HALODYN: A 3D POISSON-VLASOV CODE TO SIMULATE THE SPACE CHARGE EFFECTS IN THE HIGH INTENSITY TRASCO LINAC

A. Franchi*, M. Comunian, A. Pisent, INFN Laboratori Nazionali di Legnaro, ITALY
G. Turchetti, S. Rambaldi, A. Bazzani, Physics Dep., Univ. of Bologna and INFN-Bologna, ITALY

Abstract

We present a 3D particle-in-cell code, named HALODYN, that simulates the dynamics space charge distribution through a linac. The initial particle distribution is generated by a Monte Carlo method using the solution of envelope equations. The particles are tracked by using a second order sympletic integrator (micromaps) that takes into account the space charge effects at each step. The space charge force is computed by a full 3D Poisson Solver where the charge density is distributed on on the uniform grid by assuming cloud macro-particles. Generic Dirichelet boundary conditions can be imposed. We present simulations of the ISCL (Independent Superconducting Cavity Linac) of the TRASCO and SPES project.

1 INTRODUCTION

New proposed accelerators with application to nuclear waste transmutation, subcritical nuclear reactors, exotic beam facilities, neutrino factories, neutron spallation sources or inertial fusion require high intensity linacs. In the low energy section of such accelerators beams of tens of mA are strongly subjected to the Columbian repulsion. In order to prevent unacceptably high level or radioactivity these machines must operate with low level of beam losses ($0.1 - 1$ nA/m) and therefore the halo formation around the beam core has to be prevented. The full Liouville problem associated with a charge particle distribution cannot be faced by the actual computers and the most used approach to simulate space charge effects is the Poisson-Vlasov model where the effects of collisions are neglected. The numerical simulations track a particle distribution along the magnetic lattice and compute the self-consistent electric field on a uniform grid by solving the Poisson equation. In the proton case the dynamics should present an Hamiltonian character but the fluctuations of the number of particle in each grid cell and the discretization effect due to the distribution of the space charge in a uniform grid introduce non-Hamiltonian perturbations to the dynamics, whose effect on the nonlinear properties of the true dynamics has not been understood. A common statement is that the numerical errors can be controlled by using enough resolution for the grid, (for example 128^3) and a high number of macro-particles (of the order of $10^7 \sim 10^8$). Therefore parallelized codes are necessary. The HALODYN code has be built to study the instabilities and the halo formation in a high intensity linac in presence of mismatch effects. The program does not assume any particular symmetry for the charge distribution. A parallelized version of the code is available.

The code has been developed within the research program TRASCO [1].

2 THE CODE

HALODYN is a PIC code written in GNU FORTRAN 77. The parallelized version for multiprocessor machines or clusters, is written by using standard message passing interface (MPI) libraries. HALODYN tracks particles through a linac using s as independent variable and the Cartesian coordinates relative to the synchronous particle. The transport elements implemented in the code are drift, quadrupole, solenoid and RF gap. The last one is modeled by using the thin gap approximation and the off-axis fields are expressed in term of modified Bessel functions (assuming cylindric symmetry). The quadrupoles are supposed to be hard-edged.

The evolution scheme implemented is a second order symplectic scheme, treating the space charge force as an impulsive force [2]. The user can decide how many micromaps (and consequently space charge kicks) apply per beam-line element.

The Poisson solver is based on a 3D FFT. To reduce the CPU time, the user can choose a less precise but faster 2D FFT plus an inversion of a three-diagonal matrix. Generic Dirichelet boundary conditions can be imposed with this algorithm: the user can choose the grid box (faster) or a generic domain (slower, twice CPU time in solving the Poisson equation) as boundaries. In the current version only round pipe is available as optional geometry.

HALODYN can generate four distribution types: KV-Neuffer, Uniform, Waterbag or Gaussian. The code reads an input file compatible with PARMILA. We refer to the documentation [3] for more details about the code.

3 STATISTICAL CONSIDERATIONS AND PARALLELIZATION

The numerical study of the halo dynamics requires the knowledge of the space charge electric field with high spatial resolution. Nevertheless, artificial emittance growth appears in computer simulations due to the numerical errors. Numerical studies on the error dependence on the mesh resolution and the number of particles have pointed out the existence of an optimal ratio between these numbers [4][5].

* andrea.franchi@lnl.infn.it

Indeed a low grid resolution introduces discretization errors in solving the Poisson equation, while a low number of macro-particles introduces fluctuations in the discretization of charge density on the grid as showed in Fig. 1.

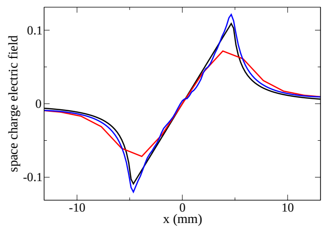

Figure 1: Space charge electric field (m^{-2}) for a transverse KV distribution: the black line represents the analytic solution, the red and the blue are the computed field by using a 16^3 and 128^3 grid with 10^5 particles.

