ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOMS055

CATHODE SPACE CHARGE IN Bmad*

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Abstract

We present an implementation of charged particle tracking with the cathode space charge effect included which is now openly available in the Bmad toolkit for charged particle simulations. Adaptive step size control is incorporated to improve the computational efficiency. We demonstrate its capability with a simulation of a DC gun and compare it with the well-established space charge code Impact-T.

INTRODUCTION

Space charge (SC) describes the interaction of electric charges in a charged particle bunch. It is an important effect especially in high brightness charged particle beams and especially when a beam has low-energy. The evolution of beam is complex when space charge and external fields are combined. Generally, numerical calculation methods are needed to incorporate space charge into particle simulations and this has been done with a number of programs including Impact-T [1], OPAL [2], GPT [3], ASTRA [4], etc. [5] Space charge methods have been incorporated in the Bmad toolkit for charged particle simulations [6, 7] but up to now the effect of space charge fields from a cathode have not been included.

When electrons are emitted from a cathode, image charges are formed inside the conductor. The space charge effect between bunch charges and image charges will modify the space charge field and this can be important close to the cathode especially with simulations of high brightness beams. Here, we report on the implementation of cathode space charge in the Bmad toolkit, describe the algorithm, and validate it by benchmarking with another well-established space charge code Impact-T [1].

CATHODE SPACE CHARGE EFFECT

The Bmad toolkit uses a stand-alone package called “Open Space Charge” (OpenSC) to calculate space charge fields from a bunch distribution [8]. OpenSC is an open-source software library developed by Robert Ryne and Christopher Mayes. OpenSC deposits charged particles on a 3D rectangular grid, calculates the space charge fields on this grid, and interpolates the field at any arbitrary point within its domain. The space charge fields are calculated in the local rest frame using integrated Green functions (IGFs), as described in [1], with fast Fourier transforms (FFT). Cathode image fields can be enabled in the code.

* This project was supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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Figure 1 illustrates the space charge field of a Gaussian bunch near the cathode at $z = 0$ using OpenSC. The cathode field is modeled as the space charge field from an equal and opposite image charge distribution inside the cathode. It attracts the bunch towards the cathode and modifies the overall field profile. This effect decays as the bunch moves away from the surface.

Bmad CATHODE SPACE CHARGE TRACKING

Cathode space charge tracking was implemented within Bmad by tracking a beam in a number time steps. At the beginning of a time step, the space charge field is calculated in the local rest frame using OpenSC. Particles are then tracked through the time step with a fourth-order Runge-Kutta time based integrator. Thus the space charge is applied smoothly during the time step.

Since the cathode space charge is most significant during emission from the cathode, an emission model was implemented with particles being “born” from the cathode over some time period. During a simulation, particles not yet emitted from the cathode do not contribute to the space charge calculation. Calculating the initial particle distribution is not part of Bmad but Bmad can read in appropriate data files generated externally. For this study, the initial particle distribution was generated by the code distgen [9].

ADAPTIVE STEP SIZE CONTROL

To improve the efficiency of the simulation, we implemented adaptive step size control. The algorithm tracks the bunch by a full step and two half steps and evaluates the difference. The error is the average difference between the two final bunches,

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

The scale of motion combines the bunch size and centroid position, and is defined as

$$scale = \sqrt{\frac{1}{N} \sum_{\text{particles}} x^2}. \quad (2)$$

The tolerance is controlled by two parameters, *rel_tol* and *abs_tol*

$$tol = rel\_tol * scale + abs\_tol \quad (3)$$

If $error < tol$ the step is accepted and the time period of the next time step duration will be 5 times the current step

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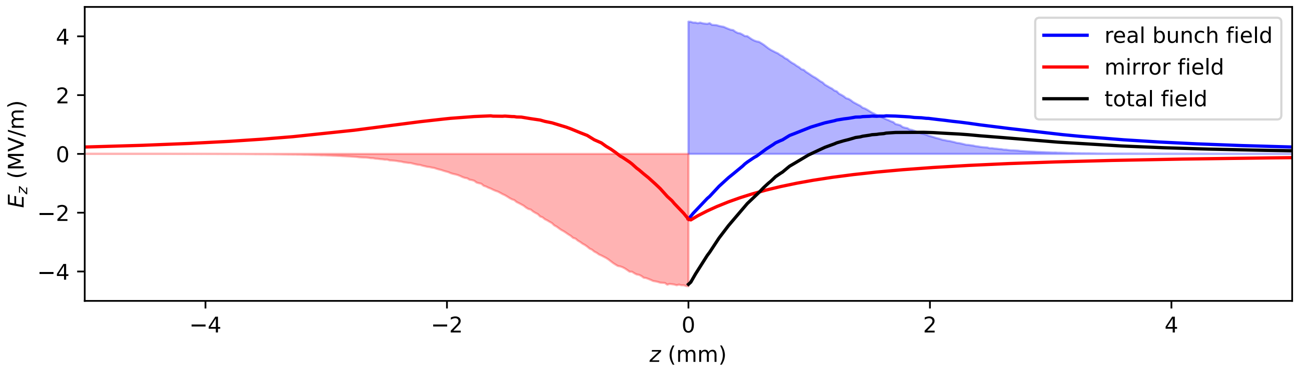


