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KOBRA3 - THREE DIMENSIONAL RAYTRACING INCLUDING SPACE-CHARGE EFFECTS

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Summary

Using the three-dimensional computer code KOBRA3, we have simulated the behaviour of the space charge compensating electrons within the potential of ion beams and magnetic fields. Measured field maps of a solenoid and a quadrupole have been used for these simulations. The predictions of the code are compared with measurements.

Introduction

The program described here was developed at GSI to compute the behaviour of high-current dc ion beams. It can be used for the simulation of problems related to the extraction of an ion beam from the ion source as well as for the transport of dc ion and electron beams including space charge and space charge compensation effects.

Program structure.

KOBRA3 consists of a number of independent programs, all written in standard FORTRAN77. In the current version the executable load module of the program needs 6 Mb storage.

These programs are organized as follows:

The first part transforms the user input into mesh information and creates a file containing all this information. The user is not obliged to mark mesh points in the non equidistant rectangular mesh. Only the real geometry has to be defined. Rectangular and cylindrical coordinate systems can be used. If the geometry does not match to the mesh, the modified mesh distances for the difference equation will be calculated by the program.

The next part of the program package is the Poisson solver. It works with the finite difference method (FDM). The solving of such a large set of difference equations (up to 90.000 mesh points) can be made by different methods: Here either the SOR (Successive Over Relaxation) or the ADI (Alternate Direction Implicit) method can be chosen. It depends on the problem, which of both will converge better.

The third part of the program creates the magnetic field distribution analytically or reads the magnetic flux density from tables. These tables can be generated by other programs or result from measurement.

Then the 'raytracer' can be started. In this part of the program the space charge map is created, too. This space charge distribution is used later in the next main iteration of the Poisson solver.

After that, space charge compensation can be generated within an ion beam by raytracing of electrons. The above mentioned space charge map will be updated accordingly.

Four other programs provide the graphic output of the results, which allows plots of trajectories, potentials and emittances.

The program works interactively. The user determines the sequence of the different program parts. Several parameters, e.g. current density, potentials, magnetic flux density or plasma parameter can be changed during the program execution.

Application

Three different examples are given in this paper in order to demonstrate the performance and possibilities of the program.

In the first figure we have simulated the tetrode extraction system for the proton ion source for the neutral beam injection system for JET[1]. In this case especially the dependence of the steering angle of the extracted beam as a function of displacement of the third, negative electrode was investigated.
With electrode potentials of 80, 72, -3, and 0 kV and a displacement of 0.4 mm, the steering angle was computed with ≈ 13 mrad. The current density in the source was changed until a parallel beam was obtained.
The number of mesh points in this run was 67500, the number of rays 1000 (in the last iteration 4000), used CPU time 30 minutes for 5 iterations.
Good agreement of the calculation with the measured steering angles was found (fig.1 and 2).

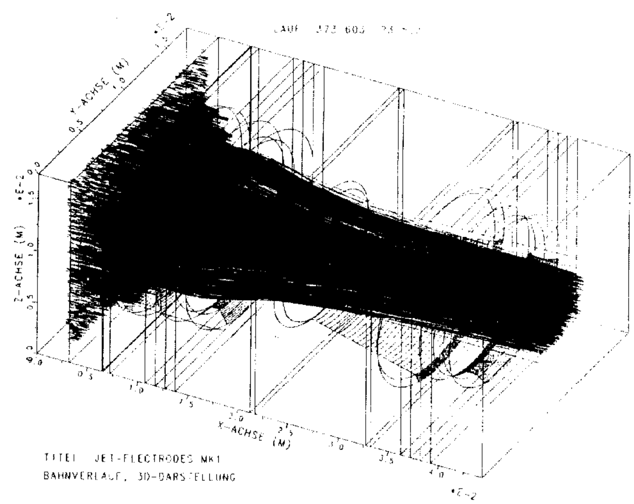

Fig.1 Geometry plot and trajectories after 5 iterations of the extraction system for the JET neutral beam injector.

