LA-UR -85-1328

CONF-850504--20

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LA-UR--85-1328

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SUBMITTED TO 1985 PARTICLE ACCELERATOR CONFERENCE
Accelerator Engineering and Technology
Vancouver, British Columbia
May 13-16, 1985

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CIRCULAR-BEAM RAY TRACING ON A MICROCOMPUTER*

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Summary

A computer code is described that traces charged particles through a system of electrostatic and magnetic solenoid lenses. This code requires symmetry about the beam axis, but it incorporates a useful approximation for handling beam emittance and variable space-charge neutralization. It features a friendly and versatile user interface and runs efficiently on an Apple II microcomputer.

There are a number of both ray-tracing and matrix beam-transport codes available for simulating particle-beam focusing and transport systems. The popular, linear code TRACE, for example, is a versatile simulation code that can trace outer beam profiles through a variety of both accelerating and transport structures. TRACE provides a first-order approximation for external fields, space charge, and beam emittance. Because the code is so common and runs relatively quickly, it is a valuable tool for checking performance of various designs.

However, I wanted a small and simple code that could run on a readily available microcomputer and that would be more interactive than many existing codes. To keep the new code short and simple, it had to be somewhat limited in versatility. The major restriction is that the beam profile must be circularly symmetric, which eliminates quadrupole transport but allows simulation of a useful variety of electrostatic and solenoidal focusing systems.

Description

A convenient form for the paraxial-ray equation is given in Eq. (1). The first two terms are the electrostatic terms, comprising the focusing effects of external electric fields. The third term is the effect of internal electric fields, arising from space charge or the collective effect of the charged particles in the beam. The fourth term is the focus effect of a solenoidal magnetic field. The divergent effect of finite beam emittance is described in the last term. Normally the emittance term is small compared to other effects, but is included for completeness.

$$r'' = \frac{-r\phi''}{4\phi} - \frac{r'\phi'}{2\phi} + \frac{kMe}{\phi^{3/2}r} \frac{1/2 I_{eff}}{r} - \frac{q}{m} \frac{1}{8\phi} \frac{B_z^2}{r} + \frac{\epsilon^2}{r^3} \quad (\text{mks units}) \quad (1)$$

where primes denote differentiation with respect to the z-coordinate

- r = radius of particle,
- ϕ = energy of particle in electron volts,
- k = 1.52×10^4 ,
- Me = particle mass in units of electron mass,
- I_{eff} = effective current inside radius r,
- q/m = particle charge/mass,
- B_z = axial solenoidal field, and
- ϵ = beam emittance (unnormalized).

The first term in Eq. (1) indicates that to provide electrostatic focusing, accelerating electric fields must increase in magnitude as z increases; whereas, decelerating fields must decrease with z.

If all terms except the first and third are set to zero, the familiar, linear, Pierce potential profile is generated. The Pierce geometry forces the accelerating field to increase at a rate that exactly compensates for the internal space-charge forces. The spherically convergent (or divergent) Pierce extractor geometry can be generated by zeroing all but the first three terms and applying some restrictions. Appropriate rearrangement of the first three terms will give

$$\phi'' = \frac{-2r'\phi'}{r} + \frac{4kMe}{1/2r^2} \frac{1/2 I_{eff}}{r} \quad (2)$$

Equation (2) is in a form that can be easily solved by numerical integration if we select the proper constant value for r' and a corresponding analytic form for r. The result is a potential profile appropriate for supporting a spherically convergent extractor.

The second term is obviously important only for trajectories that have a nonzero angle with the beam axis.

As written, the space-charge term in Eq. (1) is completely correct only for a parallel beam of infinite length. However, many simulation runs have shown this form to be reasonably accurate except in cases where the beam is strongly convergent or divergent. The current, I_{eff} , represents the "effective" current inside radius r. If the beam is partially space-charge neutralized, the effective current must be reduced by the appropriate factor.