The optimal choice corresponds to a particles number of order 10^2 inside each grid cell internal to the beam core. The increasing of the spatial resolution implies a contraction of the grid cells and more macro-particles are required to fill them. For instance a grid of 128^3 requires at least $10^7 \sim 10^8$ macro-particles [6]. If the grid covers a physical space of some cm^3, the mesh scale is of the same order than the Debye radius ($\simeq 10^{-4}\ m$) associated to the distribution and the corresponding number of particles is of the order of the particle number in a bunch. To consider lower scales will be not physical since the fluctuation due to the Coulomb collisions cannot be neglected any more.

However these numbers requires the parallelization of the code. The Poisson-Vlasov approach is easy to parallelize and guarantees a good scalability, even if the Poisson solver itself is not parallelized. If we neglect the output management and the Poisson solver (in a 128^3 grid points simulation, it requires $7 \sim 9$ seconds on a 500 MHz *Pentium III*), the CPU time of a simulation is about inversely proportional to the number of processors. The more are the particles, the more this scaling is true.

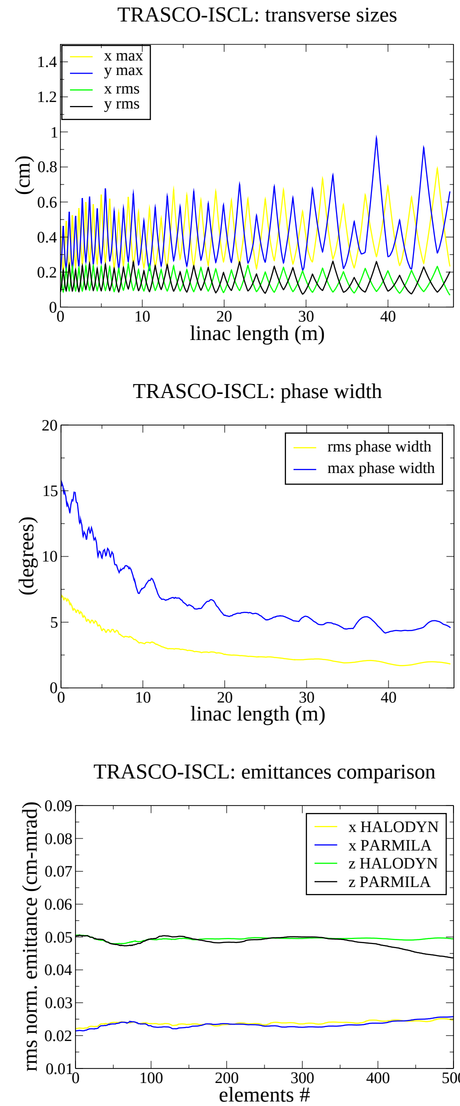

Figure 2: TRASCO-ISCL simulation.

4 SIMULATIONS

The code HALODYN is being applied for precision studies and halo formation simulations of the 100 MeV superconducting proton linac under development at LNL. The initial energy (5 MeV) and the operating frequency (352 MHz) are fixed by the TRASCO RFQ that is under construction [7].

We run the first tests of the code with two different linac design, one optimized as the first part of a 30 mA ADS plant (TRASCO design [8]), the second with a lower current (5 mA) as required for exotic ion beam production (SPES project [9]). This second linac has also been proposed as intermediate part of the driver of EURISOL [10], and can have different applications like in ADS demonstrators, medical isotope production.

The TRASCO ISCL is composed by 220 reentrant cavities, with the transverse focusing guaranteed by 51 superconducting quadrupoles, following the FODO scheme with a period increasing with β. The main features of this design is the use of a single cavity kind, with large bore aperture and fed by solid state amplifiers. This can guarantee high linac reliability and availability, since the beam is transmitted through the linac even if one cavity is off. This linac has been designed with PARMILA and we show here some precision tests done with HALODYN. The comparison is particularly meaningful since the two transverse phase advances are equal along the linac, so that the cylindrical symmetry of PARMILA space charge routine is a good approximation, while space charge has a relevant impact on the dynamics (the tune depression is in the first cells about 0.7). In fig. 2-A we show a typical simulation result (rms and maximum beam envelopes for $2 \cdot 10^7$ particles and 64^3 mesh points). The small mismatch of the rms envelopes (introduced on purpose by the incorrect settings of some initial quadrupoles) is amplified in the maximum envelope behavior, that remains anyway well within the cavity bore. The phase behavior is good (fig. 2-B). The rms emittances (2-C) calculated with the two codes are compared. The agreement is good except in the last elements where the longitudinal emittance decrease of PARMILA is not confirmed by HALODYN (perhaps due to the loss of cylindrical symmetry).