Another example is the simulation of the extraction from an ECR (electron cyclotron resonance) ion source[2]. In this case magnetic field was included as well as a charge distribution within the plasma, with a mean charge state for oxygen of 3+. The potentials on the electrodes are 22 and 0 kV, with a gap of 34 mm.
The magnetic field, created by the source coils, has the maximum flux density of 0.5 T near the extraction plane.
In this extraction system with a very low current density ($j = 0.55\ mA/cm^2$), we need 4 iterations to reach convergence.
In the emittance plot in fig.4 no influence of the magnetic field on the beam can be seen, the different charge states remain in the same emittance area.

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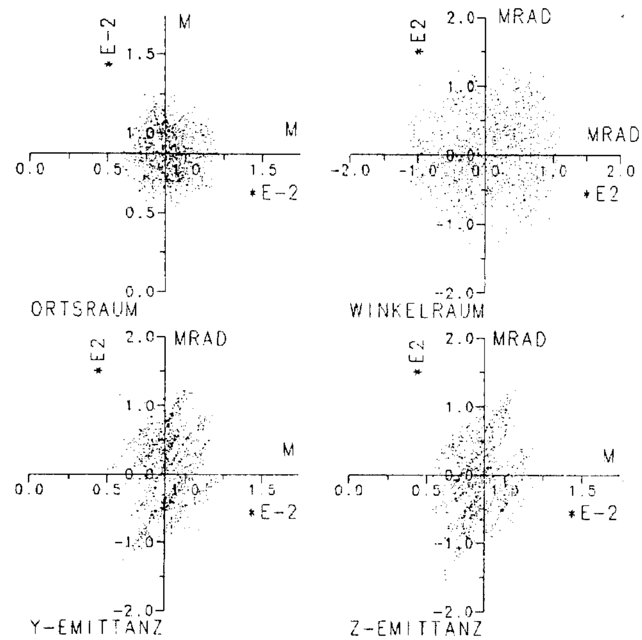

Fig.2 Emittance plot for the high current extraction for JET. In the first row projections in space (left) and divergences (right), in the second row both phase spaces in transverse directions are shown.

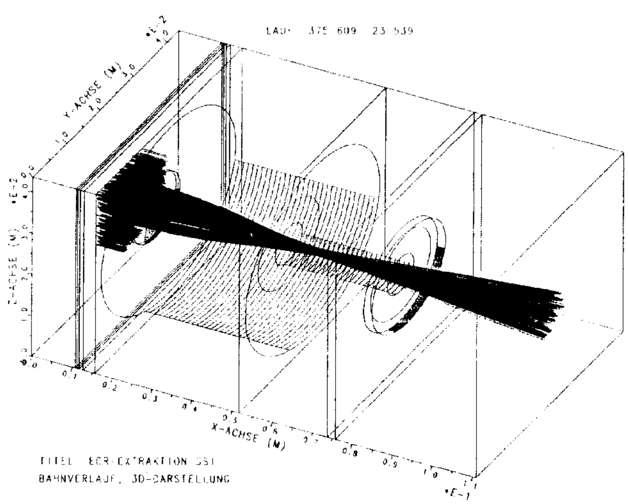

Fig.3 Trajectories and geometry plot for an ECR ion source extraction system after 4 iterations.

In both extraction calculations a self-consistent solution for the plasma boundary was obtained within 4 to 5 iterations. The sheath is found by the assumption of compensating electrons within the source plasma. The space charge has to be corrected by the formula[3]

$$\rho(U) = \rho\bullet(1-\exp[-(U_{pl}-U)/T_e]),$$

where ρ is the uncompensated space charge, U the potential at the mesh point to be calculated, U_{pl} the plasma potential, and T_e the electron temperature.

