COMPUTER SIMULATION OF HIGH-CURRENT DC ION BEAMS

Peter Spädtke
Gesellschaft für Schwerionenforschung mbH,
Darmstadt, Fed. Rep. of Germany

Summary

In the case of high-current low-emittance dc ion beams, the space-charge cannot be neglected if there is no compensation. The knowledge of local beam potentials and resulting ion trajectories is the premise to design an efficient beam transport system, but analytical solutions for the potential equation are known only for a few special distribution functions.

Two different computer codes are described, a two- and a three-dimensional one, that are of great help in optimizing extraction systems of ion sources and beam transport systems. Both programs are interactive, to ensure a fast feedback to the user.

As examples of conducted applications, the computer-aided optimization (CAO) of an extraction system as well as the injection of a beam into an acceleration-column demonstrate the possibilities of the two-dimensional code.

The three-dimensional code allows to study the beam behaviour under the influence of electrostatic and magnetostatic fields, even without any field symmetry. As an example, for a beam that is transported through a solenoid the influence of tilt and misalignment is shown.

Introduction

The self-consistent simulation of low-energy ion beams, including space-charge, is object of several computer codes. Improvements of the performance of these programs have been made during the last years as computer became faster and more storage is now available.

One item of these progresses is the interactivity of the programs. Up to now this kind of programs could be handled only by batch procession, because too much CPU time would have been consumed.

A further advantage of an interactive program structure is the possibility to control the program-flux, and to change input data during the execution of the program.

The possibility of generating fields within some Mbyte storage volume are necessary to simulate three-dimensional problems.

Both programs described here are written in FORTRAN and CALCOMP graphic-routines are used.

The two-dimensional code AXCEL:

This program was written by J.C. Whitson[1] in 1975. We have modified our version of AXCEL in several respects, but always the SOR-method (Successive Over Relaxation) for the calculation of the scalar potential and an extrapolation-method for the integration of the equation of motion are used.

We included several possibilities to generate the starting coordinates of ions or electrons: plasma conditions, initial emittance, fixed (curved) emitter and periodic transport. The last feature provides a segmentation of more complex geometries.

Depending on several conditions, the space-charge compensation is either treated according to the theory of Self[2] or by a simple assumption on the degree of compensation.

The resolution has been improved by increasing the field dimensions.

Together with the interactivity, these changes allow to find solutions for an optimized transport very quickly.

As an example the computer-aided design (CAD) of a cylindrical extraction system of a high-current ion source is demonstrated.

In the first run up to eight major iterations are necessary to achieve a self-consistent solution of a problem. A minor change in geometry can be treated by only a few iterations. This is shown in fig.1, for the variation of the outlet aperture shape.

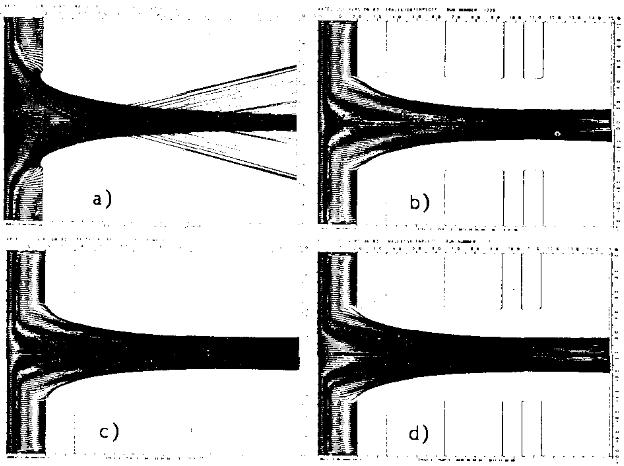

Fig.1. Rate of convergence. From a → b : 8 iterations, from b → c and c → d : 3 iterations are necessary.

For a more detailed examination of the beam quality the emittance figure (see fig.2) shows the influence of shaping the source outlet aperture.

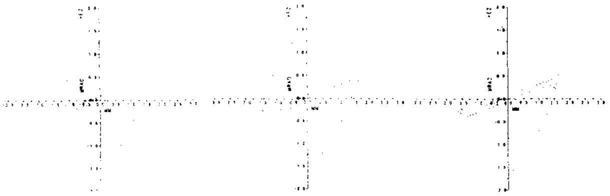

Fig.2. Beam quality described in terms of the emittance directly behind the outlet aperture of figs.1b, c, d (from left to right).

In fig.1 and 2 singly charged Ar-ions are extracted at 42 kV extraction voltage. Current density in the plasma was 60 A/m².

In the case of a plasma ion-source the ions start in a region which is charge-neutralized. The plasma boundary is well described by the theory of Self[2].

Behind the negative screening electrode the space-charge will be compensated by electrons to a very high degree. These electrons are generated by collisions of the ions with the residual gas-atoms. In this case space-charge compensation can be treated by a simple gradient-method. The influence of this compensation effect is shown in fig.3.

The results of the program are in good agreement with experiments we have done.

