G4BEAMLINE CODE DEVELOPMENT*

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Abstract

G4beamline [1] is a single-particle-tracking simulation program based on Geant4 [2], optimized specifically for beam lines. It is currently used by several hundred physicists and designers around the world, who apply it to a diverse set of interesting problems. As it includes particle decays and interactions, it is applicable to beams for which decays and interactions are important, such as modern muon facilities that involve ionization cooling. Its description language has been designed to be both versatile and user-friendly, and the program includes high-quality visualization and histogramming capabilities. This paper discusses recent code development and new features, and some interesting applications of the program. G4beamline is an open-source program freely available at http://g4beamline.muonsinc.com .

INTRODUCTION

G4beamline continues to be improved with new features and capabilities intended to facilitate its use by a larger set of beam line and accelerator designers. New features fall into two broad categories: physics and software.

MAJOR NEW PHYSICS FEATURES

- Updated to the latest Geant4 release, Geant4.9.5.p01.
- Space charge, including an example that allows users to vary the parameters while observing the effects on a quad triplet focusing to a point (Fig. 2 below).
- Spin tracking for electrons and muons, including the decays of pions and polarized muons.
- The ability to interface to Genie [3], a neutrino interaction monte-carlo, to track neutrinos and implement their interactions (with enhanced cross-sections).
- The ability to easily re-weight specific physics processes, for rare-process studies and variance reduction.
- Implemented Bethe-Heitler mu-pair production.
- Implemented synchrotron radiation for electrons and muons.

MAJOR NEW SOFTWARE FEATURES

- A completely new build system, modeled after the new build system of Geant4.9.5; it makes building from source significantly easier and more reliable.
- A new helper program to assist the user in downloading the required Geant4 datasets.
- The ability to draw electric and magnetic field lines.
- The ability for materials to filter tracks.
- Object transparency.
- Several improvements to reduce the incidence of faults, and improvements in the ability to debug them.

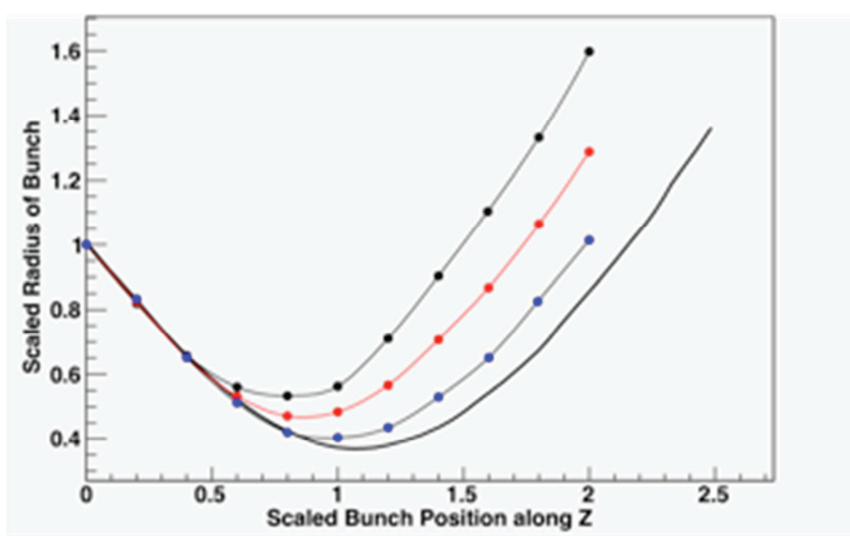

Figure 1: Comparison of G4beamline's space charge computation to a calculation in Reiser's textbook [4], showing scaled transverse beam size as a function of scaled propagation distance Z. The initial beam is a uniform cylinder which would be focused to a point at Z=1 without space charge. The solid black line is the calculation for a continuous charge density corresponding to 10^{11} μ^+; the points are for computations using 1,000 (black), 10,000 (red), and 100,000 (blue) macro-particles, each modeling a bunch totaling 10^{11} μ^+; decays are disabled.

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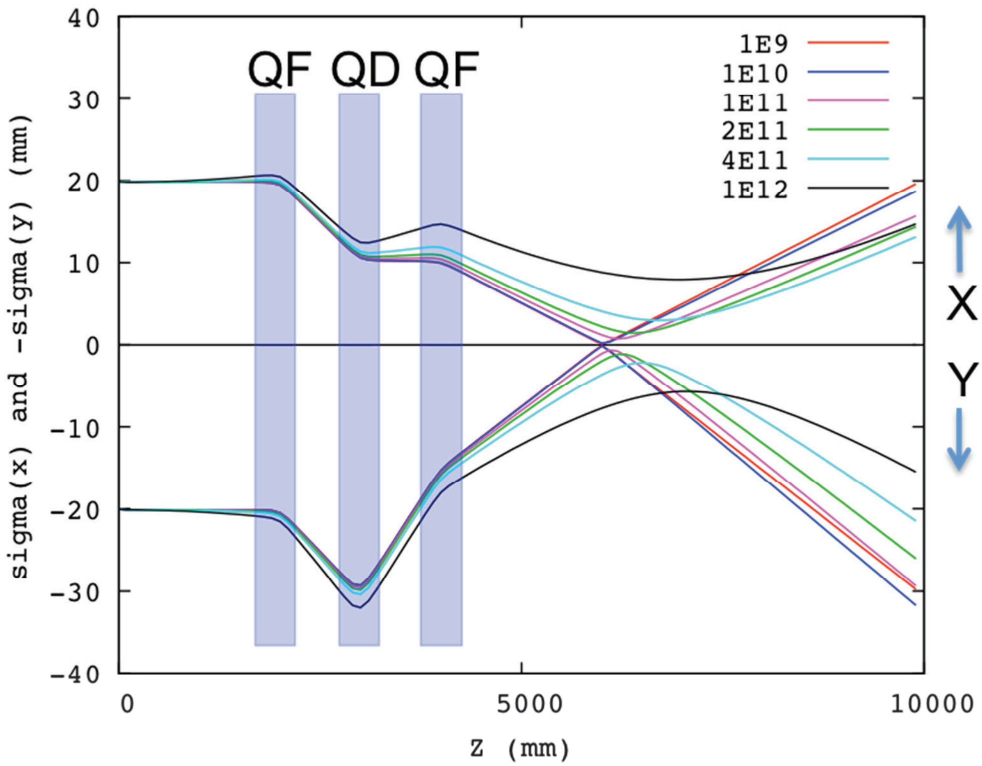

