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COMPARISON OF LINAC SIMULATION CODES*

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Abstract

The Spallation Neutron Source (SNS) project is a collaborative effort between Brookhaven, Argonne, Jefferson, Lawrence Berkeley, Los Alamos and Oak Ridge National Laboratories. Los Alamos is responsible for the design of the linac for this accelerator complex. The code PARMILA, developed at Los Alamos is widely used for proton linac design and beam dynamics studies. The most updated version includes superconducting structures among others. In recent years, some other codes have also been developed which primarily focuses on the studies of the beam dynamics. In this paper, we compare the simulation results and discuss physics aspects of the different linac design and beam dynamics simulation codes.

1 INTRODUCTION

An overview paper [1], describes the baseline design and anticipated beam performance of the SNS linac. The beam from the RFQ at 2.5 MeV goes through a MEBT-chopper section followed by a DTL. The first of the 6 tanks in the DTL has 60 cells delivering beam at 7.5 MeV.

The code PARMILA [2] used in SNS to design linac and perform beam dynamics simulation was originally written only for DTLs. Over the last several years, it has been extensively modified [3] to include coupled cavity and superconducting structures. Over the same period, several other linac codes have been developed independently. The accelerator group at SACLAY has written a code PARTRAN [4]. Two other codes, LINAC and IMPACT [5,6] now can also do linac beam-dynamics simulations. The electron linac code, PARMELA [7], has now also been adapted to simulate ion beams.

SCHEFF [8] had been the code of choice for linac studies for the past decades. A full 3D space-charge calculation algorithm [9] needing modest computational power has been written only recently. Both the codes PARMELA and IMPACT use built-in space-charge algorithms with full 3D capabilities.

As part of our effort to compare the beam simulation results from all different codes for the SNS linac, we choose to start with the first tank of the DTL (β=0.07-0.125). This is the section where the space charge forces and the gap transformations should have the most dominant effect. Also, by limiting the studies to this relatively short section, we were able to use computer-time intensive PARMELA code.

2 CODES

Details of the individual codes can be found in the references cited above. Below, we note the key differences and the relevant data used for simulations.

PARMELA is the only code that uses t as the independent variable; the rest use z to transport the beam particles through the linac described as a sequence of elements. IMPACT is specifically written for "parallel mode" computation of linac beam dynamics simulation. It can handle very large particle arrays e.g., 10^8 particles in a bunch.

PARMILA, PARTRAN and LINAC all use about the same gap impulses applied at the electrical center of the DTL cell; off axis fields are derived using Bessel function expansions. PARMELA integrates the particles through composite E_r, E_z, and H_θ field-maps (10x60 [r,z] grid for half-cell) obtained from SUPERFISH calculation. The integration step-size used by PARMELA in these simulations was 5 degrees, corresponding to 72 steps through a DTL cell. IMPACT integrates through the cell using a linear transfer map calculated from the vector potential (A_x, A_y, and A_z) truncated at the quadratic term of the radial multipole expansion.

The space-charge impulses in all of these codes use the PIC method. LINAC gives space-charge impulses at the center of every drift, the center of each quad. Since calculation at each cell involves a quad, drift to the gap, gap transformation, and a drift to the next quad, it applies three space charge kicks per cell. PARTRAN can use any number; one per cell was chosen here. In the DTL, PARMILA gives the space charge kick at the center of each cell. In PARMELA, space-charge impulses were given at every sixth integration step i.e., at every 30 degrees, about 12 times per cell. IMPACT can impart an arbitrary number of space-charge kicks per beamline element. Ten space-charge kicks were used for each cell in this study. In between the kicks, fine-scale integration is used to compute the transfer map for the external fields.

All the codes use hard-edged quads. However, LINAC has the options to take into account the effects of the fringe-fields by symplectic transformations at both ends of the quad and to conserve total momentum. These options were used in the simulations with LINAC. None of the other codes included fringe-field effects, and only PARMELA conserved total momenta in the quad magnetic fields.

3 SIMULATION RESULTS

A distribution of one million macro-particles at 2.5 MeV from the SNS 402.5 MHz RFQ was transported (using PARMELA with 3D space charge) to a point 19.45 cm

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+ Presently at Lawrence Berkeley National Laboratory.

upstream of the DTL. All the codes started with this same distribution and transported the beam through the first tank of the DTL (60 cells, 10 transverse focusing periods of $6\beta\lambda$ length) and to the center of the drift space between tank 1 and 2. All used 3D space charge calculation except PARMILA that used SCHEFF.

