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USE OF AXIALLY SYMMETRIC ELECTROSTATIC FIELDS FOR ION BEAM FOCUSSING*

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Summary

The 1/r electric field obtained between charged coaxial cylindrical electrodes is useful for focussing hollow ion beams in ion microprobe and ion implantation applications. The focussing strengths are mass independent at nonrelativistic energies. Focussed particle densities can be enhanced by using a diverging-converging pair to flatten the dependence of focal length on incoming beam radius. Transport of 425 keV and 1 MeV protons has been simulated and results are presented.

Introduction

Electrostatic coaxial lenses (ELCO) have been used recently for transporting and focussing low-energy ion beams.[1] This makes them potentially useful in ion microprobes or for ion beam implantation applications. Further work by Krejcik[2] suggested their use even for focussing GeV beams with modest voltages. The equation of motion for an ion in a radial electric field E_r is given by $\ddot{r} = eE_r/m$ where m is the mass of the ion. An ELCO lens consists of two coaxial cylinders charged to a potential difference V; the equation of motion becomes

$$r'' = \frac{eV}{Tr\ \mathrm{Log}_e(r_b/r_a)} \qquad (1)$$

where $r'' = d^2r/dz^2$, T is the ion kinetic energy, r_b/r_a is the ratio of the radii of the outer and inner cylinders, respectively. Beam propagates in the +z direction. The lens focal length increases with r. Thus the lens is unattractive for dealing with conventional beams. A hollow beam ($\Delta r \sim$ small) can be well-focussed with little aberration, however.

Further investigation showed that the variation of focal length with radius could be significantly reduced by combining ELCO lenses into, e.g., doublets.[3] The best results are obtained by operating the system as a defocussing-focussing pair. Thus the thickness (and current) of a hollow beam can be increased relative to that of a single lens for a given application.

We have performed Monte-Carlo studies of ion trajectories for 425 keV and 1 MeV protons in both singlet and doublet (D-F) lens configurations. Comparisons were made in regard to spot sizes and effective emittance growth. We also calculated the beam envelopes through the lenses for nonzero beam currents. In Sec. II, we develop the equations for beam transport. In Sec. III, we specifically discuss the examples.

Solution of Equation of Motion

If space charge is included we can rewrite (1) as

$$r'' = \frac{e}{2T}\left[\frac{I}{2\pi\varepsilon_o c\beta} f(r) - \frac{V}{r\ \mathrm{Log}_e(r_b/r_a)}\right] \qquad (2)$$

where $\beta = v_z/c$ and I is the beam current in amperes. For an annular beam of inside/outside radius r_i/r_o, we find $f(r) = 1/r$ for $r > r_o$, $f(r) = 0$ for $r<r_i$, and $f(r) = (r^2 - r_i^2)/[r(r_o^2 - r_i^2)]$ for $r_i<r<r_o$. The beam envelopes are obtained by choosing $r = r_o$ and $f(r) = 1/r$; then Eq. (2) can be written in the form $r'' = K/r$ where

$$K = \frac{e}{2T}\left[\frac{I}{2\pi\varepsilon_o c\beta} - \frac{V}{\mathrm{Log}_e(r_b/r_a)}\right] \quad . \qquad (3)$$

After the beam has been focussed by a lens system, the minimum radius occurs downstream with a value

$$r_{min} = r_e \exp[-r_e'^2/(2K_f)] \qquad (4)$$

where r_e, r_e' represent the beam conditions at the downstream end of the final lens and K_f is given by Eq.(3) with V = 0.

The solutions to Eq. (1) can be obtained using a series approach as has been done by Krejcik et al,[1] or one can numerically integrate the equations through the lenses and drift spaces. The lens voltages are varied to obtain the desired zero current focal distance $F = r_e/r_e'$.

Numerical Examples

A. Transport of 425 keV Protons

This case corresponds exactly to that studied by Krejcik et al.,[3] and was performed to verify their results. Ray traces were obtained by integrating the equations of motion (1) through the lenses and drift spaces. The lenses were taken to be 10 cm long with outer and inner radii r_b = 7.75 mm, and r_a = 0.0375 mm, respectively. The voltages were adjusted to obtain a focal length of 21 cm for an initial beam radius of 3.0 mm. Figure 1(a) shows the ray traces obtained using a singlet lens with V = 1.425 kV for initial radii of 2.5, 3.0, 3.5, and 4.0 mm. The large variation in focal length with radius is

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evident. The circle of least confusion occurs about 2.5 cm downstream of the focal point and has a radius of ~1.5 mm. The area in the initial beam $A_i = \pi(4^2 - 2.5^2) = \pi(9.75)mm^2$. The final spot is confined in an area $A_f \sim \pi(2.25)mm^2$ - a reduction of x4.33. Figure 1(b) shows the results of going to a doublet geometry with $V_1 = -3.45$ kV and $V_2 = +9.375$ kV with an inter-lens spacing of 3 mm. The radius of the beam spot is less than 0.25 mm and the beam area is reduced by x178.