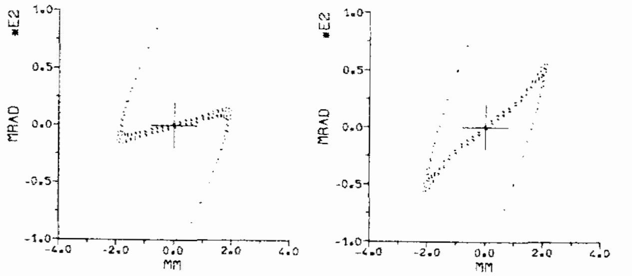

Fig.3. Ion beam emittance under the influence of space charge (right); with compensation (left).

The three-dimensional code KOBRA3:

In the non-symmetric case the calculation of potentials and trajectories has to be done in three or six dimensions, respectivly: three space and three velocity coordinates. For this purpose the program KOBRA3[3] was developed.

This program calculates the distances in the difference-equation for every node-point exactly. The mesh size can be varied in every direction. The maximum number of node-points is 90.000.

Electrostatic fields are calculated with the ADI-method (Alternate Direction Implicit method). Magnetostatic fields can be evaluated analytically or read in from tables.

Raytracing with up to 1000 rays is carried out by the same method as in the AXCEL code.

The load-module of the program which has been already linked to the necessary libraries takes about 5 Mbyte storage. To increase the flexibility of the program we broke it into logical parts. The organisation of the program is shown in fig.4.

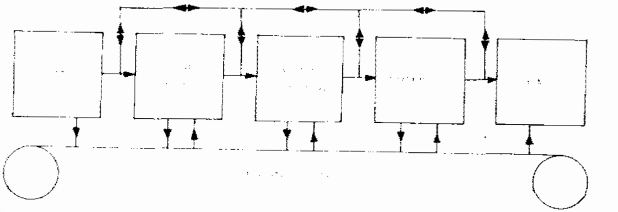

Fig.4. Partitioned organisation of KOBRA3. Information is always saved on a file. Loops and branches are possible within the structure.

In the following example a drift tube is simulated. The diameter of this drift tube is 80 mm. Two magnetic solenoids are used to focus the beam. The distance of both solenoids is 200 mm (see fig.5). The magnetic field has been calculated with a two-dimensional POISSON-program[4].

The physical status of the O^{6+}-beam with 90 keV is described by its emittance (see fig.6 and 7). In fig.6 the beam is well aligned, whereas in fig.7a the ion beam starts with a tilt of 50 mrad in the vertical plane. After the first lens the tilt has changed to a displacement in both planes, horizontal and vertical (fig.7b). Behind the next solenoid this displacement leeds again to a tilt, but now in the horizontal plane (fig.7c). The aberrations, which lead to an emittance growths, are exclusively caused by the non-ideal field. These calculations have been done under the assumption of charge-neutralization.

Fig.5. Geometry and magnetic field.

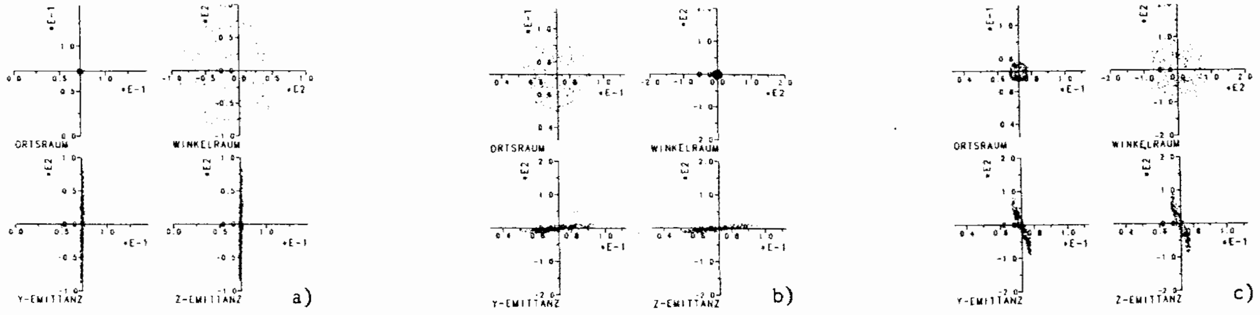

Fig.6. Physical status of the beam. First line: real space and angle space, second line: both transversal emittances. a) at the starting point (200mm mrad) b) between both solenoids and c) at the end of the beam-line.

