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Comparison of Simulation Codes for the Beam Dynamics of Low-Energy Ions

K. Hanke, S. Heising, G. Probert, R. Scrivens

Abstract

Results are presented of the simulation of low-energy ion dynamics with three different codes: KOBRA, IGUN and CPO. To share work between different codes one needs to be confident that they agree. For test cases, good agreement was found between the codes and analytical solutions. Where possible, results have been compared to experimental data from the CERN Laser Ion Source. These simulations are in general agreement with the data of the real beam line.

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1 Introduction

Simulation of the extraction and low-energy transport of ions is a complex problem. In the case of the CERN Laser Ions Source (LIS) the beam is space-charge dominated and consists of a variety of charge states. To simulate the transport of beams through electrostatic fields, one starts from a set of measured beam parameters at the entry of the beam line. The result of the tracking depends then on the precision of the measurement, the field solver and the integration routine for the equation of motion of the particles.

The simulation of particle transport in the space-charge domain can be shared between different codes if they have been cross-checked against each other. At CERN, the three codes KOBRA, IGUN and CPO are available. We have cross-checked these codes against each other with simple examples and have compared the results with experimental data available from the CERN LIS. The input beam distribution was identical for all codes. The codes were compared using two tests:

1. Expansion of a space-charge dominated beam in a drift region without external fields;
2. Transport of particles in the electrostatic field of a Gridded Electrostatic Lens (GEL) [1] as used on the CERN LIS (see later description).

2 Simulation Codes

2.1 KOBRA

KOBRA3-INP [2] is a three-dimensional program for the simulation of steady state problems. The program contains a Vlasov solver, which finds the solution of the Poisson equation and of the particle distribution function via the space-charge map which is then included in further iterations of the Poisson equation.

2.2 IGUN

IGUN [3] is a 2D ray-tracing simulation code that is designed for the simulation of ion extraction and transportation in electrostatic and magneto-static systems. The code is based on an electron ray-tracing code (EGUN) with additional modelling of the compensation of the ion space-charge by electrons in a plasma.

2.3 CPO

Charged Particle Optics (CPO)[4] is a three-dimensional code that uses the surface charge method. In contrast to the other codes, the electrical fields are determined by charges deposited onto surface elements of the conductors within the volume. A comparison of finite element methods and the surface charge method is given in [5, 6].

3 Space Charge Expansion

The first example used to cross-check the codes is the space-charge expansion of a beam with given parameters going through a drift space. For this study, a uniform beam of Ta^{20+} ions was generated with 30 mm initial diameter and zero emittance ('pencil beam'). The initial kinetic energy was set according to an extraction voltage of 60 kV. The drift length was 10 cm and two beam currents of 60 mA and 120 mA were simulated.

The three simulation codes give the output beam parameters shown in Table 1. Note that IGUN provides only two-dimensional results (r , r') and that the emittances calculated by IGUN are significantly lower compared to other codes. KOBRA and IGUN agree to within 1% and CPO to within 2% to the approximate analytical solution of the radius. We are therefore convinced that space-charge is treated correctly in the three codes.

Table 1: Output beam parameters for space charge expansion computed with the three codes.

	KOBRA		IGUN		CPO	
	60 mA	120 mA	60 mA	120 mA	60 mA	120 mA
r [mm]	17.5 ^a	19.6 ^b	17.3	19.6	17.2	19.2

