

PUTTING SPACE CHARGE INTO G4BEAMLINE*

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Abstract

The G4beamline program is based on the well-established Geant4 toolkit used to simulate the interactions of particles and photons with matter. Until now, only a single particle at a time could be tracked and there are no interactions between particles. Recent designs for high pressure RF cavities and other novel devices achieving extreme muon cooling require that the effect of space charge be included in the simulations. A new tracking manager in G4beamline propagates a number of particles (typically 1,000-10,000) in parallel, stepping all particles in time. This allows all of the usual Geant4 physics interactions to be applied, plus collective computations. A simple macroparticle-based model is used to represent $\sim 10^8$ charges with an ellipsoidal charge density. At intervals the appropriate macroparticle size and shape are recalculated, the electric and magnetic fields are determined, and an impulse is applied to the simulated particles. Comparisons to a space charge experiment are presented.

INTRODUCTION

The Geant4[1] toolkit is the leading tool in the world for simulating the interaction of particles and photons with matter, but mastering Geant4 requires an extensive knowledge of C++ as well as the physics. The G4beamline[2] program provides a simple interface to the power of Geant4, allowing one to create and run simulations in hours rather than months.

To date, Geant4 considers each particle in turn; a particle may stop, decay, scatter, but essentially only one particle is considered at a time. G4beamline has provided a means of considering many particles more-or-less simulatenously, but that still leaves the question of how to best describe the interactions among the particles. The most important of these is space charge.

This particle-particle interaction was encapsulated into a single collective routine, allowing developers and users to easily insert their own models without modifying G4beamline itself. This first attempt only considers space charge in vacuum, but for our applications of interest this method must be extended to cover space charge in matter, too.

CONCEPT

The electromagnetic interaction of two charge particles is well understood; the whole problem of space charge in beams is that of using a very small number of "particles" ($\sim 10^3$) to predict the behavior of many (10^{9-20}) particles. Such "macroparticles", essentially large overlapping blobs of charge, came into wide use; some more recent codes use particle-in-cell

(PIC) models with many more point-like particles and fields calculated on a grid.

The macroparticle model is very attractive for use with G4beamline – the number of particles used is very small (10^4) and the calculation intuitive. A package called kbb_sc5 was linked into G4beamline; this package was developed solely to test various macroparticle models and to compare the results with various versions of the well established Parmela [3] [4] space charge program. While kbb_sc5 is very similar in concept to TJNAF Parmela, it contains no Parmela code.

PHYSICAL MODEL

The simplest possible model is to just naively apply Coulomb's law to point particles. While some kind of screening is required to avoid singularities when two particles get very close, the method is trivial and ensured all the units were correctly chosen.

The first improvement was to put in the relativistically correct interaction where the moving particle creates both an electric and a magnetic field. As in TJNAF Parmela, the retarded time was not used by default, but may be optionally enabled.

The next was to replace the point-like particles with macroparticles. For the purpose of their propagation, macroparticles are point-like; for the purpose of calculation the electric field from their charge distribution, they are extended globular objects that may be either uniformly or non-uniformly charged inside with either a hard or soft edge. Each of the N macroparticles is assigned 1/Nth the charge of the whole bunch.

Table 1. kbb_sc5 bit-packed options.

bit	option	101510	1318	3206	99590
1	KBB_SC_OPT_DISABLE				
2	KBB_SC_OPT_ENABLE	*	*	*	*
4	KBB_SC_OPT_MACROPARTICLE	*	*	*	*
8	KBB_SC_OPT_FUZZYEDGE				
16	KBB_SC_OPT_DISCARDOUTLIERS				
32	KBB_SC_OPT_XYZMACROPARTICLE		*		
64	KBB_SC_OPT_PARMELALIKE				
128	KBB_SC_OPT_JACKSON	*		*	
256	KBB_SC_OPT_COULOMB		*		*
512	KBB_SC_OPT_CUBICMP				
1024	KBB_SC_OPT_CENTEROFMASS	*	*	*	*
2048	KBB_SC_OPT_RETARDED	*		*	
4096	KBB_SC_OPT_BOOST2CM				
8192	KBB_SC_OPT_REITZMILFORD				
32768	KBB_SC_OPT_KLUDGEDRIFT	*			*
65536	KBB_SC_OPT_TIMEZONE	*			*
1073741824	KBB_SC_OPT_RUNSELFTEST				

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The dimensions of the macroparticles are derived from the bunch and usually updated from time-to-time

based on the distribution of the entire bunch. The best formula for this is open to debate [6].