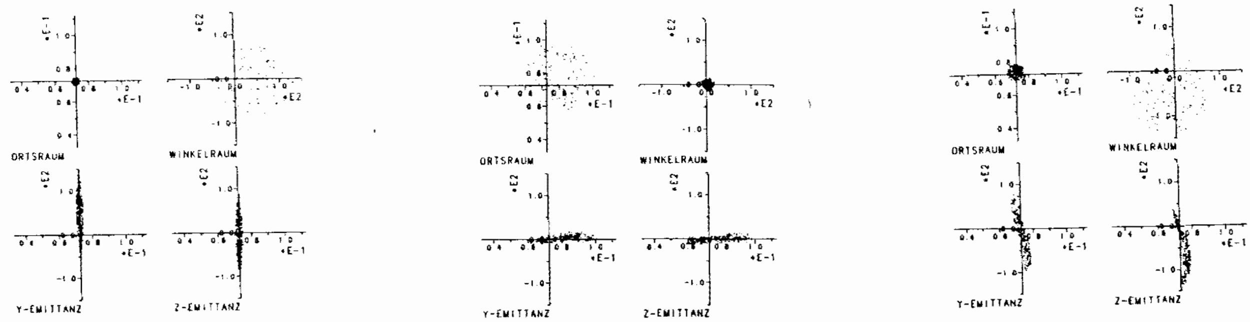

Fig.7. Tilted beam, shown at the same coordinates as in fig.6.

If space-charge is not negligible the electrostatic field of the beam has to be considered, too, and further iterations have to be carried out, to find a self-consistent solution. The resulting potential for a 10 mA, 50keV Ar beam is shown in fig.8.

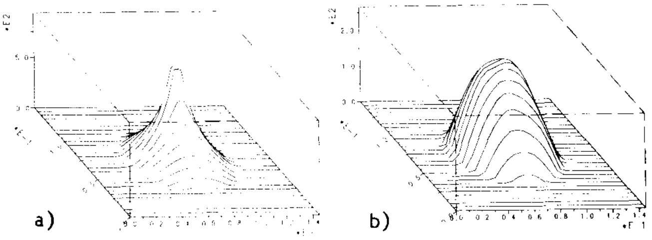

Fig.8. Potential distribution within the grounded beam-line of 0.5 m length.
a) near the starting point of the beam (diameter of the beam: 10 mm)
b) at the end of the beam-line (diameter of the beam: 80 mm)

These fields lead to a more divergent beam than in the zero current case, see fig.9 and 10.

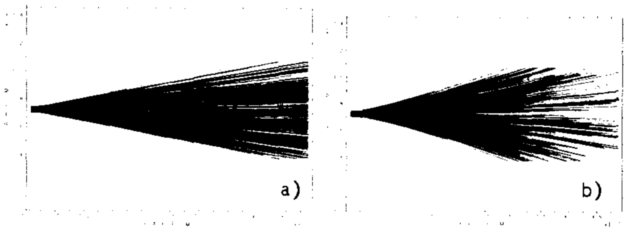

Fig.9. Trajectories in a drift tube. a): without space-charge and b): influenced by space-charge.

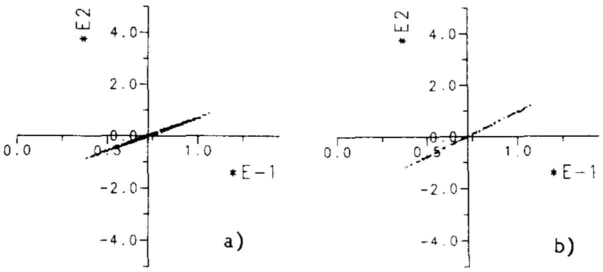

Fig.10. Emittance at the end of the beam-line: a): without and b): with space-charge (60% losses).

If there are collisions between the ions and the residual gas atoms, the electrons remain within the beam and compensate its space-charge. The path of such an electron is shown in a 3-D graph in fig.11.

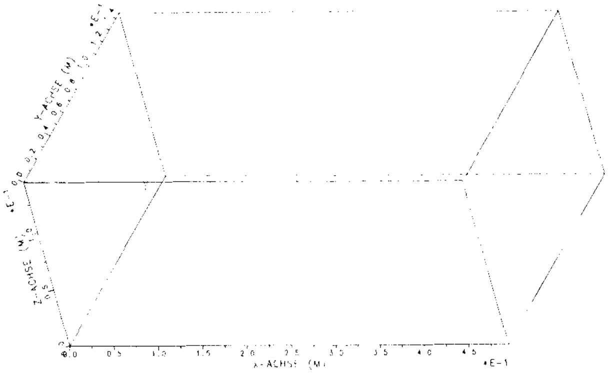

Fig.11. Electron motion in the space-charge potential well of the beam.

References

[1] E.F. Jaeger and I.C. Whitson, Numerical Simulation for Axially Symmetric Beamlets in the Duopigatron Ion Source, ORNL/TM-4990, Oak Ridge Tennessee (1975)

[2] S.A. Self, Exact Solution of the Collisionsless Plasma-Sheat Equation, Phys.Fluids 6, 1762 (1963)

[3] N. Schmitt, Entwickeln und Austesten eines Programms zur Bestimmung der elektronen - und ionenoptischen Eigenschaften elektrostatischer und magnetostatischer Anordnungen. Thesis, FH Wiesbaden (1983)

[4] K. Halbach, A Program for Inversion of System Analysis and its Application to the Design of Magnets, Proc. Second Int. Conf. on Magnet Technology, Oxford (1967)