The curves in Fig. 1 indeed verify Krejcik's results[3] and show that the focal length variation with radius can be significantly reduced using a doublet.

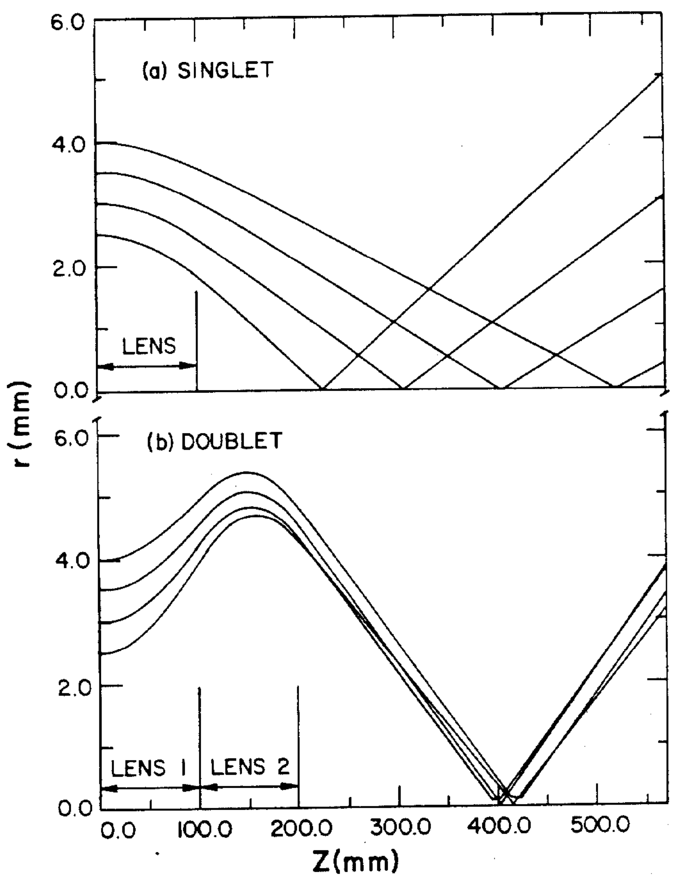

Fig. 1 Ray traces for 425 keV protons. (a) Single lens V = 1.425 kV; (b) Doublet ELCO lens system: $V_1 = -3.45$ kV, $V_2 = 9.375$ kV.

B. Transport of 1 MeV Protons

For this case, we choose a lens length of 15 cm, $r_b = 10$ mm, $r_a = 0.5$ mm, and F = 25 cm for an initial beam radius of 4.0 mm. A program was written which solves for the lens strengths using the series approach as explained in Reference 1. For a singlet, the solution is one-valued; for a doublet the program returns the voltage of the second lens for specified voltage on the first lens. In each case, after the voltages are obtained, then several rays are passed through the lenses at different radii in order to see how the focal length depends upon radius. Figure 2 shows the variation for several cases. The variation is greatest for $V_1 = 0$ (singlet case) and continues to decrease as $|V_1|$ is increased. Accordingly, we show in Figs. 3(a) and 3(b) the ray traces for singlet ($V_1 = 0$, $V_2 = 2.0$ kV) and doublet ($V_1 = -2.8$ kV, $V_2 = 7.95$ kV) obtained by numerically integrating Eq. (1) through the system. These graphs are similar to Fig. 2 and again demonstrate the advantage of doublet focussing.

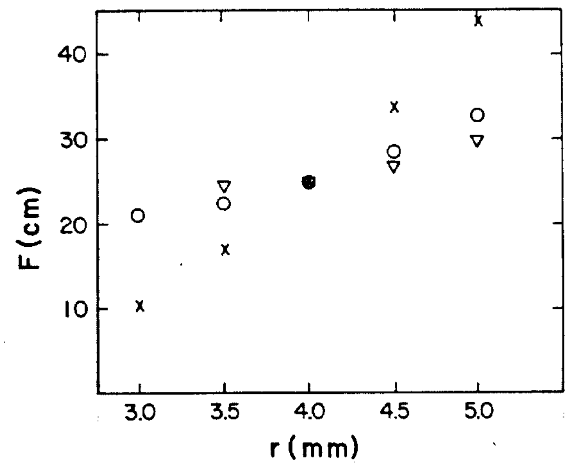

Fig. 2 Dependence of focal length upon input radius for 1 MeV protons using Doublet ELCO lens. (x) $V_1 = 0$, $V_2 = 2.0$ kV (singlet). (O) $V_1 = -2.0$ kV, $V_2 = 5.96$ kV, (∇) $V_1 = -2.8$ kV, $V_2 = 7.95$ kV.

