SIMULATION RESULTS WITH AN ALTERNATE 3D SPACE CHARGE ROUTINE, PICNIC

N. Pichoff, J.M. Lagniel, S. Nath*
CEA-Saclay/DSM/DAPNIA/SEA,
* On sabbatical from LANL, Los Alamos, NM, USA.

Abstract

One of the major problems in the beam dynamics calculation dealing with high current linacs is the treatment of space charge effects. The widely used SCHEFF routine - originated and developed at Los Alamos, is often critiqued as being simplistic because of its inherent assumption of transverse symmetry. Here we report preliminary work on an alternate fully 3D space-charge routine for a bunched beam. It is a particle-in-cell approach based on numerical-calculation of the interaction between cubes (PICNIC). The principle underlying the method and the comparative results of simulation with SCHEFF and PICNIC are reported.

1 INTRODUCTION

Increase in the interest for high-current accelerators with very low loss-rate demands a high degree of confidence to the space-charge simulation tools. PARMILA is one of the more well known and widely used tools in the design of such accelerators [1]. Its space-charge routine, SCHEFF, is fast, but is not a fully 3D code. It assumes cylindrical symmetry around the longitudinal axis. We have written a new 3D space-charge routine, PICNIC, based on the same principle as SCHEFF, but making no assumption on the bunch shape. We made simulations with PARMILA, both with SCHEFF and PICNIC. Studies were done for the front section of the APT linac [2] (98 mA RFQ-output beam with energy form 6.7 MeV to 100 MeV) as well as in continuously linear focusing 3D channel (50 m, $k_{x0}=k_{y0}=k_{z0}=1\ m^{-1}$, with 10 space charge calculations per meter).

2 LIMITATION OF SCHEFF

In the SCHEFF routine the space is mapped with a 2D (r, z) mesh, r and z being respectively the radial and the longitudinal position in the beam. The number of particle in each elementary volume (a ring such that $r \in [r,r+\delta r]$ and $z \in [z,z+\delta z]$) is calculated, and the field induced by each ring, considered as uniformly charged, is computed at the mesh node. The field at each particle position is interpolated from that of the neighbouring nodes. Thus, SCHEFF is very well suited for transverse round-beam, but becomes increasingly inaccurate as when the transverse aspect ratio $\alpha = Y/X$, **X** and **Y** being respectively the x and y beam rms-sizes, differs significantly from 1, or when the beam has no cylindrical symmetry (e.g. in the RFQ output beam due to image charge forces).

In PICNIC, the space is mapped with a 3D (x, y, z) mesh. The number of particles in each elementary volume (cube) with $x \in [x,x+\delta x]$, $y \in [y,y+\delta y]$ and $z \in [z,z+\delta z]$ is calculated, and the field induced by each cube (considered as uniformly charged) is computed at the mesh node. The field at each particle position is then interpolated from those of the neighbouring nodes. No beam symmetry is assumed.

In figure 1 we represent the results of emittance-growth calculation of a non cylindrical ($X=Z=Y/\alpha$) beam (100mA, 6.7 MeV) in a continuously focusing channel ($k_{x0} = 1\ m^{-1}$). For both SCHEFF and PICNIC. The initial beam distribution is of type 8 in PARMILA (uniform); 9,000 particles are used. It clearly shows the problems with SCHEFF calculations for larger values of α. Simulations have also been done under the same conditions but with a transversally round beam ($X=Y=Z/\alpha$). In those cases PICNIC and SCHEFF give nearly the same results, i.e. those of fig.1.b.

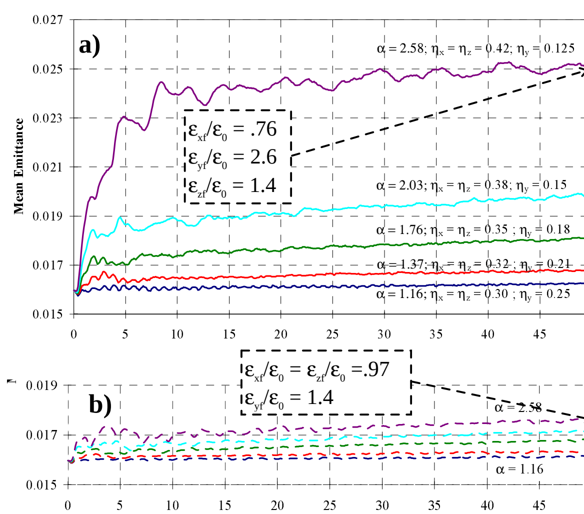

Figure 1: Emittance growth of non cylindrical beam in a continuously focusing channel. a) SCHEFF results, b) PICNIC results. We have Z = X.

The emittance growth observed at the beginning with PICNIC comes from the initial beam relaxation towards a space-charge equilibrium; the nonzero slope of the curves is due to a poor statistics for this severely depressed-tune beam (see **§ 3.b**).