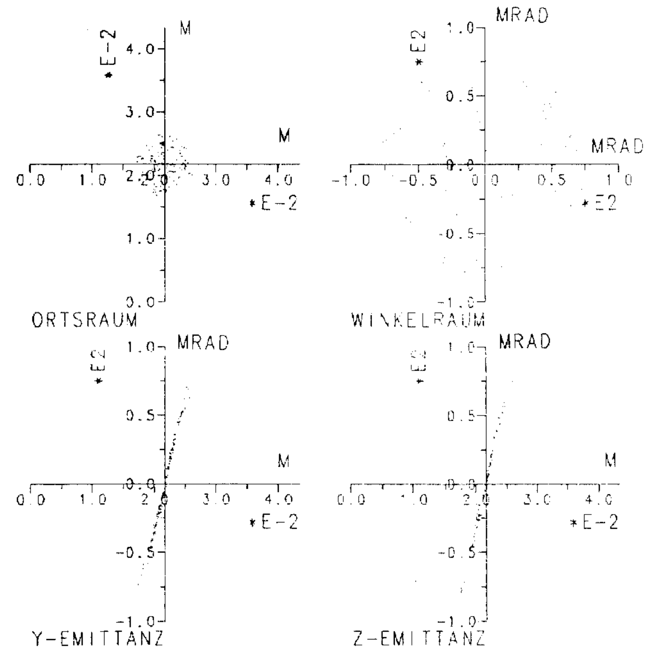

Fig.4 Emittance plot, same order as in fig.2.

This strong dependence of the space charge from the potential is the reason of why an iterative solver is better suited for the solution of Poisson's equation compared to a direct solving method.

The next example is the simulation of the space charge compensation of a dc ion beam within a solenoid.

Real raytracing of both ions and electrons is used, instead of an analytic model.
To simulate the behaviour of such an ion beam with an unknown space charge distribution, we repeat the following procedure until convergence is reached:

raytracing of ions and
creation of a space charge map

raytracing of electrons and
compensation of the above space charge map

recalculation of the potential

The compensating electrons will be created on the path of an ion, with the assumption for the starting energy of a few eV. They have a given lifetime, due to capture or any other losses. On their way the space charge map of the ions will be compensated.
A 10 mA singly charged 12 keV He-beam (see fig. 5) is started with three beamlets, each with 100 mm mrad emittance. The length of the beam line in the calculation is 0.6 m. The solenoid has a maximum field of 0.5 T and is 140 mm long.
The difference between the compensated and decompensated beam is shown in fig.6. The solution for this beam converges after 5 iterations.

For the compensated beam we have varied the magnetic flux density, to show the optical properties of the lens. The emittance plots were made always at the same place at the end of the beam line (see fig.7).

In our measurement the image of the ion extraction system (seven apertures with diameter Ø5 mm) was reproduced on a copper foil (Fig. 8).

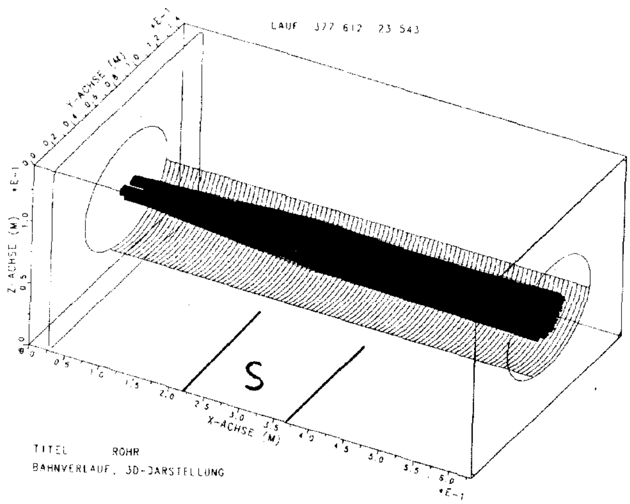

Fig.5 Trajectories of the compensated beam. The solenoid (S) is located in the middle of the beam line.

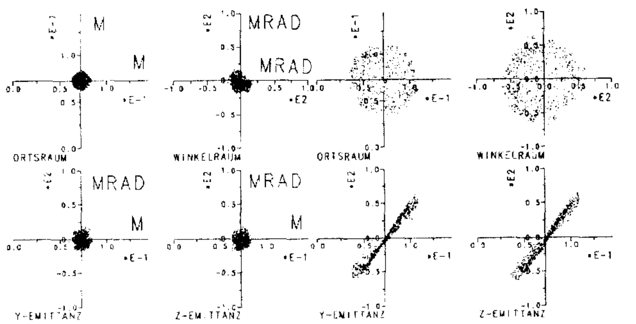

Fig.6 Emittance of the compensated (left) and uncompensated (right) beam at the end of the beam line (constant magnetic flux density).

