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SIMULATION OF THE EXTRACTION AND TRANSPORT OF A BEAM FROM THE SILHI SOURCE WITH THE WARP CODE*

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Abstract

In a low energy beam transfer (LEBT) line, space charge effects are dominant and make the motion of the particles strongly non-linear. So, the beam dynamics is directly dependent on the 6D distribution of the particles after the ion source extraction system. It is thus essential to simulate accurately the source extraction region and the space charge compensation after it to try to reach an agreement between the simulations and the measurements. Generally, the ion source extraction system is simulated with electrostatic codes (often using simple model for space charge) from which the 6D beam distribution is derived. Then, this distribution can be used as an initial condition to simulate the beam transport in the LEBT with a time dependent PIC code that takes into account space charge compensation. We propose here to simulate accurately the SILHI source extraction system with the Warp and AXCEL-INP codes. The SILHI ion source will be quickly presented and some simulations results will be given and discussed.

INTRODUCTION

One of the corner stones of an ion accelerator are often the emittance and the intensity of the beam. From that point of view, the ion source and the downstream low energy beam transfer (LEBT) are critical components because of the interaction of the beam with its own potential (space charge) and with the residual gas. These interactions are strongly non linear, coupled and very sensitive to the beam initial distribution, which makes critical the simulation and the design of the ion source extraction system. It is necessary to use auto-consistent codes to take into account the different interactions occurring in the vicinity of the ion source. We propose here to simulate the extraction of an Hydrogen beam from the SILHI source [1] with two codes: AXCEL-INP [2] and WARP [3]. We will compare the results and discuss the possible discrepancies between them.

AXCEL-INP is based on a so-called Vlasov-solver using a Finite Difference Method (FDM). That implies to solve the Poisson equation and determine the particle distribution function which influences the Poisson equation itself. The space charge map is created during the tracking of the particles. The self consistent particle distribution is found by an iterative process. AXCEL-INP works for axisymmetric and planar steady state problems. The limitations of AXCEL-INP are:

- The maximum number of particles.
- The space charge compensation (SCC) rate is constant and user-defined (arbitrary). It does not simulate the ionization of the residual gas but assumes that a given space-charge compensation rate takes place at a given potential.
- A limited control of the simulation initial conditions (plasma).

That is why we wanted to compare it with another code: WARP, which was successfully used for the simulation of the Venus source extraction system [4]. The WARP suite of simulation codes was initially developed in the pursuit of heavy-ion driven inertial confinement fusion and is well adapted to the simulation of intense ion beams. The WARP code combines the PIC (Particle In Cell) approach commonly used for plasma modeling with a description of the accelerator lattice of elements. With a PIC algorithm, the beam is simulated by quite small number of macro-particles which interact via their space-charge. The space-charge effects are included by a global solution of Poisson's equation, giving the electrostatic potential, at each time step. WARP is very modular with a Python interface and enables to include some physics packages like the ionization of the gas or Coulombian collisions.

SIMULATION MODEL

The used model for the beam extraction is the same as the one used for the simulation of VENUS source. The following assumptions are made.

- The plasma is at the thermal equilibrium.
- A so called plasma sheath [5, 6] forms between the plasma and the extraction electrode.
- There is a potential drop between the electrode and the plasma.
- Neither collision nor ionization takes places within the sheath.

The characteristic length of the plasma sheath is the Debye length λ_D given by:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_{e0} e^2}} \tag{1}$$

where ϵ_0 is the vacuum permittivity, e the electron charge and n_{e0} the electron density within the plasma. Typically, the Debye length is about a few tens of micrometers for ion source plasmas. That is why we can consider that the plasma is at the equilibrium at a few millimeters from the extraction electrode.

The heating of the plasma is not considered here. Within the plasma sheath, the electrons have a Maxwell-Boltzmann distribution n_e:

$$n_e \propto \exp\left(\frac{\phi - \phi_p}{kT_e}\right) \tag{2}$$

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where ϕ is the potential at the considered position, ϕ_p is the plasma potential, kT_e is the electron temperature (in eV) of the plasma. In WARP and AXCEL-INP, the code adds this electron distribution to the computed ion distribution when solving the Poisson equation.