3 PICNIC PROPERTIES

a) Choice of the number of cells

With PICNIC, as with SCHEFF, one must choose number of cells (**N_c** is the half cell number) in each direction. The PICNIC mesh extends to ±3.5·X, ±3.5·Y and ±3.5·Z. Electric field at positions outside the mesh is calculated as that of a gaussian beam with the same rms-sizes. For example, a value of N_c=7 means step-size=.5X.

Figure 2 shows the transverse emittance growth versus N_c for 2 different particle number **N_p** (10K and 100K) for the APT linac at 100 MeV. It exhibits the existence of an optimised mesh number dependent on the number of particles used in the simulation.

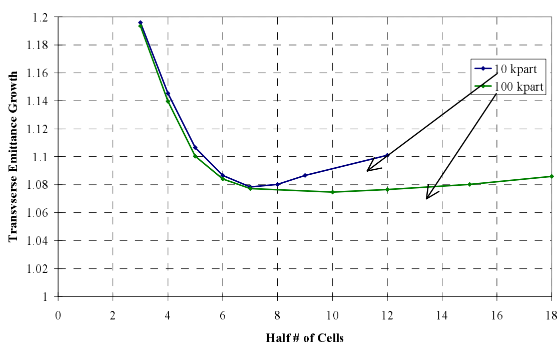

Figure 2: Emittance growth dependence on the number of cells and the number of particles.

When N_c is small, we have a lack of resolution inducing an emittance growth. When N_c large, the number of particles per cell is small inducing statistical noise and emittance growth, this is less sensitive with a higher number of particles. There is a optimum value for N_c, depending on N_p, which gives the best results. Choosing N_c=8 seems to be a good choice; it will induced an error lower than 1 %, whatever the particle number. However, results presented in **§4** in a continuous channel favour larger Nc.

b) Sensitivity to the statistics

When the beam is highly tune depressed, and the transverse and longitudinal temperatures are not the same (non-equipartionned), the rate of emittance growth per meter dε/dz in the direction with lower temperature depends on the number of particles. However, theoretically once at equilibrium (after some betatron periods), the beam should not undergo any emittance growth. This dependence on statistics is nearly the same with SCHEFF and PICNIC, it has been illustrated in fig. 3.

This results from an spurious exchange of energy between the "hotter" transverse direction to the "colder" longitudinal direction. This phenomenon has been demonstrated in [3]. A space-charge routine should therefore be validated in the context of "spurious collision" in order to avoid erroneous conclusion in term of equipartitioning. In all cases, however, it is better to work with large N_p. Even in such case, a very small emittance growth is observed. This is explained in **§4.c**.

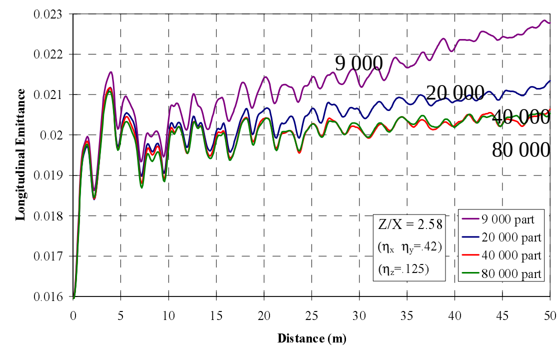

Figure 3 : Longitudinal Emittance growth of a highly tune-depressed beam, for different number of particles (PICNIC results) with X = Y = Z/2.58.

c) Computation time

Computation time for PICNIC and SCHEFF has been explored in terms of particles and cell numbers. They are represented in fig.4.

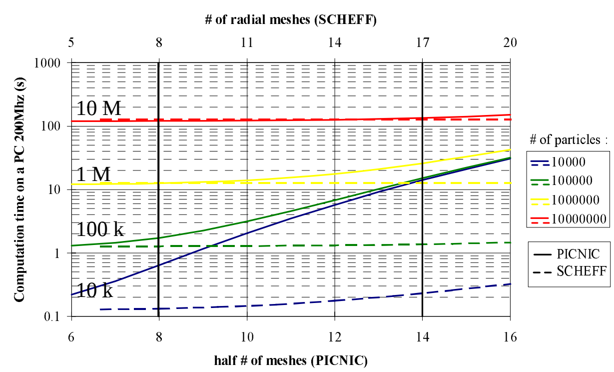

Figure 4: Space-charge computation time with a PC (fortran 77) for SCHEFF and PICNIC.

In a PIC code, one part of the computation-time depends linearly on N_p. It represents the time used to count the particles in the mesh cells (~10%), and to compute the field at each particle position (~90 %). This linear dependence can be seen when N_c tends to 0.

The other part of the computation-time depends on the method used to calculate the field at the mesh nodes. It depends only on N_c. For SCHEFF it is nearly proportional to N_c^4 and for PICNIC to N_c^6 ! New developments in PICNIC, not reported here, should reduce this part by a factor 5 to 10.

PICNIC computation-time is very reasonable with Nc=8. It is nearly the same as that of SCHEFF (with Nc=20) with more than 100,000 particles. Use of fully 3D routines thus seems to be feasible even with a small computer (PC) !