a) Analytical value is 17.4 mA

b) Analytical value is 19.6 mA

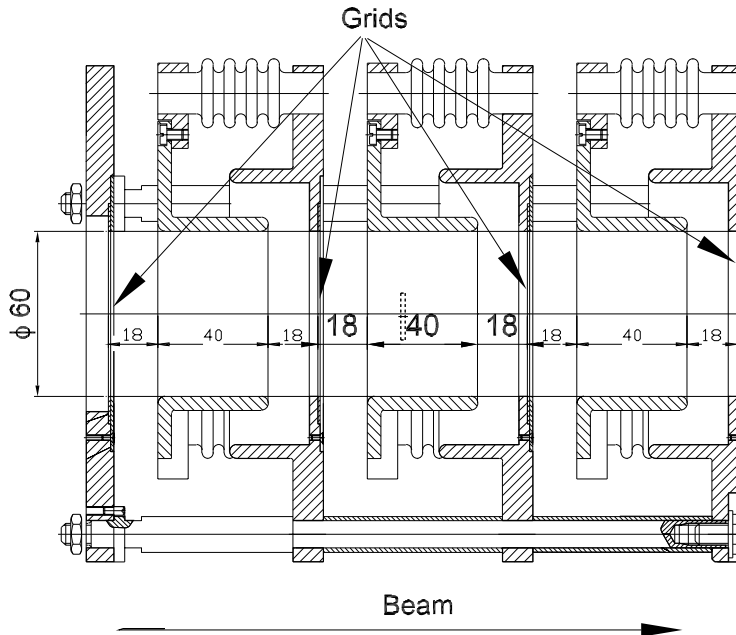


Figure 1: Gridded electrostatic lens LEBT. All dimensions in mm.

4 Simulation of LEBT

We will now consider beam transport through an electrostatic focusing element as used in low-energy beam transport (LEBT) lines. The input beam parameters are in general accessible to measurements and therefore known within the measurement precision. The electrostatic field is computed by the field solver of the codes. This is also a possible source of discrepancy between codes.

The gridded electrostatic lens LEBT used on the CERN LIS was chosen as an example. It consists of three long (40 mm) electrodes at variable potential separated by grids at ground potential. The complete GEL set-up is shown in Fig. 1. It is used to match the beam from the extraction system to the acceptance of the subsequent Radio-Frequency Quadrupole (RFQ).

As a test case to verify the correct beam transfer in the three codes, we have considered one single GEL element at $V = 30$ kV. The geometry used was a 30 mm drift, one GEL element and a 30 mm exit drift region. The GEL element consists of a grid at ground potential, a drift of 18 mm, the 40 mm long electrode at 30 kV, a second drift of 18 mm and a second grid at ground potential. Ta^{20+} ions at a kinetic energy corresponding to 110 kV extraction were transported. Space-charge effects were suppressed for this test case.

4.1 Potential on Beam Axis

The field solvers of the three different codes were compared. The potential map for the given geometry and potentials was computed, and the potential along the z axis was plotted