Since the physics model in kbb_sc5 is controlled by a bit packed integer, it is easy to change the model and compare results (Table 1).

COMPARISON WITH OTHER CODES

A simple field free drift space was used for the first tests. A single bunch of macroparticles was injected at one end of a field free region and allowed to drift; the paths of the particles under various models were compared.

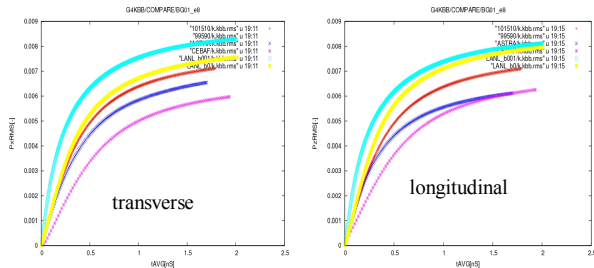


Figure 1: Simulated results for Pxrms and Pzrms (MeV/c) for a spherical bunch in various models. The kbb_sc5 results are in shown in red.

The first test just used a 16 pC spherical Gaussian bunch with a 1mm radius and $\gamma=0.1$. The kbb_sc5 results for the simplest and better models lie atop one another and between the ASTRA, LANL Parmela ($b=0$ & $b=0.001$), and CEBAF Parmela results.

The next test used a uniform “slug” of electrons with radius=1 cm, length=0.909 cm, $Q=6$ nC, and $\gamma=1$ that had been used for earlier comparisons.[6]

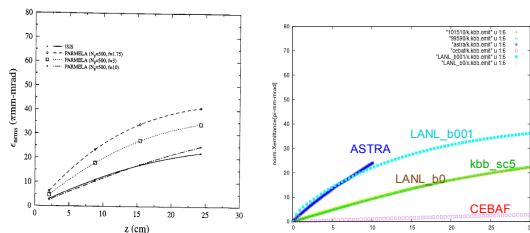


Figure 2: Emittance results for ISIS and CEBAF Parmela [6] and results from ASTRA, LANL Parmela with parameter $b=0$ and 0.001 , CEBAF Parmela (with default parameters), and kbb_sc5 for a uniform slug of charge.

Even in this fairly simple case, the results strongly depended on the program and the parameters chosen. The CEBAF Parmela run used the default parameters for the CEBAF injector, a poor match for the slug.

The agreement of various quantities between the various simulations varied widely depending on the circumstances and the quantity of interest with no obvious pattern to suggest that one code was consistently far superior to the others.

COMPARISON WITH REAL DATA

While new space charge codes are often tested by comparing with existing space charge codes [5] [6], it is much better to compare to real data.

Fortunately, a very careful experiment to measure space charge and compare with existing models has recently been published [7] [8] [9]. This electron photoinjector beamline consists of a photocathode, electrostatic gun, emittance compensation solenoid, slits, scanners, and imaging systems.

This beamline is unusual in that its primary purpose is to study space charge. The slits allow sampling of the distribution transversely, but rather than moving the slits the beam is displaced to the side by a matched pair of air core dipoles.

The important components of the beamline were modeled in G4beamline (Figures 3 and 4) using only 75 non-comment lines in the input file, 2 field maps, and an initial distribution based on the paper.[9]

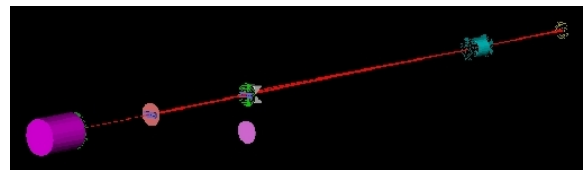


Figure 3: The Cornell beamline line in g4beamline; cathode is on the right; dump on the left; the viewer is retracted.