4 LIMITATIONS

a) Highly tune-depressed beam emittance growth

The transport of a highly tune-depressed beam (η down to 0.1) has been studied in a continuous focusing channel with phase advance per meter without space-charge $k_0 = 1m^{-1}$. The initial beam is a uniform sphere (type 8), filled with 9,000 particles.

Simulations with PICNIC (fig. 5) and SCHEFF have shown a linear emittance growth, important for η < 0.3.

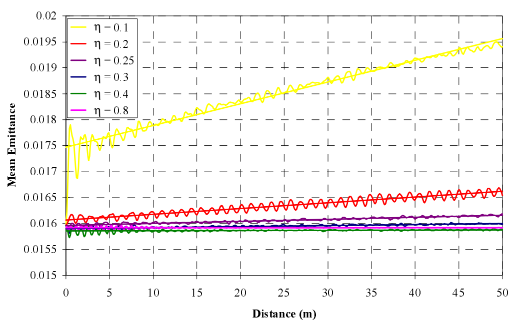

Figure 5 : Emittance growth observed with PICNIC for different tune depressions.

The growth rate (fig. 6) increases with the severity of tune-depression, and varies with the number of mesh: a large N_c seems to be better for η=0.2 (optimum for N_c=14).

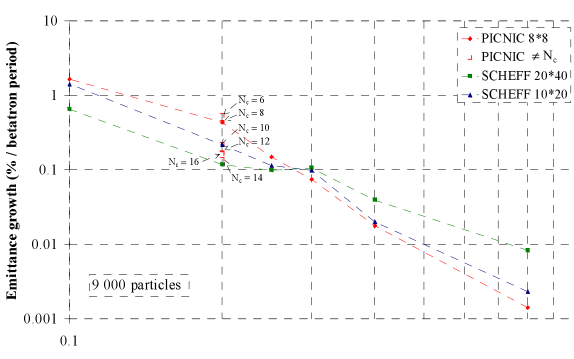

Figure 6 : Emittance growth rate in % per betatron period with depressed tune. Both PICNIC and SCHEFF results are shown

The origin of this observed emittance growth is under study. The growth-slope however quickly decreases when the beam density distribution is smoothed out. For example, the slope decreases by a factor ~3.5 when each cell is assigned the mean value of the neighbouring 27 ($=3^3$) cells with N_p=9,000 and N_c=8. It is independent on the initial beam distribution (as type 22 (~Water-Bag)) and the number of particles (up to 80,000).

b) Field calculation accuracy with small N_c

Figure 7 shows the space-charge field applied on the particles of a spherical Gaussian beam. Calculations were done with PICNIC and SCHEFF for 2 different N_c values and results are compared with the theoretical curve. With a too small value of N_c, the field is calculated as if the beam was less dense at the centre. This effect seems to be a common feature for all PIC routines; the same has been observed with the routine 3DPIC [4]. However, this seems to have a negligible effect on the emittance growth, but might change the space-charge equilibrium of the beam somewhat.

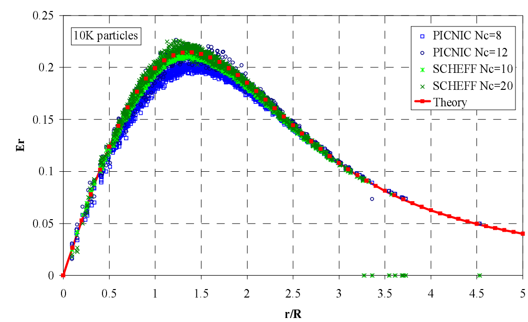

Figure 7 : Computed space-charge field on particles of a spherical Gaussian beam, compared with analytic prediction.

5 CONCLUSION

3D space-charge calculations appears to be realistic on a personal computer and PICNIC is a good candidate for this. It benchmarks very well with SCHEFF for test cases. It should be emphasised tha each space-charge routine needs to be carefully studied before application for appropriate parameters (i.e. N_c, N_p, number of space charge calculation per betatron period ...).

Some of the parameters could be used to quantify and compare the applicability of the routines, e.g. the coupling between directions (**§3.b**), the emittance growth per betatron period (**§4.a**), the computation speed (**§3.c**)... All these parameters depend on N_p and N_c (or parameters such as the screen distance in a PPI routine).

6 REFERENCES

[1] G.P. Boiscourt, «Linear Accelerator and Beam Optics Codes», Proc. of AIP Conf., 177 (1988).

[2] J. D. Schneider, «APT Accelerator Technologie», Proc. of LINAC96 (1996).

[3] J. Struckmeier, «Concept of entropy in the realm of charged particle beams», *Phys. Rev. E* **54** (1), 830-837 (1996).

[4] R. D. Ryne and S. Habib, «Beam dynamics calculations and particle tracking using massively parallel processors», *Part. Acc.*, **Vol. 55**, 365-374 (1996).