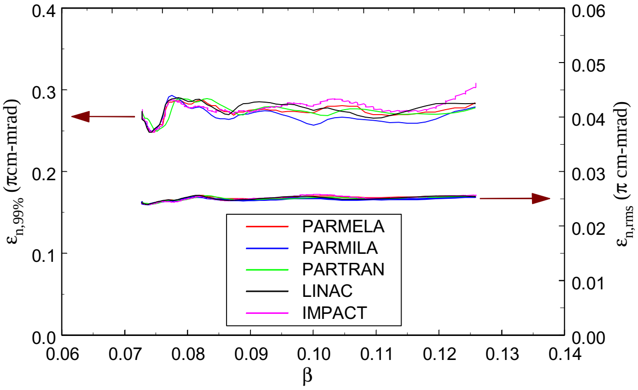

Figure 1. Transverse RMS and 99% emittance profiles through tank 1 of the DTL.

Figure 1 shows the transverse rms and 99% emittance profiles as a function of β along the first tank. RMS profiles are virtually indistinguishable from each other. The 99% emittance profiles however show some differences all being confined to a spread of ~7 % $\varepsilon_{t,99\%}$.

The RFQ beam when transported through the MEBT at the input to the DTL has already developed visible tails in the transverse and longitudinal phase spaces. This is shown in figure 2. Figure 2 also shows the x-x′ and w-φ phase spaces at the output (7.5 MeV) simulated by the five different codes. These plots provide a qualitative comparison of the output particle distributions. In the x-x′ space, PARMILA, LINAC and IMPACT predict most pronounced tails. However, in the longitudinal phase space, IMPACT predicts less halo formation while all the others show very similar pattern.

To put the results on a quantitative footing, we plot the radial distribution of the particles at the output as predicted by the different codes. This is shown in figure 3. Up to ~2.5σ, which essentially represents the core of the beam, all the codes predict virtually identical distributions. The largest divergence occurs around the edges i.e. halo region of the bunch. PARMELA and PARTRAN both predict maximum beam extent to ~6.1σ. The largest value is predicted by LINAC, which puts the number at ~6.9σ. This results in a total difference of ~12% in the maximum radius among all the codes.

To investigate into the effect of space charge alone on the beam behavior, we compare the results from LINAC code with 2D SCHEFF and 3D PICNIC. Transverse (x-x′) and longitudinal (w-φ) phase space plots at the output using the two codes are shown in figure 4. Qualitatively, no distinguishing features are seen between the results with 2D and 3D algorithms. In both cases, halos extend to about ± 1.0 cm in the (x-x’) space. The shape and the size of the core also do not exhibit any visual difference. In the longitudinal space, both indicate formation of similar tails.

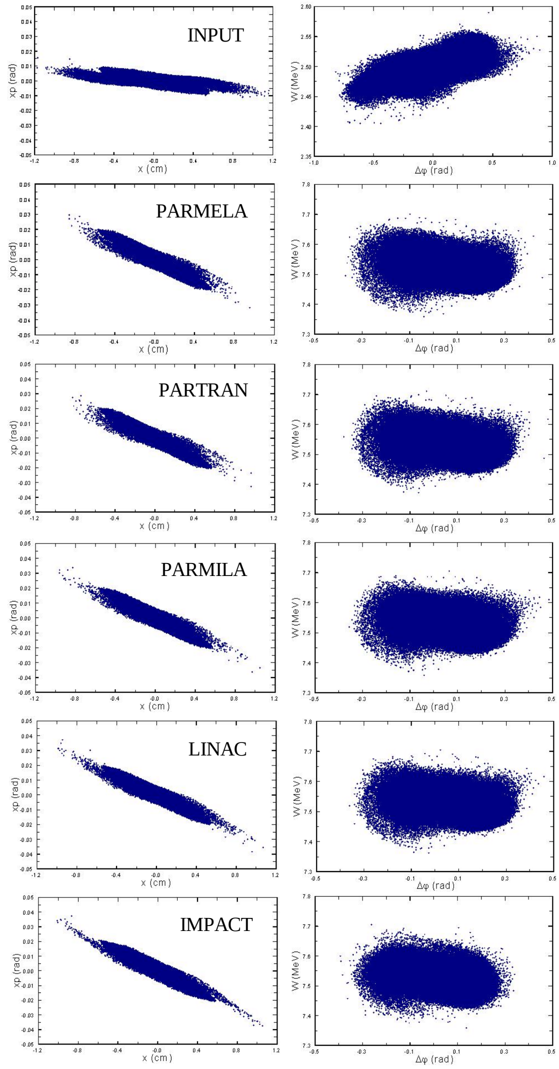

Figure 2. Transverse (x-x’) and longitudinal (w-φ) phase space plots at the input and output from different codes.