We have also applied the new code to SPES ISCL [11], that is a linac based on four gap and two gap cavities (12 ladder and 90 HWR). The basic focusing structure is a FODO, with a constant period length in each cryostat. The period length is longer in the cold transitions and increases changing the cryostat kind. Beam envelopes and beam rms dimensions corresponding to 5 mA current are plotted in fig. 3. The residual mismatch due to the transitions can be seen, but the maximum beam dimensions are well below the bore radius, the emittance increase is negligible and the bore to rms radius is well above 7 times all along the linac. As a first test of tolerance to alignment errors we show the same plots for an initial envelope quadrupole mismatch of $\sqrt{2}$. Also in this case the transmission is 100%, the emittances are conserved and there is no evidence of halo formation.

5 CONCLUSIONS

A new full 3D PIC code for the halo dynamics investigation has been written. To simulate tens of millions macroparticles the code has been parallelized by using standard MPI libraries. The TRASCO-ISCL has been simulated and comparison with PARMILA has shown a good agreement. Further updates of the code will regard the thick gap, new optional boundary conditions, intra-beam scattering and the description of all typical transport elements.

6 REFERENCES

[1] http://trasco.lnl.infn.it .

[2] G. Turchetti, S. Rambaldi et al.,"3D solution of the Poisson-Vlasov equation for a line of FODO cells", submitted to *European Journ. of Physics*.

[3] A. Franchi, "HALODYN Documentation" , INFN-LNL Internal Report, 2002.

[4] J. Struckmeier, "Concept of entropy in the realm of charged particle beams", *Phys. Rev. E* **54**, 830-837 (1996).

[5] N. Pichoff et al., "Simulation results with an alternate 3D space sharge routine, PICNIC", Proc. of LINAC98, p.141, 1998.

[6] R. Ryne, "Beam dynamics simulations using a parallel version of PARMILA", Proc. of LINAC96 (1996).

[7] A. Pisent et al "TRASCO RFQ" proceedings of of Linac 2000 Conference, Monterey, California.

[8] M. Comunian, A. Facco, A. Pisent "A 100 MeV Superconducting Proton Linac: Beam Dynamics Issues." Linac 1998 Proceedings pp. 64-66.

[9] "SPES Technical Design for an Advanced Exotic Ion Beam Facility at LNL" LNL-INFN(REP) 181/02 (2002).

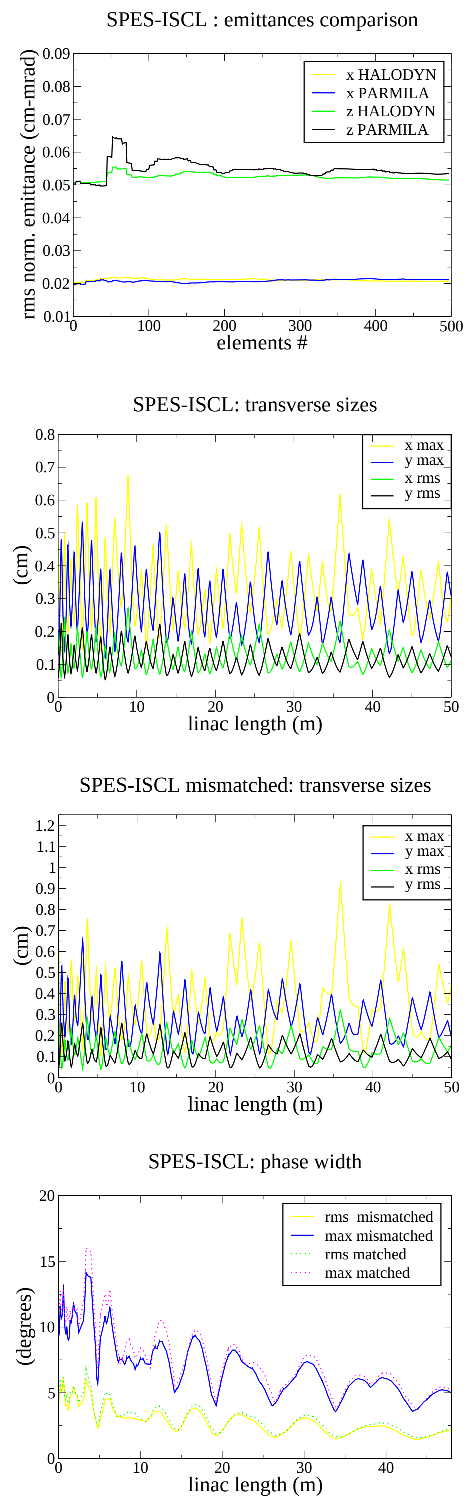

Figure 3: SPES-ISCL simulation.

[10] J-L. Biarrotte et al. "High intensity driver accelerators for EURISOL", EPAC 2002, Paris 2002

[11] A. Pisent, G. Bisoffi, M. Comunian, A. Facco, E. Fagotti "Study of a Superconducting 100 MeV Linear Accelerator for Exotic Beam Production", EPAC 2002, Paris 2002