According to Bohm criteria, the ion species j, of ionic temperature $T_{i,j}$;, of mass $m_{i,j}$ and of charge $q_{i,j}$ must enter the plasma sheath with a velocity greater than the acoustic speed $C_{s,j}$ defined by (for an isothermal plasma):

$$C_{s,j} = \sqrt{\frac{k\left(T_e + T_{i,j}\right)}{m_{i,j}}} \tag{3}$$

The plasma potential is then given by:

$$\phi_p = \phi_e - \frac{kT_e}{e} \log \frac{\sum\limits_{j=1}^{k} q_j n_{i,j} \sqrt{2\pi \frac{m_e}{m_{i,j}} \left(1 + \frac{T_{i,j}}{T_e}\right)}}{\sum\limits_{j=1}^{k} q_j n_{i,j}} \tag{4}$$

where ϕ_e is the potential of the extraction electrode and $n_{i,j}$ is the ion density in the plasma.

THE SILHI SOURCE

The SILHI source is a 2.45 GHz ECR source which was developed in Saclay more than 15 years ago in order to meet the beam requirements of high power light ions accelerators. It produces, with a high reliability, a 95 keV–130 mA total beam with a proton fraction higher than 80% [1]. H^+, H_2^+ and H_3^+ ion species are extracted from the source; their relative proportion was experimentally determined by measurement with a Wien filter. In the simulations, we have used as input the initial ion density in the plasma, taking into account the ion species proportion. Indeed, it is not possible with AXCEL-INP, contrary to WARP, to adjust the initial conditions to reach the expected extracted current. The electrons and ions average temperature in the source plasma are also inputs of the simulations: we considered, respectively, 5 and 0.23 eV. The initial parameters for the plasma in SILHI are given in Table 1.

Table 1: Initial Parameters for the Ions

		H^+	H_2^+	H_3^+
Electron temperature	eV		5	
Ion temperature	eV		0.23	
Current density	A/m^2	1697	195	58.5
Acoustic speed	m/s	22375	15822	12918
Plasma potential	V		14.3	
Extracted current	mA	103	12	4

The SILHI source is made of 5 electrodes (a plasma electrode, a puller electrode, a grounded electrode, an electron repeller and finally, a second grounded electrode) at the following potentials: 95 kV, 55 kV, 0 kV, −2.8 kV and 0 kV. The potential map of the source extraction system, without the beam, is given in Figure 1.

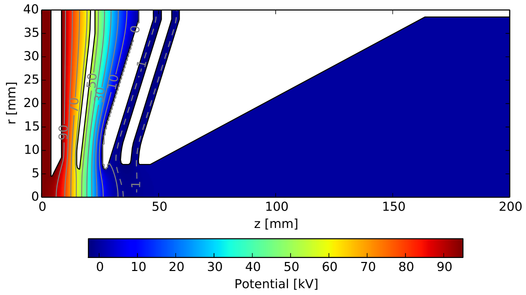


Figure 1: Potential map along the source (without the ion beam). The electrodes are drawn in white. The contour lines (in Gray) are given from 0 kV to 90 kV by 10 kV.

SIMULATION RESULTS

In both codes, we have used the same grid with a radial step of 0.05 mm and a longitudinal step of 0.5 mm. In AXCEL-INP, the number of particles is directly linked to the number of radial subdivisions, which explains the choice of radial steps. The time step is 25 ps for the particles to run a longitudinal step for several time steps. In both codes, the steady state is assumed by relaxation methods on the potential. At the step i, an initial set of ions is tracked in the potential map computed at the step $i - 1$. The trajectories of the ions are then projected on the grid to obtain the distribution of the ions. The potential map for this new ion distribution is computed with the Poisson solver. The potential map at the step i is a weighted mean (depending on the relaxation factor) between this computed distribution and the potential map at the step $i - 1$.

In the AXCEL-INP code, we assumed that the space-charge compensation takes place where the potential is less than 100 V (after the electron repelling electrode), which corresponds to the position $z = 32$ mm in the potential map. The space-charge compensation rate is assumed to be 96.5%. The profile of the simulated beam is given in Figure 2. The profiles obtained with the two codes are in reasonable agreement. In order to have a better comparison between the two codes, we have plotted the particle phase space distribution at two locations: z =10 mm after the extraction electrode and z =200 mm at the source exit (see Figure 3). The beam is more distorted in the WARP case. We assume that this difference is due to numerical issues. Within the plasma chamber, some numerical approximation in the distribution implies numerical errors on the potential map (of a few Volts), which perturbs itself the beam distribution. Nevertheless, the results are quite comparable in both cases.