The emittance term used in Eq. (1) is the unnormalized value that corresponds to a beam of radius r and current I_{eff} . If the effect of aberrations is neglected, the normalized value of transverse beam emittance may be assumed to remain constant in the systems under consideration. The unnormalized emittance will vary with beam energy and can be determined from

$$\gamma = 1 + \phi/m \quad (m \text{ in eV}) = E/m_0 c^2 \quad (3)$$

where $E = T + m_0 c^2$, where T = ion kinetic energy
 m_0 = ion rest mass

$$\beta = \sqrt{1 - 1/\gamma^2} \quad , \text{ and} \quad (4)$$

$$\epsilon = \frac{\epsilon_N}{\beta\gamma} \quad (\epsilon_N \text{ is normalized emittance}) \quad (5)$$

Features

Space-charge forces dominate in most "real" cases of high-perveance transport. However, the actual space-charge forces are usually uncertain because of partial space-charge neutralization. Space-charge neutralization arises from the presence of charged particles created by ionization of the residual gas by the beam particles. Variables such as magnetic and electric fields and differing gas pressures cause the

*Work supported by US Dept. of Defense, Defense Advanced Research Projects Agency, and Ballistic Missile Defense Advanced Technology Center.

neutralization effects to fluctuate along the beam. This code allows the specification of variable residual space charge along the beam path. Determination of the actual value of space charge must be done by separate means, either by measurement, or by estimation. The real effects of varying neutralization can be determined only by running trajectories with different values of space charge.

To facilitate calculations utilizing varying beam neutralization, arbitrary electric potential, and arbitrary solenoidal fields, the program input consists of a number of points along the beam axis. Input can be from the keyboard or from a disk file. Electric potential, axial magnetic field, and effective current may be specified at any axial position. This small number of input data pairs are then fit with a cubic spline routine that weaves a smooth line through each of the input data points. A simple routine allows the determination of the function value, plus first and second derivatives at any longitudinal position. A standard integration routine can then be used to trace the beam profile through the transport system.

An approximately analytic form can be specified for the axis potential for many standard electrostatic lenses. Arbitrary expansions from this on-axis potential can give a useful approximation to higher order terms. Either measured or accurately calculated fields can be used also. For the latter application, a bicubic spline-fitting routine is often most useful. Many of the commonly available field-calculating routines (such as POISSON) assume circular symmetry as well.

One distinct advantage of this method over the use of pseudoanalytic formulae is that the ray-tracing routine allows us to see the details of beam trajectories through real elements. This feature is most significant for comparing "hard" and "soft" edge fields and for studying the effects of overlapping fields. For convenience, particle trajectories are plotted rather than tabulated. Other routines allow plotting of the electric potential, magnetic field, or space charge versus longitudinal position. This feature is essential for verifying that input data represent a realistic situation.

Sample Optimizer

Let us consider one manner in which this code can be used to design an array of electrostatic lenses. Assume that we start with a desired trajectory for an ion beam and that we specify beam energy at the beginning and end of the section to be designed. The problem then becomes simply determining the axial potential needed to support those particle trajectories.

We will make the restriction that the beam profile must remain circularly symmetric. We can allow the use of magnetic solenoid lenses and variable space charge, but we must specify their values as a function of position along the beamline. The optimization procedure can then be reduced to a few simple steps.

- Translate the general paraxial-ray equation, Eq. (1), into the following form:

$$\phi'' = \frac{-4\phi r''}{r} - \frac{2r'\phi'}{r} + \frac{4kMe^{1/2}I_{eff}}{\phi^{1/2}r^2} - \frac{q}{m} \frac{B_z^2}{2} + \frac{4\phi_e}{r^4} \quad (6)$$

- Input the desired beam profile as a succession of r,z data pairs
- Do a cubic-spline fit to these data to determine r' and r'' at all z-locations
- Select initial values for ϕ and ϕ'
- Integrate Eq. (6) through the system to determine $[\phi(z)]$
- Expand the axial electric potential in r to the desired order to determine approximate electrode values and locations.
- Iterate as necessary until a practical solution is found.

Conclusions

A description is given of many of the important features of a user-friendly computer code based on the paraxial-ray equation. Although this code may be adequate for final design of low-perveance lenses, its primary utility is that of quickly investigating potential lens configurations before use of a more exact model.

The code described here performs several functions. First it allows one to quickly determine the general profile of a circularly symmetric beam through an arbitrary pattern of electrostatic and magnetic solenoid lenses. It can also predict major effects of chromatic aberrations and, with inclusion of higher order terms, can allow estimation of spherical aberration effects. Expansion of the on-axis potential profile will determine the approximate placement of electrostatic electrodes. Finally, it is possible to determine the potential profile needed to support a desired transverse beam profile. Accelerating columns can be modeled easily, if care is taken to avoid high perveance or extremely high field gradients.