BEAM DYNAMICS STUDY OF C-ADS INJECTOR-I WITH DEVELOPING P-TOPO CODE*

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Abstract

A parallelized, time-dependent 3D particle simulation code is under developing to study the high-intensity beam dynamics in linear accelerators. The self-consistent space charge effect is taken into account with the Particle-In-Cell (PIC) method. In this paper, the structure of program and the parallel strategy are demonstrated. Then, we show the results of code verification and benchmarking. It is proved that the solvers in P-TOPO code and parallel strategy are reliable and efficient. Finally, the beam dynamics simulation of C-ADS Injector-I at IHEP are launched with P-TOPO and other codes. The possible reasons for the differences between results given by separated codes are also proposed.

INTRODUCTION

A new particle simulation code Parallelized-Trace of Particle Orbits (P-TOPO) is now under development to study space charge effect at high intensity linacs [1-5]. The motivation is to improve the efficiency and calculation capability, based on the OpenMP techniques, of the TOPO code [6]. In the P-TOPO code, the basic elements, which supply external field to particles in linear accelerator, such as multi-pole, solenoid, RFQ, superconducting cavities, are modelled analytically or represented by field map obtained from CST. The internal interactive space charge filed between particles is solved with the classic PIC method [7].

The Injector-I of Chinese Accelerator Driven Sub-Critical System (C-ADS) project is composed of ECRIS, LEBT, RFQ, MEBT1, SC section and MEBT2, which is under beam commissioning in IHEP. In recent experiment, a 10.1 MeV, 10.03 mA pulse beam is successfully achieved [8]. In this paper we will give a brief introduction of Injector-I and show the beam simulation results in detail with P-TOPO code. In section 2, the brief structure and parallelization strategy of P-TOPO are introduced. In section 3, code verification and benchmarking are given. In section 4, simulation results of C-ADS Injector-I are given by P-TOPO code and other widely used codes. Several reasons are proposed to interpret the difference among results given by P-TOPO and other codes. Conclusion and summary are given in section 5.

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P-TOPO

P-TOPO is developed with C++ language and parallelized based on the OpenMP techniques to achieve a high beam processing. Now, it can be run at PC with any number of cores. The structure of this program is as Fig. 1.

1) The MAIN class is in charge of getting the electric-magnetic field from external elements or inner space charge field, and particle updating under the effect of these obtained fields.

2) The Lattice class composed of elements class could be used to establish accelerator lattice with great flexibility. The external field supplied by certain element could be represented by a field map from CST or by analytical approximation.

3) The Beam class saves the beam information and calculates the beam parameters, like twiss parameters, emittance, beam size, et.

4) The Distribution class serves as initial particle distribution generator for specific type.

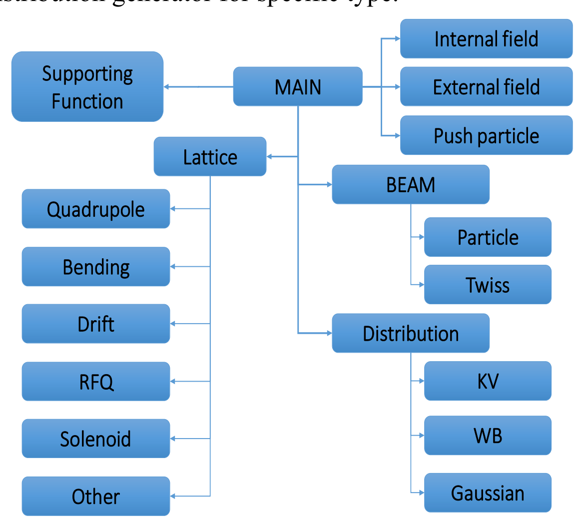

Figure 1: Layout of P-TOPO.

The parallelization occurs mainly in getting internal field, external field and particle pusher, where no interaction exists between different processing. Take the PIC module for example, it requires 4 separated steps to get the internal space charge field.

Step1, Weighting particles to grids;

Step2, Solving potential on the grids by FFT;

Step3, Obtaining the electric field on grid by the difference of the electric potential field;

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Step4, Getting electric field particles feel.

