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# EIC COOLER INJECTOR SPACE CHARGE BENCHMARK*

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*Abstract*

In this paper, we present the benchmark results of Bmad space charge tracking on the Electron-Ion Collider cooler injector lattice. Bmad, GPT, and Impact-T are compared in terms of accuracy and performance. We highlight the importance of space charge algorithm and demonstrate that the adaptive step size control improves the performance of Bmad space charge tracking.

## INTRODUCTION

Space charge is a dominant effect in high brightness charged particle beams especially at low energies. Accurate simulation of this effect is crucial for the design and optimization of low-energy accelerator systems, where space charge can have a significant impact on beam quality. There are many established programs that include space charge into particle simulations, such as Impact-T and GPT. In our previous work, we implemented low-energy space charge tracking with cathode image fields in Bmad [1,2] and demonstrated its accuracy by comparing to Impact-T [3] on a DC gun benchmark.

In this work, we extend our previous work to showcase the Bmad space charge tracking capabilities on the Electron-Ion Collider (EIC) cooler injector. Two space charge codes, GPT [4] and Impact-T, are used as benchmarks on the same lattice. We shall compare results from all three codes as well as their performance.

Efficient simulation algorithms are essential for realistic applications of space charge tracking, and in this work we present an optimized adaptive step size control algorithm in the Bmad code. By improving the efficiency of the simulation, we can better utilize Bmad space charge tracking for computation-intensive problems like injector optimizations.

## ADAPTIVE STEP SIZE CONTROL

We implemented an adaptive step size control algorithm in Bmad to efficiently determine the time step size between space charge field calculations. It scales time step sizes based on local error estimates. The process involves tracking the particles by a full step and two half steps and evaluating the difference. We define the error to be the average difference between the two final bunches.

$$error = \frac{1}{N}\sum_{\text{particles}} |x_{\text{full}} - x_{\text{two halves}}|. \tag{1}$$

The user can control the simulation accuracy by setting the tolerance through two parameters, *rel_tol* and *abs_tol*. The tolerance is defined as

$$tol = rel\_tol * scale + abs\_tol, \tag{2}$$

where $scale$ is a measure of the typical motion of particles and is defined as

$$scale = \sqrt{\frac{1}{N}\sum_{\text{particles}} x^2}. \tag{3}$$

If $error < tol$ the step is accepted and if $error > tol$ the step is rejected.

To efficiently pick a good step size for the next space charge calculation, we measured the relation between $error$ and the step size taken. In regions where the external fields are slowly varying and step sizes are small, the error is proportional to the square the step size. Hence, we can scale the next step size by

$$0.9\,(err/tol)^{-0.5}\,. \tag{4}$$

The adaptive step size control algorithm allows simulations to use small step sizes when the fields are varying rapidly and make large steps whenever possible. It makes one additional space charge calculation per time step, a 50% overhead, but it's possible to significantly speed up the simulation when the appropriate step sizes are orders of magnitude different. We will demonstrate the speedup using the EIC cooler injector benchmark.

## EIC COOLER INJECTOR

The current EIC cooler ERL [5] is designed to provide high quality electron beam for Strong Hadron Cooling (SHC) to cool the hadron beam at 275 GeV and 100 GeV. It's also capable to serve as the precooler for the 41 GeV hadron. The layout of a SHC and precooler hybrid ERL is shown in Fig. 1. The 400 kV HVDC gun generates a beer-can distribution beam of 1 nC with a normalized emittance of 1.1 mm-mrad and repetition rate of 98.5 MHz. Two 197 MHz quarter-wave cavities and a single cell 591 MHz third-harmonic cavity accelerates the beam to 5.6 MeV. The voltage of 197 MHz cavities is 2.9 MV and the beam is nearly on crest. The third-harmonic cavity is used to reduce the longitudinal energy spread. The initial particle distribution was generated by the python library distgen [6]. We used a uniform initial distribution in both radial and longitudinal direction, with a maximum radius of 3.78 mm and a bunch length of 100 ps. The total bunch charge is 1 nC with an MTE of 130 meV.

The lattice for the EIC cooler injector was initially constructed in GPT and translated to Bmad and Impact-T. All

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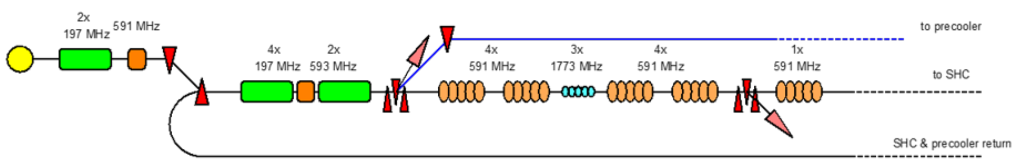


Figure 1: Layout of the EIC cooler ERL. Injector is the top left section. Adapted from [5].

lattice elements use the same fieldmaps and ends at 6-meter mark from the cathode. We verified that the lattices are identical for the three codes by matching their single-particle tracking results. Furthermore, their multiparticle tracking without space charge and cathode effects produced identical results, which confirmed the consistency.