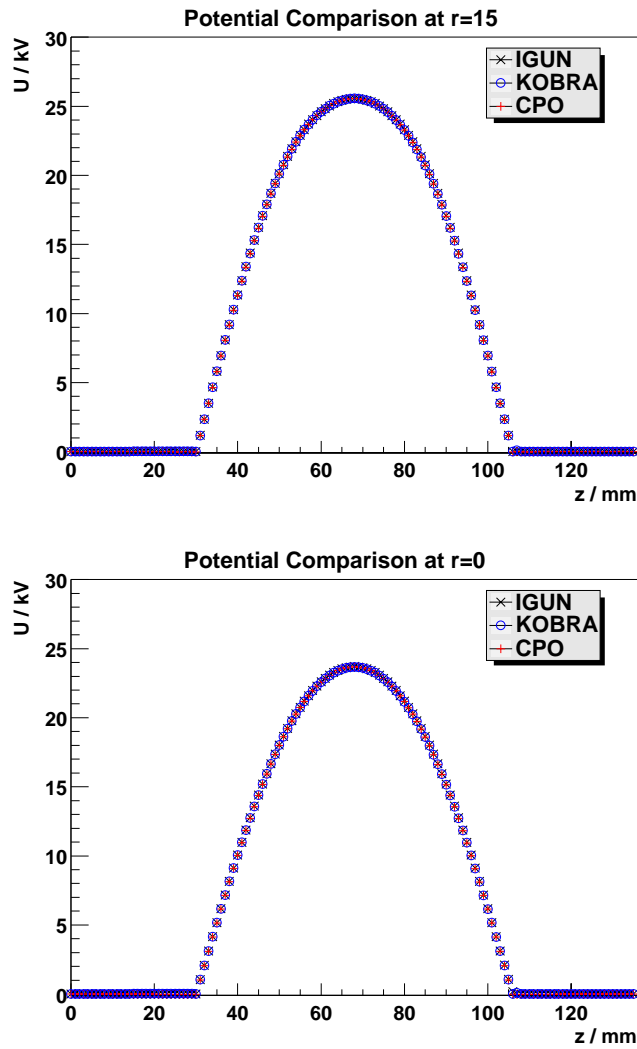


Figure 2: Potential at $r_{x,y} = \pm 15$ mm (upper plot) and $r_x = r_y = 0$ mm (lower plot) as computed by the three codes. No discrepancy is visible.

for the three cases ($r_x = 15$ mm, $r_y = 0$ mm), ($r_x = 0$ mm, $r_y = 15$ mm) and ($r_x = 0$ mm, $r_y = 0$ mm). The resulting plots are shown in Fig. 2. The difference plot is shown in Fig. 3, where the largest deviation is below 50 V. Therefore it is concluded that the calculation of the potential map is done correctly in all three codes.

4.2 Transport of Test Rays through GEL

Single test rays were traced through the potential map. The test rays started at 5 mm, 10 mm and 15 mm from the axis in x - and y -direction. A plot of the trajectories is shown in Fig. 4, where the rays overlap perfectly.

4.3 Beam Transport through GEL

Finally we transported a typical LIS beam with a current of 74 mA through the three-cell GEL as shown in Fig. 1. The parameters for the initial distribution are taken from a measurement at the entry plane of the GEL. The emittance at 50 mm after the exit grid as well as the current into a Faraday cup with two input apertures was obtained. The double-aperture cup has two

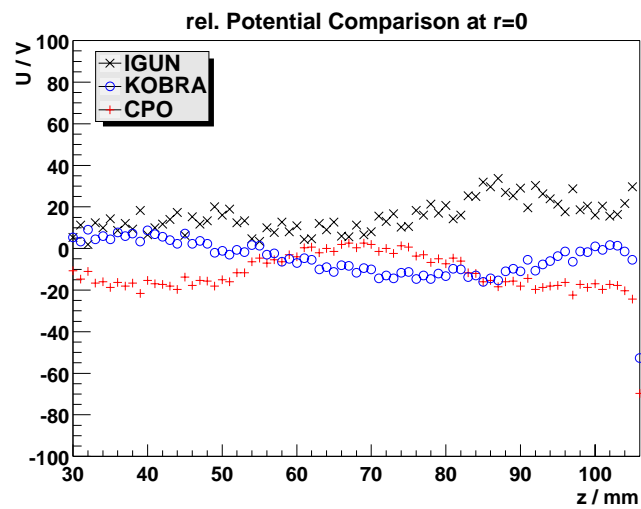
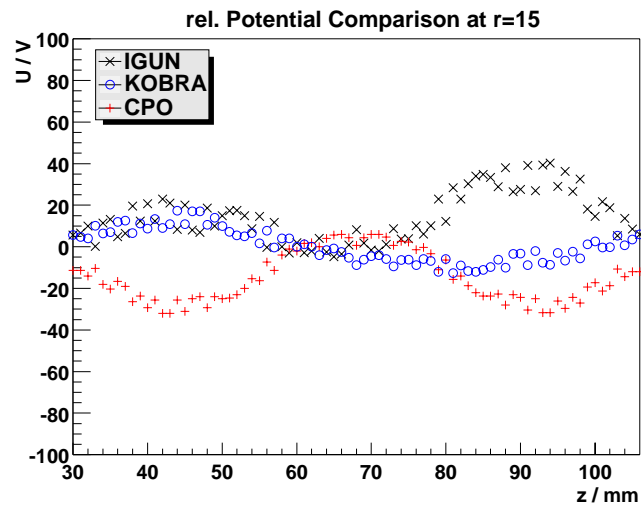


Figure 3: Difference of the potential calculated by the three codes from average potential. The upper plot corresponds to $r_{x,y} = \pm 15$ mm and the lower one to $r = 0$ mm.