In step 1 and step 4, the grid parallelization is taken and each thread handles different grids. The reason is the potential confliction that different threads may process a grid at the same time when they operate on different particle. It would be inefficient if we take strategy to avoid the conflict. In step 2 and step 3, the main part of solving field on grids is the Fast Fourier Transform. The fftw library is used in the solver and the inner parallelization strategy of fftw is also taken combined with OpenMP.

A performance test with space charge is taken at a common PC with 4 cores. With all the parallelization strategy, when the code runs in 4 threads, the speed is 3.6 times as fast as the single thread.

CODE VERIFICATION AND BENCHMARKING

Internal Field

The potential of a point charge state is used to verify the result of PIC solver. The grid number is 128*128*64. Dirichlet boundary condition is used in transverse direction and periodic boundary condition is used in longitudinal direction. Fig. 2 shows the comparison of P-TOPO result and theory expectation in transverse and longitudinal direction. The electric potential field from code agrees well with theory result. The slight deviation comes from the numerical noise of discretization.

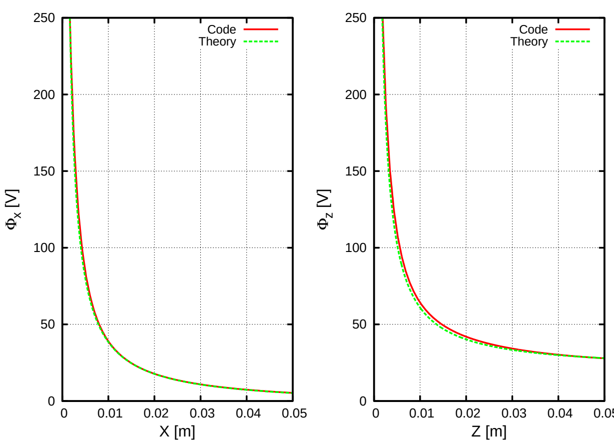

Figure 2: Comparison of the potential of point charge between P-TOPO and theory prediction.

Beam Evolution in FD Structure

The beam evolution along the periodic focusing channel could be expressed in the form of 2.5D rms envelope equation. The amplitude of the beam size oscillation is related to mismatch, and the phase advance and is related to the space charge force [9, 10]. Fig. 3 shows the evolution of beam rms size given by P-TOPO and theory expectation from rms envelope equation with 0mA and 15mA beam current in a FD structure. In the condition of zero beam current, the red solid curve is beam rms size from theory expectation and the green dashed curve is from P-TOPO. In the condition of 15mA beam current, the results form P-TOPO and theory expectation are represented by the blue dashed and purple solid curves. The turquoise solid line represents the external quadrupole field strength variation. It could be seen that these results agree well in both 0 and 15 mA cases. The slight differences between P-TOPO result and rms envelope equation is induced by numerical randomness and the evolution of emittance in P-TOPO simulation, which is supposed to be constant in rms envelope equations model.

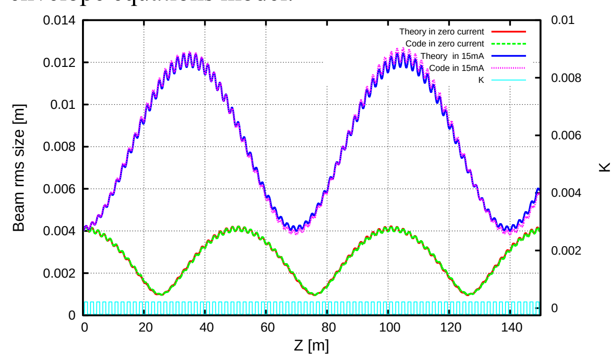

Figure 3: RMS size of the beam by P-TOPO and theory expectation in zero current and in 15mA.

BEAM DYNAMICS STUDY OF INJECTOR-I.

Injector-I of C−ADS is made of RFQ, MEBT1, CM1, CM2, and MEBT2 as shown in Fig. 4. In the following, we show the P-TOPO simulation separately with KV initial beam. The mesh number for space charge calculation is 64*64*32.

