 4(B\rho)^2 / \overline{B_z^2} \bar{L} , \tag{1}$$

where $\overline{B_z^2}$ is the mean-square axial field, $\bar{L}$ is the corresponding effective length, and $B\rho$ is the ion magnetic rigidity. The latter is proportional to the ion momentum p, divided by the charge q_i. Thus f is a function of p^2/q_i^2.

We have studied methods of canceling the charge-state and chromatic dispersions using special solenoid magnet and/or radial electric field lens configurations.

I. DEVICES

A. Long solenoid: Least common focal length

Normally a short solenoid is set to focus only one (primary) charge state [Eq. (1)]. However, if one uses a *very long* solenoid with f equal to $f(q_i = 1)$, one finds that *all*

TABLE I. Characteristics of various ion collectors designed to focus 60-MeV ^{16}O ions, $\theta \pm 5^\circ$.

Device	Long solenoid (Fig. 1)	Radial E (ELCO) lens (Fig. 2)	Solenoid and radial E lens (Fig. 3)
Length	4.7 m	30 cm, 206 cm	115 cm (B), 53 cm (E)
Radius	5 cm	10 cm, 26 cm	8 cm (B), 5 cm (E)
Field[a]	6T	663 kV, − 848 kV	4T(B), 160 kV (E)
ΔTOF[b]	0.011%	~0%	0.074%
q Focus[c]	All charge states	All charge states	A few, selected states
	First-order focus	Very weak	Weak
θ Focus[d]	(3–10°)	(4.5°–5.5°)	(4.5°–7.0)
$d\Omega$[e]	87 msr	9.6 msr	27 msr
$\frac{\Delta r^f}{\Delta \theta}$	0.1 cm/deg	0.6 cm/deg	0.7 cm/deg
Comments	Least common focus method $f = q_{\max} f(q = 1)$	Achromatic over a ~ 40% E range	Achromatic over a ~ 15% E range

[a] Central magnetic field or potential on electrodes.

[b] Spread in ion time-of-flight through the device (60 MeV ^{16}O).

[c] Focus of $q_i = 1^+, 2^+, 3^+, \ldots q_{\max}$ charge states.

[d] Typical angular focusing properties ($\theta \pm 5^\circ$) and angular range for a usable focus (few cm diameter at focal plane). The calculations for the ELCO lenses are only approximate and do not include aberrations due to the fringe fields.

[e] Solid angle for angular range indicated.

[f] Radial dispersion at the focal plane as a function of angular dispersion at the target (object) for 60 MeV ^{16}O, $\theta \pm 5^\circ$.

0034-6748/87/020220-03$01.30

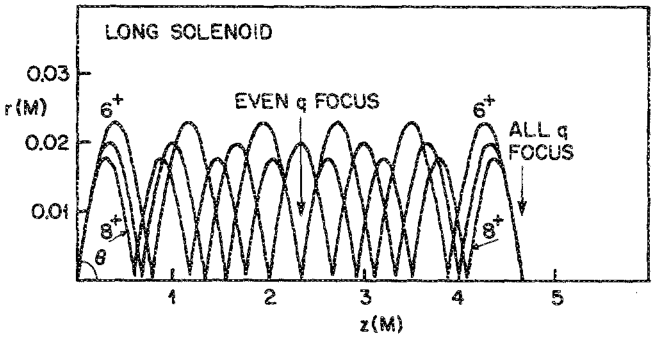

FIG. 1. Calculated orbits for ^{16}O ions ($E = 60$ MeV), $\theta = 5°$, in charge states $q_i = 1^+, 2^+, ..., 7^+, 8^+$, in a long, uniform, solenoid lens. The solenoid length and field strength are such that after $n = q_{\max} = 8$ orbits [Eq. (1)], all charge states are brought to a first-order focus. The parameter r is distance from the solenoid axis as the particles spiral through the magnet. Other properties are given in Table I. (Note different horizontal and vertical scales.)

charge states can be brought to a common focus. In this mode each ion makes q_i spirals and, hence, a long magnet is required to focus an energetic ion (Table I). Fortunately, long, small-bore, air-core, superconducting solenoid magnets are relatively easy to construct, and several have been built commercially.[11] Ray-tracing calculations for this type of magnet are shown in Fig. 1. Note that all even charge states are brought to an intermediate focus at half the length needed to focus all q_i.