While Bmad and Impact-T both calculate the space charge field using the Integrated Green Functions (IGF) algorithm, while GPT implements several different space charge methods. For this benchmark, we used Spacecharge3Dmesh which is the most similar to the IGF method. It deposits particles on a non-equidistant mesh and calculates the space charge field using a Poisson solver. All three codes include the cathode field effect. Although the space charge effect will vary in subtle ways depending on the exact implementation, we picked similar user parameters and step sizes in order to have a fair comparison.

## RESULTS

First, we examined the transverse bunch statistics along the beam line (Fig. 2). The final beam size is 0.5 mm and the normalized emittance is 1.6 mm-mrad. GPT transverse momentum is smaller than the other two codes, but the beam size and emittance stay close. Overall, the three codes agree to a satisfactory extent in the transverse direction.

In contrast, significant discrepancies were observed between GPT and Bmad/Impact-T in the longitudinal direction (Fig. 3). Bmad and Impact-T show excellent agreement in the longitudinal bunch size and energy spread, whereas the GPT values are much smaller. The final bunch length is 17 mm from GPT and 19 mm from Bmad/Impact-T. This discrepancy is also reflected in the longitudinal phase space (Fig. 4). The GPT bunch clearly has a different longitudinal shape than the other two codes and also have a shorter time of flight.

The observed difference in tracking results are primarily attributed to the space charge effect, which is modeled differently in each code. Both Bmad and Impact-T uses the IGF algorithm, however, GPT implements a different Poisson solver. A previous study [7] has shown that the GPT Spacecharge3Dmesh method may give poor estimates of the space charge field at large or small aspect ratios. The aspect ratio for the benchmark case is sufficiently small near the cathode, on the order of $10^{-1}$ to $10^{-2}$. This suggests that the GPT Poisson solver may have taken approximations that are not applicable to the EIC cooler injector benchmark, and may explain the observed differences in tracking results.

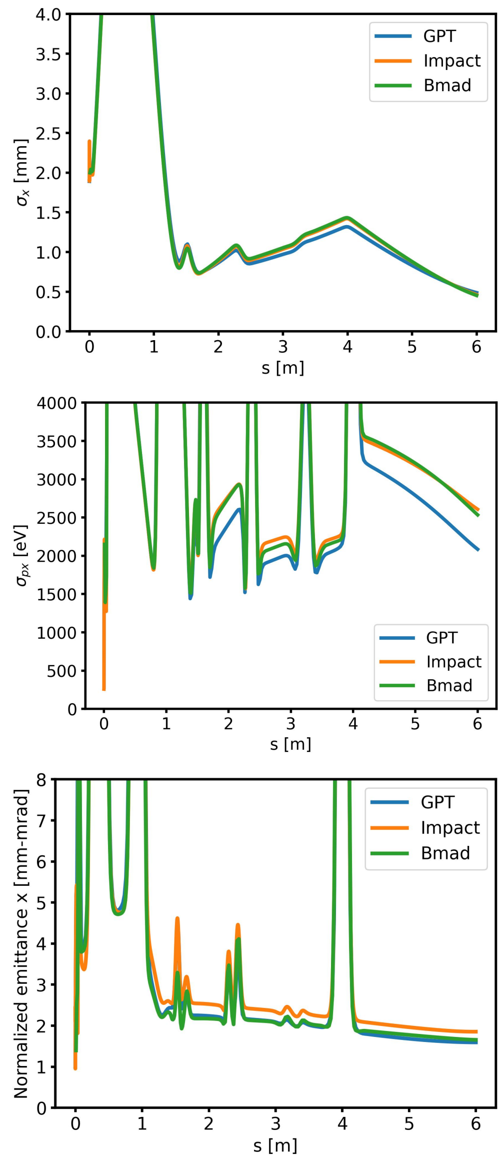


Figure 2: Transverse statistics from GPT, Impact-T, and Bmad. Top: RMS transverse beam size. Bottom: RMS transverse momentum spread.