RFQ

The RFQ is designed with PARMTEQM at a frequency of 325MHz, and proposed to deliver proton beam from 35KeV to 3.2 MeV with a beam current of 15mA. In P-TOPO simulation, started with rms matched beam condition, the KV beam composed of 10K marcoparticles is used to show the beam evolution along the RFQ. The field of RFQ is obtained with 8 terms expansion in form of Fourier Bessel function. Fig. 5 shows the transverse and longitudinal emittance evolution of P-TOPO and TRACK in the condition of 0mA and15mA beam current.

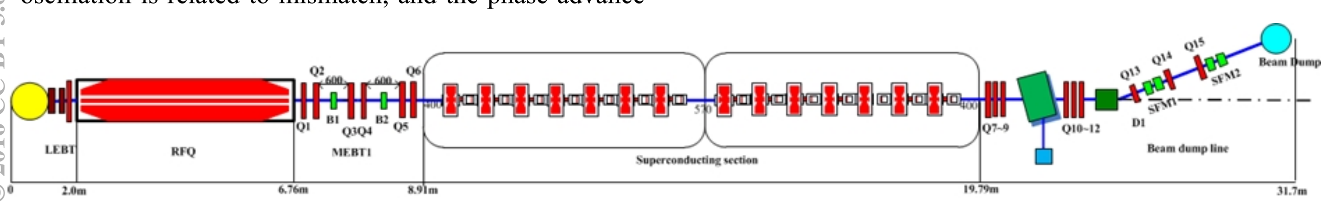

Figure 4: Layout of the ADS Injector-I testing facility

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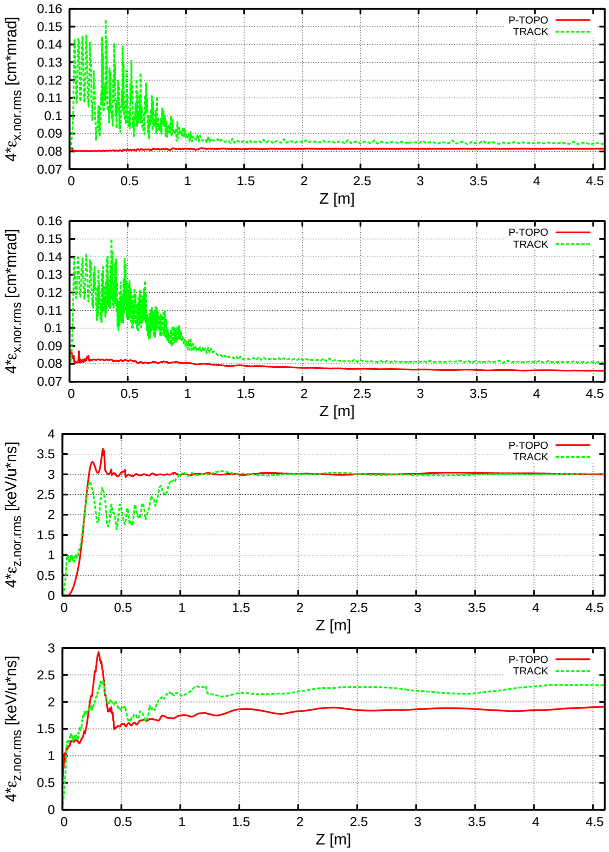

Figure 5: Transverse and Longitudinal emittance given by P-TOPO and TRACK in the condition of 0mA and 15mA.

In both of the transverse and longitudinal directions, the P-TOPO code shows much smoother emittance variation, especially in the front of the RFQ, where beam filamentation takes place and fierce bunch rotate. The deviation of final beam emittance and transmission given by TRACK and P-TOPO is in the reasonable region.