The long solenoid has optical properties resembling the more conventional electron solenoid lens,[9] viz. first-order angle focusing, and thus, can be run at very large solid angles if higher-order aberrations can be tolerated.[10]

The existing short, air-core, superconducting solenoid used by our group[8] could also be used in this mode at low ion energies. As indicated by Eq. (1), the maximum energy that can be focused for $n = q_{\max}$ orbits will be $1/q_{\max}^2$ times that for focusing $q_{\max}$ with $n = 1$ (i.e., no crossover), which is the normal solenoid operational mode. The properties of a typical design are listed in Table I.

B. Radial electric field lens (ELCO lens)

Electrostatic lenses using grids or cylinders are well known in electron and low-energy ion optics.[12] Such lenses become impractical for high ion energies and large apertures. The axial magnetic field of the solenoid lens discussed previously suggests the use of a *radial* electric field lens to provide a $\mathbf{B} \times \mathbf{E}$ system. We have therefore studied the properties of radial electric field (ELCO) lenses.[13–16] Such a lens system is shown in Fig. 2. The configuration in Fig. 2 is symmetric, consisting of two short, diverging lenses and a longer, central, converging lens (i.e., a DCD ELCO lens). This arrangement minimizes some of the aberrations inherent in a single lens.[14] ELCO lenses alone, like other E devices, require rather high fields to focus energetic ions; but unlike the short solenoid, all charge states can be brought to a common focus, and the ions' flight times do not differ (Table I). This device can have large spherical aberrations, but these can be minimized by an appropriate lens design[14] and suitable shaping of the fringe fields. It can be made with an

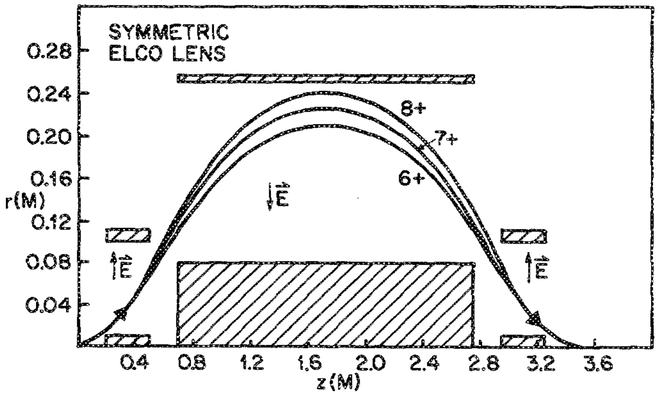

FIG. 2. First-order calculations, i.e., neglecting fringe fields, of 60 MeV ^{16}O ion orbits, $\theta = 5°$, in a radial-electric-field lens (ELCO lens) consisting of inner and outer concentric cylinders. (Note different horizontal and vertical scales.)

aperture comparable to a solenoid magnet, without the use of wire grids. The latter are generally not desirable in this type of application due to secondary scattering, etc. ELCO lenses have been built[15] for proton ion probes, $KE_p \leqslant 1$ MeV (i.e., for ions $\leqslant 1$ MeV per nucleon) and designs for very high-energy particles have been described.[16]

C. Combination of solenoid B and radial E

Combining the B and E devices described above yields a $\mathbf{B} \times \mathbf{E}$ ion filter which can exhibit less aberrations than either a short solenoid or a radial-electric field lens alone. It can produce an acceptable focus for a range of ion charge states with modest differences in TOFs. One particular arrangement is shown in Fig. 3, and the properties for it are listed in Table I. Again, the use of an air-core solenoid would expedite the construction of such a device.

The system shown in Fig. 3 uses a converging solenoid lens and a diverging ELCO lens to produce a semi-achromatic focus, at least for a limited range of angles. Since the focusing is provided by the magnet, the ELCO lens can be operated at lower fields (100–200 kV) than those used for an ELCO lens alone (Table I).