Figure 1: Space charge field for a Gaussian bunch and its image charges near the cathode at z=0. Left axis is the field strength and right axis is the charge density. The space charge field pushes particles in the head of the bunch forward and particles in the tail backward. The image field attracts the bunch towards the cathode surface, the effect of which is important close to the cathode.

duration. If $error > tol$ the step is rejected and a new step starting at the original starting point before the step will be made with step duration being scaled by

$$0.9 \times (error/tol)^{0.25} \tag{4}$$

Thus tracking will use a smaller step size when the fields are varying rapidly and will make larger steps when possible. The tracking is sped up in regions such as drifts while ensuring accurate final results.

VALIDATION AND PERFORMANCE

We tested our implementation of space charge in Bmad against Impact-T which also tracks particles with space charge. Impact-T uses an IGF FFT method similar to that in OpenSC. The test lattice is a 750 kV DC gun as shown in Fig. 2. The initial bunch has a uniform radial distribution of 0.5 mm radius and a Gaussian longitudinal distribution with σ_z = 8.5 ps. The total bunch charge is 20 pC and 1000 particles are tracked.

Three scenarios are simulated using a fixed stepsize of 10^{-12} s and compared in Fig. 4: 1) no space charge, 2) with space charge, and 3) space charge + image charge. The transverse phase spaces are nearly identical and the longitudinal phase spaces have good agreement. The small shift in p_z in the no space charge case is due to numerical inaccuracies in scaling the field to 750 kV.

With adaptive step size control, a lower tolerance level leads to greater accuracy but longer computation time. Figure 3 demonstrates the step sizes taken at two different tolerance levels and their runtime. Small steps are taken near the cathode where the electric field is changing rapidly and the simulation speeds up in the region away from the cathode.

We also compared the performance of space charge tracking in Bmad against Impact-T. The lattice and initial distribution are the same as the validation. At a fixed step size of 10^{-12} s, Bmad and Impact-T achieved similar runtime. Adaptive step size control successfully speeds up the simulation by 4.3x.

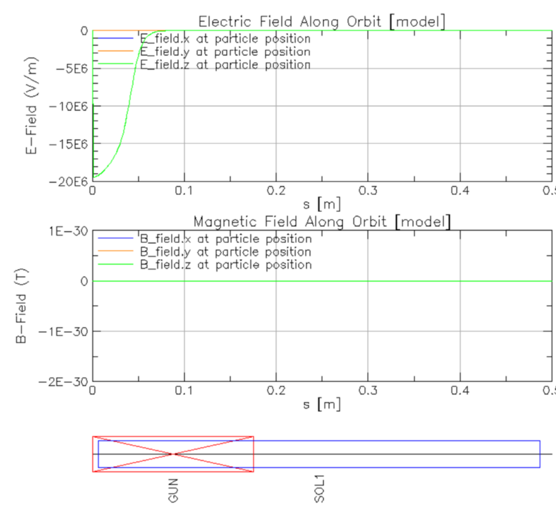
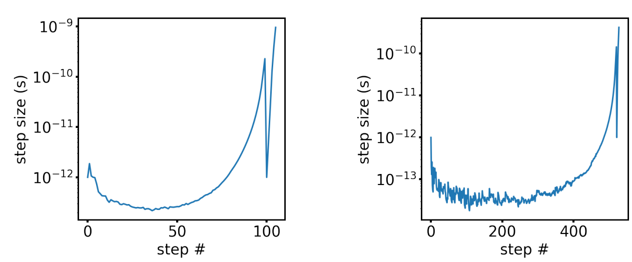


Figure 2: A lattice of a 750 kV DC gun is used for validation of cathode space charge tracking. The solenoid is turned off.



(a) rel_tol = 0.1 runtime = 47 s

(b) rel_tol = 0.01 runtime = 181 s

Figure 3: Time steps taken by adaptive step size control under two tolerance settings and their runtime. abs_tol = 10^{-6} in both (a) and (b).