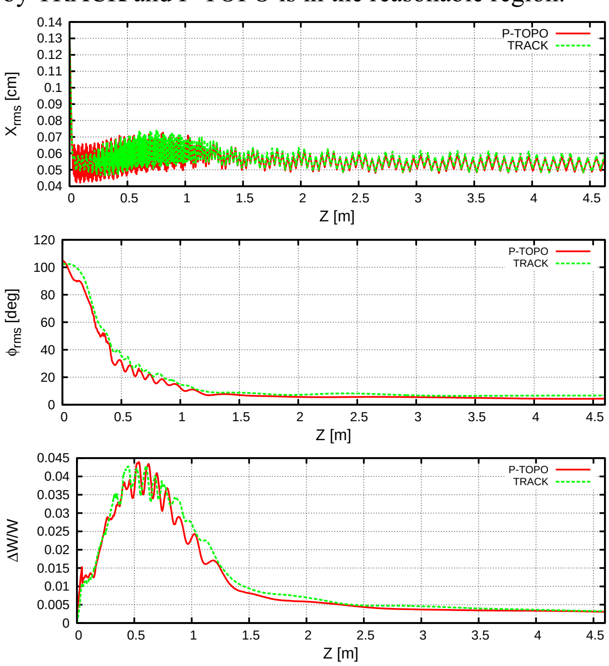

Figure 6: RMS beam size and energy spread.

Figure 6 shows the evolution of transverse and longitudinal rms beam size and energy spread. The rms size got from the P-TOPO and TEACK consist with each other. Still, slight discrepancy exists as the amplitude of envelop got from P-TOPO is a little larger than that from TRACK at the beginning of RFQ cells. At the end of the RFQ, longitudinal phase given by TRACK is a little advanced than that given by P-TOPO,

SC Section

In the SC section, the field in bunchers and SC cavities are represented by the field map. As said, the numerical interpolation is used to obtain the field that single particle feels. With the designed 15mA beam current, the 3.2 MeV proton beam at the exit of RFQ are bunched and transported to the entrance of SC section by the MEBT, where the beam are supposed to be rms matched. The SC section sustainably accelerates the beam into 10MeV. The TraceWin code is used for benchmarking. The output result from P-TOPO is 10.01 MeV, and the result from TraceWin is 10.06 MeV.

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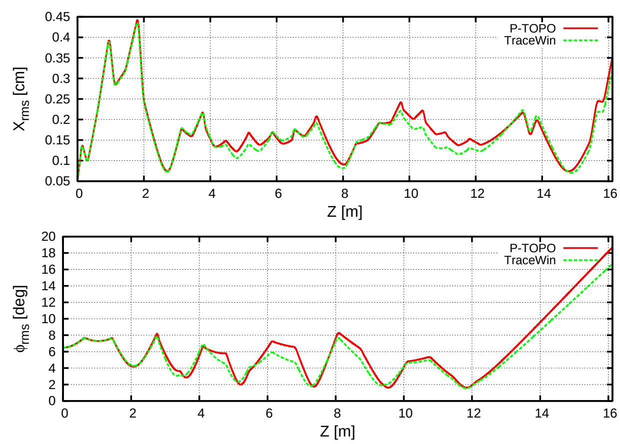

Figure 7: RMS beam size and phase envelop.

Figure 7 shows the rms beam sizes evolution in the transverse and longitudinal directions. The red solid curve is from P-TOPO and the green dashed curve is from TraceWin. The rms envelop is consist well with each other. Little deviation exists because of the different methods of the synchronous phase calculation.

Through P-TOPO simulation, the beam size and beam loss is effectively controlled and the emittance basically keeps constant along the Injector-I of C-ADS.

In the above study, besides the differences lied on initial beam distribution used, discrepancies among different codes are due to the differences of date processing and methods used in detail. Generally, one is the differences between T-code (P-TOPO) and Z-code (TRACK and TraceWin), which results in the differences of particle information collection and parameter calculation. The other is the criteria for beam loss, which actually happens only when particle touches the beam pipe.

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CONCLUSIONS

The P-TOPO code has been verified. The method used to get space charge force has been tested with point charge and is proved to be fast and accuracy. The result of FD structure simulation and its comparison with theory expectation illustrate that the code is reliable. Parallelized with OpenMP, the performance of the whole program is obviously better than single thread program. In the future, P-TOPO would be transplanted to the cluster in IHEP.

The P-TOPO code has been employed at the study of Injector-I of C-ADS. The RFQ and the other part is simulated separately. The P-TOPO simulation proves the current design is in control. No sufficient beam loss and emittance growth appear. In future study, efforts will be focused on comparison between simulation and experiments.

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