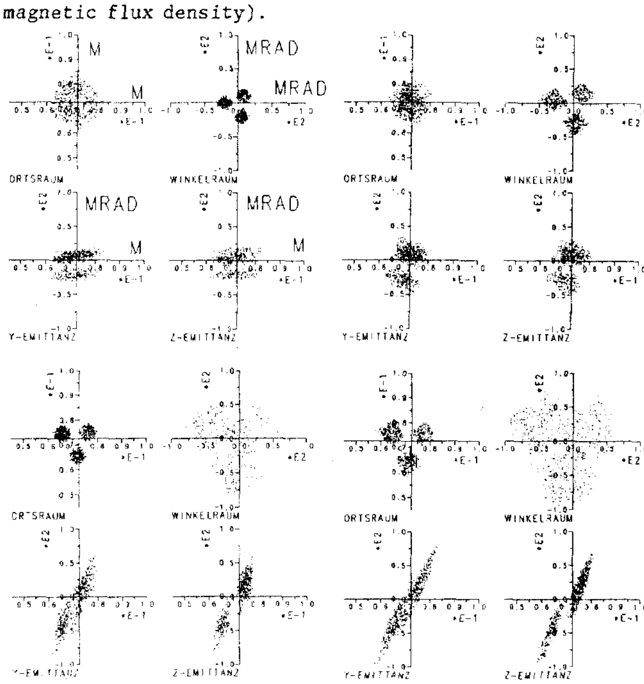

Fig.7 Emittances of the compensated beam at the end of the beam line with increasing magnetic flux density. First row : 0.3 T (left) and 0.35 T (right), second row 0.45 T (left) and 0.5 T (right).

If we assume that the beam (15 keV He, 20 mA, pulsed operation, frequency 50 Hz, pulse length 2 ms) was space charge compensated to a very high degree (≥ 90 %, the pressure in the beam line was in the range from 10^{-5} to 10^{-4}mbar) a good agreement with the calculation for the compensated beam is obtained.

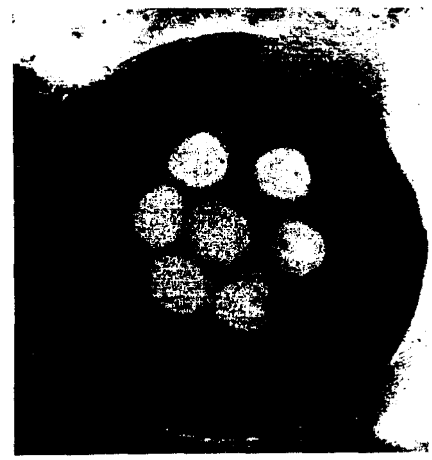

Fig.8 Measured profile of the beam at optimized field strength of the solenoid (image on a copper foil).

With KOBRA3 we have calculated the electron trajectories within the ion beam. If electrons are created between ion source and solenoid and behind the solenoid, these electrons are trapped by the beam potential, but within the solenoid they compensate only on the beam axis. If no electrons would be created inside the solenoid, the beam would remain uncompensated there.

The experiment indicates, that the number of electrons created within the magnetic field is sufficient to compensate the space charge after a build-up time less then one ms even within the solenoid.

In fig.9 the electron cloud is shown in this case at different iteration steps. In the beginning (left) the high potential of the uncompensated beam traps the electrons, after the build-up time (right) the beam is compensated only outside the fringing fields.

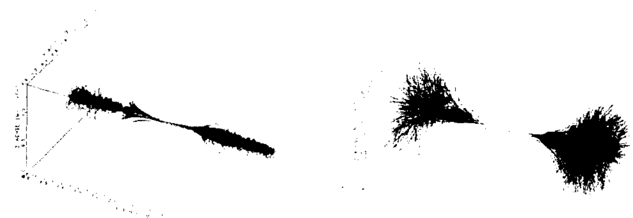

Fig.9 Distribution of space charge compensating electrons in a beam going through a solenoid (see fig.5). left: at the beginning, right: at maximum space charge compensation.

Conclusion

The program can be used for the simulation of the behaviour of particle beams including internal and external fields. Correct results are obtained, if the physical boundary conditions are known.

References

[1] A.J.T. Holmes, private communication (1984)
[2] H. Schulte, GSI Scientific Report, Darmstadt (1982)
[3] S.A. Self, Exact Solution of the Collisionless Plasma-Sheat Equation, The Physics of Fluids 6 (1963)