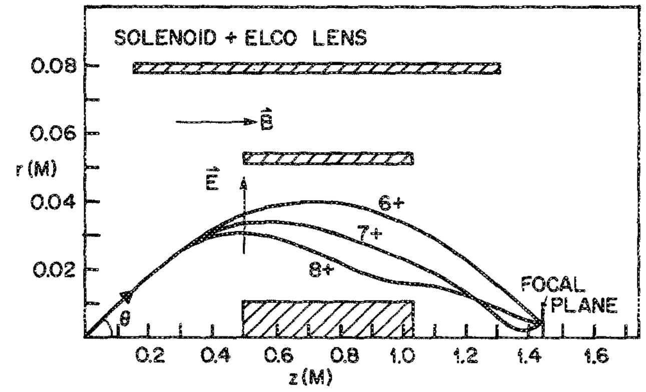

FIG. 3. Calculated ion orbits for a combined magnetic solenoid and radial-electric-field (ELCO) lens system with parameters adjusted to focus a range of charge states for 60 MeV ^{16}O, $\theta = 5°$. Other properties are given in Table I. (Note different horizontal and vertical scales.)

II. CONCLUSIONS

We have considered the problem of collecting and focusing, with a large-solid-angle, multiply charged energetic ions. Several suitable devices which utilize large solenoid magnets, radial electric field (ELCO) lenses, or a combination of these have been studied. Each system exhibits particular optical and kinematic focusing properties, but all can provide a common focus for more than one charge state and, hence, they can be used as large-solid-angle energetic ion collectors. We hope to test, in beam, one or more of these collectors in the near future.

ACKNOWLEDGMENTS

We thank Professor J. Jänecke and Professor J. Kolata for useful comments and discussions. This work has been supported, in part, by the U. S. National Science Foundation, Grant No. PHY 8308072.

[1] *Heavy Ion Collisions*, Vols. 1–3, edited by R. Bock (North Holland, Amsterdam, 1980).

[2] M. Langevin and R. Anne, in *Instrumentation for Heavy Ion Nuclear Research*, Vol. 7, edited by D. Shapira (Harwood, New York, 1984), p. 191.

[3] H. E. Betz, Rev. Mod. Phys. **44**, 465 (1972).

[4] T. M. Cormier, M. G. Herman, B. S. Liu, and P. M. Stwertka, Nucl. Instrum. Methods **212**, 185 (1983).

[5] P. Spolare, J. D. Larson, C. Signorini, S. Beghini, X. Zhu, and H. Si, Nucl. Instrum. Methods **A238**, 381 (1985).

[6] J. A. Nolen, L. H. Harwood, M. S. Curtin, E. Ormand, and S. Bricker, in *Instrumentation for Heavy Ion Nuclear Research*, edited by D. Shapira (Harwood, New York, 1984), Vol. 7, p. 171.

[7] J.-P. Schapira, F. Azaiez, S. Fortier, S. Gales, E. Hourani, J. Kumpulainen, and J. Maison, Nucl. Instrum. Methods **224**, 337 (1984).

[8] R. Stern *et al.*, Proceedings of the Conference on Instrumentation for Heavy Ion Research, ORNL Publ., CONF-841005, 1984, p. 95.

[9] K. Siegbahn, *Alpha, Beta, and Gamma Ray Spectroscopy* (North Holland, Amsterdam, 1968).

[10] J. P. Schapira, S. Gales, and H. Laurent, Orsay Rep. IPNO-PhN-7921, 1979 [English translation: E. Charnock and R. Stern, University of Michigan, UM-BE-10, 1985 (unpublished)].

[11] American Magnetics, Inc., Oak Ridge, TN.

[12] V. E. Cosslett, *Introduction to Electron Optics* (Oxford, London, 1950).

[13] W. G. Mourad, T. Pauly, and R. G. Herb, Rev. Sci. Instrum. **35**, 661 (1964); N. S. Oakey and R. D. MacFarlane, Nucl. Instrum. Methods **49**, 220 (1967).

[14] P. Krejcik, R. L. Dalglish, and J. C. Kelly, J. Phys. D. **12**, 161 (1979); P. Krejcik, B. V. King, and J. C. Kelly, Optik **55**, 385 (1980); Colton and J. C. Kelly, IEEE Trans. Nucl. Sci. **NS-30**, 2734 (1983).

[15] P. Krejcik, J. C. Kelly, and R. L. Dalglish, Nucl. Instrum. Methods **168**, 247 (1980).

[16] P. Krejcik, Nucl. Instrum. Methods **171**, 233 (1980).