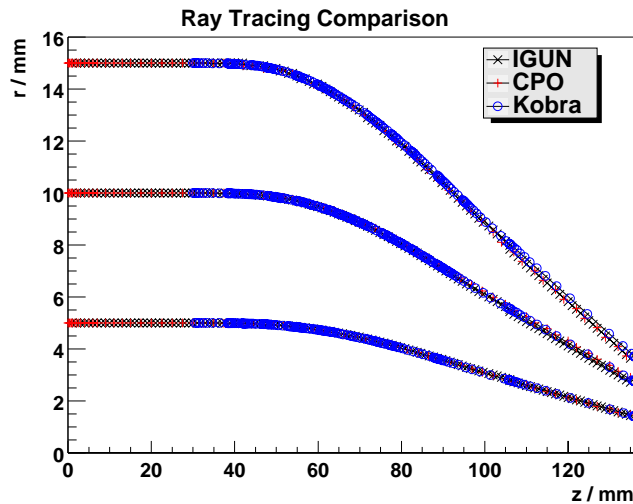


Figure 4: Tracking of test-rays through one cell of the GEL. All codes agree.

Table 2: Output beam parameters for a 240π mm mrad emittance beam through a three-cell GEL. The initial distribution used is based on the measured emittance at the entrance of the GEL. $\varepsilon_{i,f}$ are the initial and final emittances, I_{DA} is the current into a double aperture cup.

	KOBRA	IGUN	CPO	experiment
rays	15000	500	11000	
$\varepsilon_{4\text{rms},i}$ [π mm mrad]	240	233/241	242	242
$\varepsilon_{4\text{rms},f}$ [π mm mrad]	420	234/421	434	365
I_{DA} / mA	41	36.5	41	25
I_{DA} / mA (scaled ^c)	33.5	29.8	33.5	25

c) Taking into account losses at the grids.

square apertures of 5.9 mm spaced 44 mm apart, with the first aperture positioned 30 mm downstream of the GEL exit grid. In Table 2, the input and output parameters are summarized for all codes and compared to the experiment. For the 2D-code IGUN the input rays were transformed to polar coordinates (r, θ) and the result re-mapped to Cartesian coordinates. Since in IGUN all problems are radially symmetric, the apertures represent circles and hence the current was scaled by $\frac{4}{\pi}$ for comparison with a square aperture. IGUN uses only 500 rays which leads to different emittances in x and y . A similar behaviour was seen with CPO when only up to 1000 rays could be used.

5 Conclusion

Three codes for simulation of low-energy ion dynamics were compared to each other as well as to known solutions and experimental data. The codes reproduce an approximate analytical solution for space-charge calculations to within 2%. Differences of the potentials from the field solvers are in the order of 10^{-3} of the maximum voltage. Single rays traced through a test case coincide.

When simulating the low-energy line of the CERN LIS, the three codes exhibit good agreement. However, comparison with the experimental data shows an underestimation of the emittance by 20% and an overestimation of the transmitted current by 30%.

The simulations presented here do not include the following characteristics of the real

line: (i) variation of the beam parameters during the current pulse; (ii) more accurate representation of the GEL structure (including for example the grid wires); (iii) space-charge compensation. Furthermore, the average beam parameters include experimental errors and the effect of the measurement equipment on the beam itself. Further simulations can begin by taking these processes into account.

The characteristics of LIS (current, emittance, extraction geometries) change with different laser configurations and target materials. The good agreement between different codes and experiments shows that with these tools the estimation of source parameters within acceptable tolerances is possible, limiting tedious and costly experiments.

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