Another comparison criteria is the energy distribution at the end of the source extraction system. We have plotted the energy of particles versus their radius at z =200 mm, corresponding to the end of our simulation domain (see Figure 4). As a Neumann boundary condition has been used, the potential at z =200 mm and thus the particles energy should depend on their radius. The expected energy of the

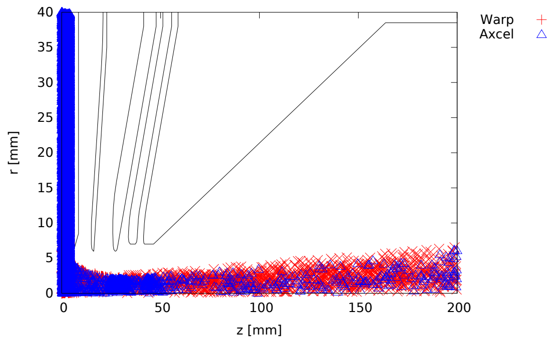
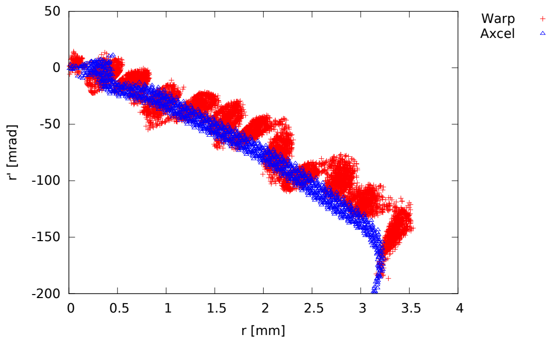
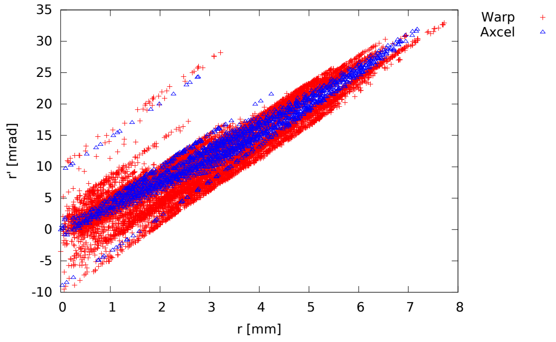


Figure 2: Beam profile (in red cross with WARP and in blue triangle with AXCEL-INP) along the source extraction for the parameters given in Table 1. The electrodes are drawn in black lines.



(a) z = 10 mm



(b) z = 200 mm

Figure 3: Phase space at two locations z =10 mm and z =200 mm (in red cross with WARP and in blue triangle with AXCEL-INP) for the parameters given in Table 1.

beam at the exit of the domain is the source voltage more the plasma potential, i.e. 95.014 kV. From this point of view, WARP has a better agreement with the expected final energy. Moreover, the potential difference between the core and the external part of a 100 mA 95 keV beam is a few hundreds of Volts. With a SCC of 96.5%, we expect an potential difference within the beam of a few tens of Volts, which is observed with WARP. The final beam energy seems to be underestimated with AXCEL-INP.

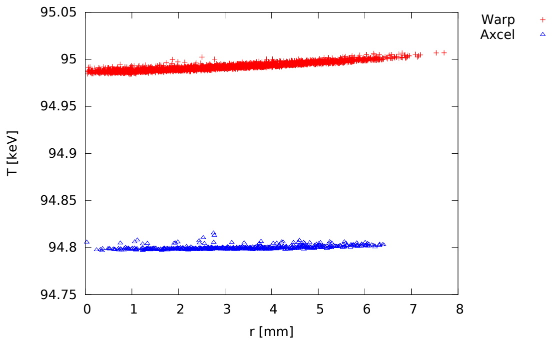


Figure 4: Kinetic energy at the location z =200 mm (in red cross with WARP and in blue triangle with AXCEL-INP) for the parameters given in Table 1.

CONCLUSION

A benchmark between the codes AXCEL-INP and WARP has been done for the SILHI source extraction system. The results have shown a quite good agreement between the two codes. The beam presents more perturbations in the phase space with WARP, which implies a higher emittance. Nevertheless, the mean energy and the energy spread seem to be more realistic with WARP than with AXCEL-INP. The comparison with measurements is difficult because they can only be done in the LEBT, an area in which space charge effects (and SCC), are still dominant. Nevertheless, some emittance measurements as close as possible to the ion source are planned on the FAIR proton linac injector (which will be equipped with a SILHI-like source).

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