For a quantitative comparison, we show the output radial distribution of the particles in figure 5. The core of the beam (up to ~ 2.5σ) shows no difference in size or shape. The radial density appears to be marginally higher beyond the core of the beam with 3D PICNIC code. The difference around the extreme outer edges of the beam is at the level of ~ 10 nA. In this figure, we also plot the distribution with the fringe field and total momentum conservation option turned off. This seems to make no difference in the radial density distrbution of the beam.

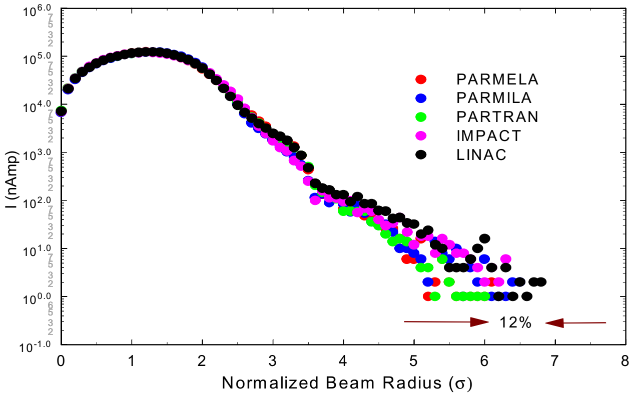

Figure 3. Simulated radial distribution at the output with different codes.

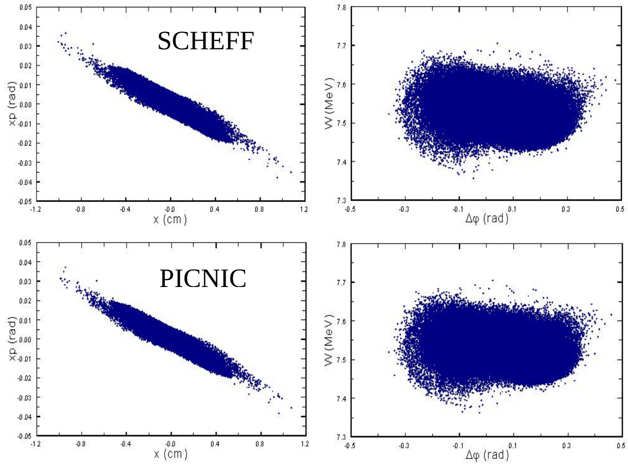

Figure 4. Transverse (x-x') and longitudinal (w-φ) phase space plots at the output.

4 CONCLUSION

The studies presented here show remarkable agreement between the predictions from different codes. It leads to the conclusion that no gross errors have been made in the physics or writing of the codes. The closeness of the results from PARMELA (t-code) and all the other four codes (all z-codes), suggests that simulations based on t or z code make very little difference in beam dynamics calculations. The results from IMPACT show some differences around the edges of the beam especially in the longitudinal phase space. One possible explanation could be the linear variation of E_r and H_θ with r assumed in the IMPACT code. One of the surprising findings is the apparent insensitivity of the results to space charge calculation with 2D and 3D algorithms for the code studied here. It should be noted that, such insensitivity had previously been observed [9] with well-matched simulated ideal beams and transverse aspect ratios below about 2. Also, the fringe field and conservation of momentum in the quad fields seem to have little effect on the output distribution. These should be further investigated with other codes. Further studies on the comparison of results through an entire linac and with mismatched beams, should include studies of single particle trajectories located strategically at various positions in the bunch.

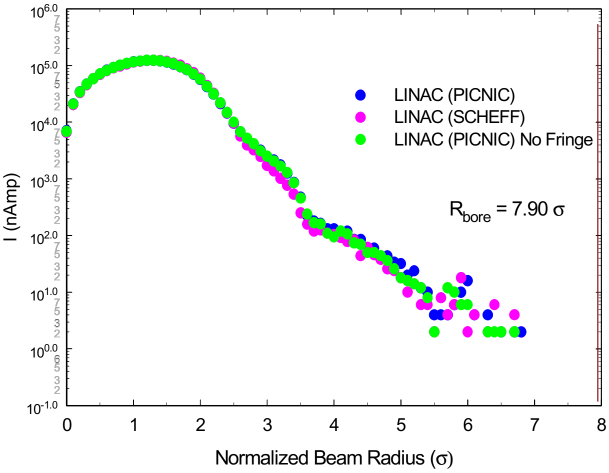

Figure 5. Simulated radial distribution at the output from LINAC with PICNIC and SCHEFF.

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