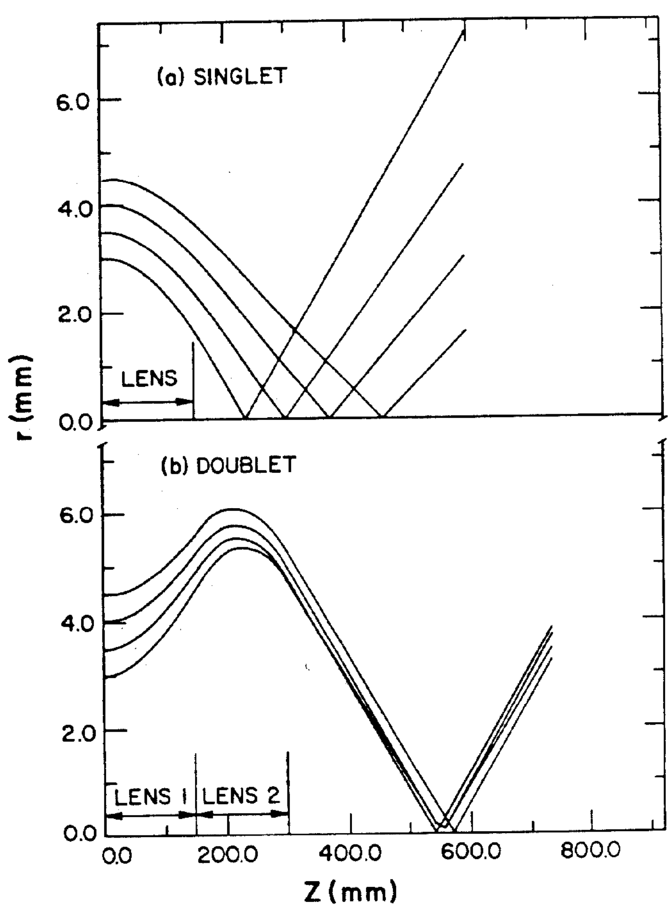

Fig. 3 Ray traces for 1 MeV protons. (a) Singlet lens V = 2.0 kV; (b) Doublet ELCO lens system: $V_1 = -2.8$ kV, $V_2 = 7.95$ kV.

A Monte-Carlo approach was used to evaluate the spot size and x growth in the r.m.s. emittance after passage through the focussing system. Ten-thousand rays were generated with an intensity distribution proportional to r and in the range $3 < r < 5$ mm and $|r'| < 2.0$ mr. These rays were tracked through the system to the nominal focus 25 cm downstream of the second lens. The r.m.s. value σ_r decreased from 1.56 mm to 1.2 mm for V_1 decreasing from 0 to -2.0 kV--we expected this from Fig. 2. Similarly, the growth in r.m.s. emittance decreased from x1.15 down to 1.00 77 over the same range in V_1; we define the r.m.s. emittance as $\varepsilon_{rms} = [\sigma_r^2\sigma_{r'}^2 - \sigma_{rr'}^2]^{1/2}$ where e.g., $\sigma_r^2 = \langle r^2\rangle - \langle r'\rangle^2$.

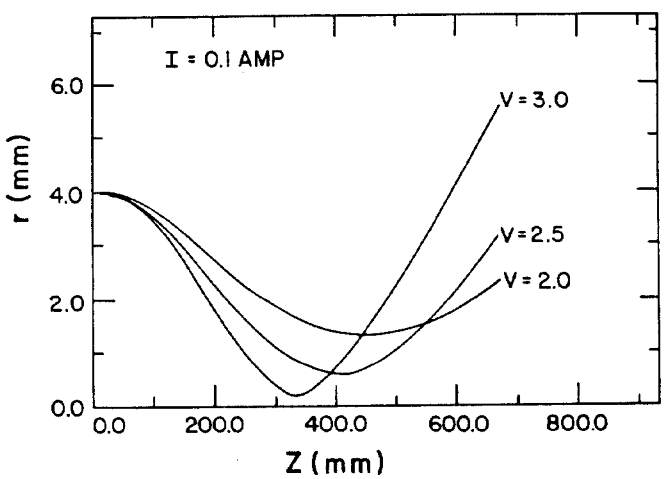

Fig. 4 Beam envelopes for I = 0.1 amps of 1 MeV beam of protons for singlet lens. The voltages are indicated.

C. Effects of Space Charge

The beam envelope for I = 0 can be calculated using Eq. (3). As an example, we show in Fig. 4 the beam envelope behavior for 100 mA of 1 MeV protons passing through a singlet lens. The current defocusses the beam. The three curves represent different lens voltages. The small spot can still be maintained at a value given by Eq. (4) by increasing the lens voltage. Beam at the inner radius will feel no space charge forces and would be overfocussed by increasing the lens voltages, however.

Conclusion

Development of hollow beam sources and accelerators is in progress.[4] This should facilitate use of the electrostatic lens concepts for inexpensive focussing.

References

1. See e.g., P. Krejcik et al., 5. Phys. D; Appl. Phys. 12, 161 (1979).

2. P. Krejcik, Nucl. Instrum. Meth. 171, 233 (1980).

3. P. Krejcik et al., Nucl. Instrum. Meth. 168, 247 (1980).

4. See e. g., P. Krejcik, "The Hollow Beam Concept for Producing Intense Beams, "Symp. on Accel. Aspects of Heavy Ion Fusion, Darmstadt, March 29-April 2, 1982.