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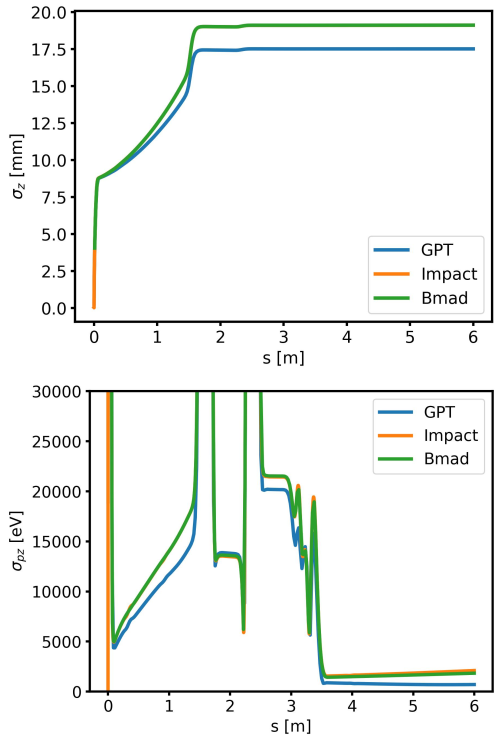


Figure 3: Longitudinal statistics from GPT, Impact-T, and Bmad. Top: RMS bunch length. Bottom: RMS longitudinal momentum spread.

Table 1: Runtimes of Three Codes on Benchmark

| Code | Runtime |
|---|---|
| Bmad | 44 min |
| Impact-T | 40 min |
| GPT | 25 min |

We measured the single core performance of the three codes on this benchmark. Their runtimes are listed in the Table 1. GPT finished twice as fast while Bmad and Impact-T took similar amount of time. Figure 5 demonstrates the benefit of adaptive step size control. Apart from the cathode where the space charge field fluctuate abruptly, the algorithm was able to suggest good time steps for space charge calculations. It took significantly larger steps in drift regions and slowed down when necessary. This helped to reduce the total number of steps by several orders of magnitude.

## CONCLUSION

We used Bmad, Impact-T, and GPT to simulate the EIC cooler injector with cathode and space charge effect. Three codes reached good agreement on the transverse statistics, but GPT had a shorter bunch length and energy spread in the longitudinal direction. This discrepancy is due to different space charge algorithms implemented by each code. The benchmark suggests that Integrated Green Functions method is more robust when the bunch aspect ratio is large or small.

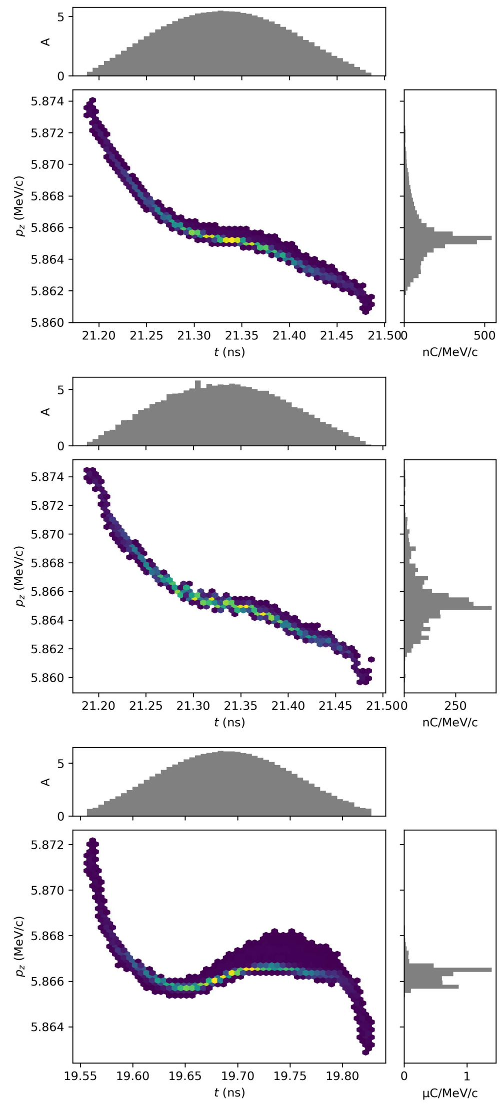


Figure 4: Longitudinal phase space of the particles at the end of the injector. Top to bottom: Bmad, Impact-T, GPT.

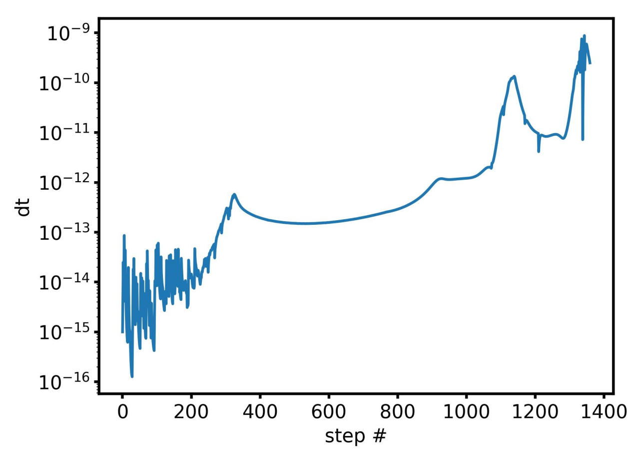


Figure 5: Step sizes taken by the adaptive step size control in Bmad during the benchmark simulation.

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