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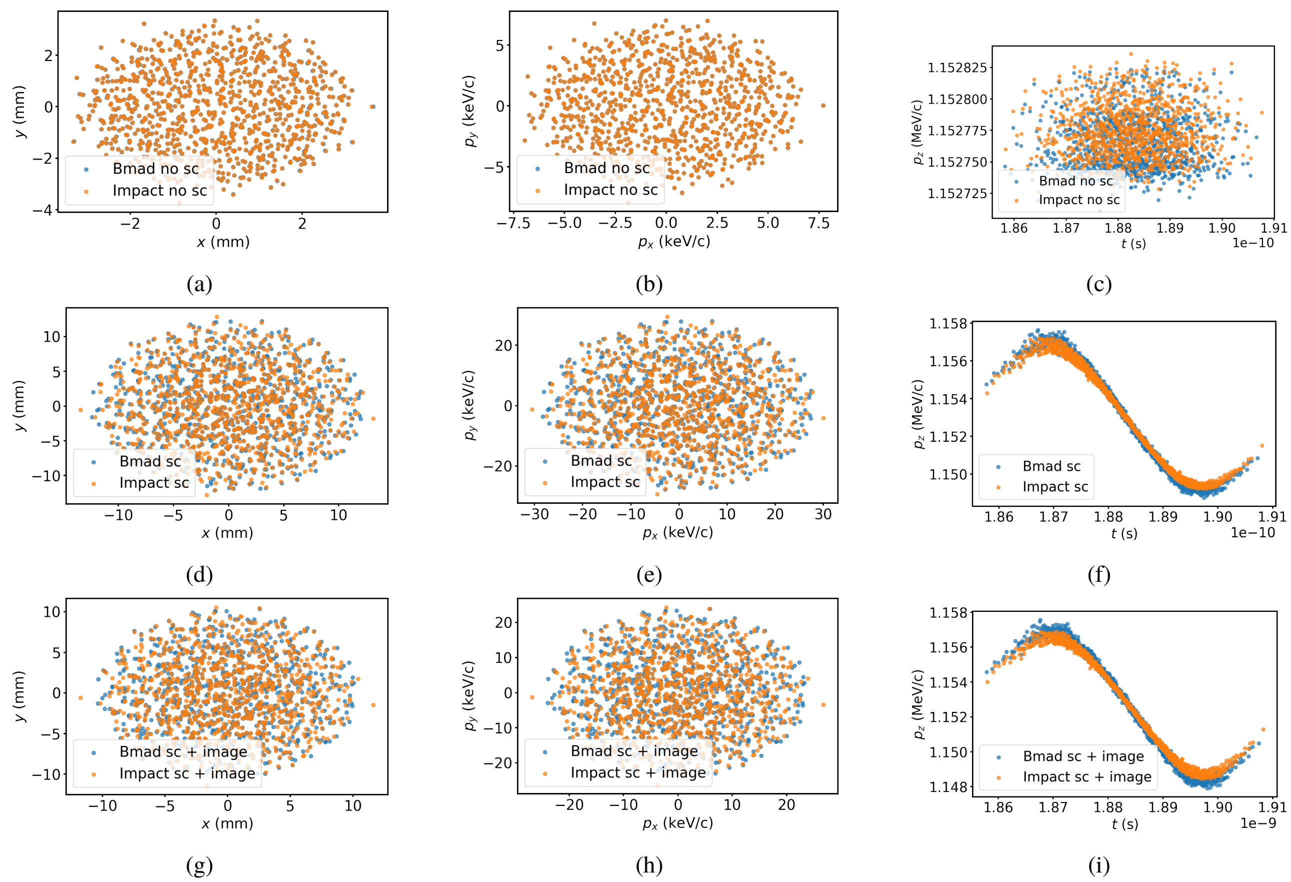

Figure 4: Phase space comparison at the end of a DC gun between Bmad and Impact-T. (4a,4b,4c) No space charge effect. (4d,4e,4f) With space charge. (4g,4h,4i) With space charge and image charge.

Table 1: Performance comparison of three tracking methods. Fixed timestep methods uses a step size of 10^{-12} s.

Method	Runtime	Speedup
Impact-T fixed timestep	201 s	1x
Bmad fixed timestep	274 s	0.73x
Bmad adaptive	47 s	4.3x

CONCLUSION

Bmad now provides particle tracking with cathode space charge effects, an important element for tracking from an electron gun. It is available in recent Bmad distributions [6]. Simulations show excellent agreement with the well-established space charge code Impact-T. We are currently working to compare against other space charge codes and run cathode space charge tracking on realistic lattices.

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