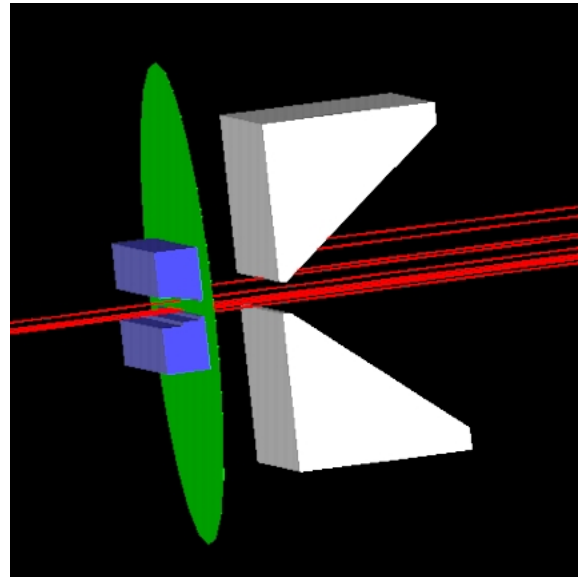


Figure 4: Close up of armor (white) and fine (blue) copper slits; the virtual detector (green) records the electrons (red) but has no physical existence.

Initial testing revealed some discrepancies between this model and data from the beamline, so a direct comparison between the data and our simulation isn't possible at this time. These deficiencies will be corrected and the simulations rerun later.

The first measurement was to retract the slits and vary the current of the emittance compensation solenoid, then compare low and high current behavior at the image screen, 124.4 cm from the photocathode.

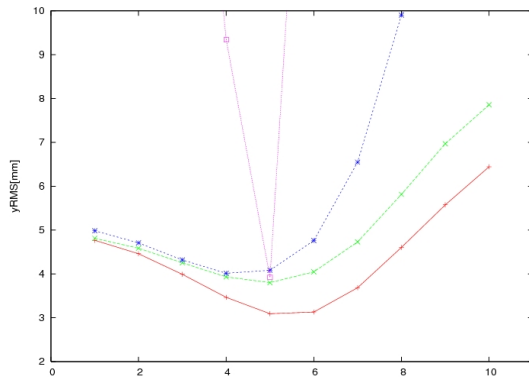


Figure 5: YRMS as a function of solenoid current for 0.5 (red), 20 (green), and 80 (blue) pC/bunch using a realistic interaction mode 1 (option=3206) and 80 (magenta) pC/bunch using the simplest model (option=1318).

A comparison of the simplest macroparticle model and a much more sophisticated model shows that the simplest model greatly overpredicts the space charge, as would be expected. The qualitative behavior agrees with the data; the differences are likely due to our misunderstanding about the solenoid's construction and will be addressed later.

The next step involves inserting the slits and using them to scan the beam transversely. This is done using two air-core dipoles to move the entire beam to the side.

A problem arises when the beam strikes a narrow slit, as most of the beam (and the macroparticles) are lost, resulting in very poor statistics. This is a general problem with of the macroparticle method that we are investigating.

For faster testing, the slit was opened to +/-1 mm.

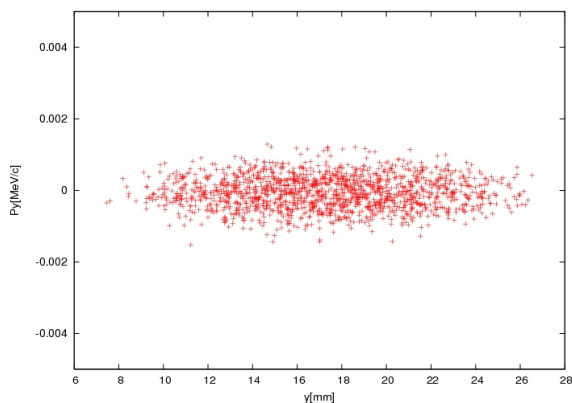


Figure 6: P_y vs y just after slit A for a 20pC bunch (option=3246).

CONCLUSION

These very preliminary results demonstrate that the collective mode modifications to g4beamline were successful, but the evidence suggests that the physical model needs to be improved before any hard conclusions can be made about the quality of this macroparticle space charge model. It also exposed several obstacles that need to be overcome before a practical system can be constructed, the most important here being of how to deal with the loss of simulated macroparticles.

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