Figure 2: The effect of total bunch charge on a quad triplet focusing to a point at Z=6000. Particles are 200 MeV/c μ^+, initially in a parallel Gaussian bunch with $\sigma_x=\sigma_y=\sigma_z=20$ mm. Bunches smaller than 1E9 are indistinguishable from it.

SPACE CHARGE

The G4beamline space charge computation uses FFTs for the efficient convolution of the Green's function with the charge distribution on a grid in the beam rest frame; it can use up to about 1 million macro-particles. Boundary conditions are infinite open space. This includes radical revisions to the code of the Geant4 RunManager and EventManager to track particles in parallel for steps in time (not in space), preserving the ability to model all decays and interactions. Fig. 1 (above) presents a comparison of G4beamline's space charge computation to a calculation in Reiser's textbook [4], showing how increasing the number of macro-particles in the bunch makes the simulation approach the value for a truly continuous distribution. That computation uses no external fields; Fig. 2 (above) shows the effect of the total bunch charge on a quad triplet focusing to a point.

SPIN TRACKING

By simply setting a parameter of the *physics* command, G4beamline will use the Geant4 processes for tracking the polarizations of electrons and muons, including the decay of pions to polarized muons and the decay of polarized muons to electrons and neutrinos. Figure 3 shows the polarization precession of a single μ^+ in a magnetic field.

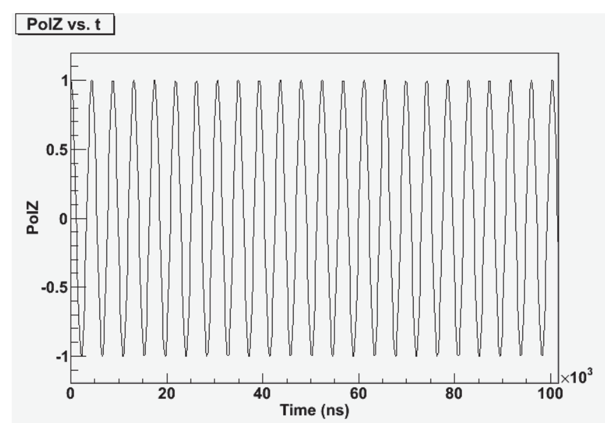

Figure 3: The polarization of a 3.094 GeV/c μ^+ precesses correctly in a 1.4513 Tesla magnetic field.

NEUTRINO INTERACTIONS

Geant4 does not implement the interactions of neutrinos, so an external Monte-Carlo program, Genie [3], was selected to provide this functionality for G4beamline. Once installed, the interface to Genie provides a G4beamline command, *neutrino*, which handles all the details. The Genie cross-sections are used to determine the neutrino interaction length, which is multiplied by a large factor to improve statistics (this factor is also used in weighting the tracks); the user specifies the desired interaction length to the *neutrino* command, which determines the factor for each track based on its neutrino flavor and energy. When a neutrino interacts, Genie is

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again used to model the interaction. The secondaries from the interaction are tracked as usual in G4beamline, including any outgoing neutrino(s).

This code is intended for various background and radiation studies; it has been used to model the interaction rates in various combinations of detectors and neutrino factory designs. It has also shown that the neutrino interaction rates in the detector of a muon collider can be as high as one per crossing – a muon collider is also a neutrino factory on steroids, with thousands of events per second in the collider detectors.

PHYSICS PROCESS RE-WEIGHTING

The *reweightprocess* command will modify the cross-section and weight of any discrete Geant4 physics process. This permits the user to concentrate CPU time on events of interest. By using weighted histograms, the correct distributions are given, and with proper use their variance can be significantly reduced for a given run time. This also permits the efficient study of rare physics processes, and of small but important backgrounds.

BETHE-HEITLER MU-PAIRS

A parameter of the *physics* command enables the Geant4 process $\gamma \rightarrow \mu^+\mu^-$ (in the presence of nuclei). This is disabled by default, but can be an important background in some facilities and detectors.

SYNCHROTRON RADIATION

A parameter of the *physics* command enables the Geant4 process for synchrotron radiation of electrons; a separate parameter enables it for muons (experimental). This is disabled by default, but can be an important effect in some facilities. When combined with the collective tracking of the space charge computation, this ought to be able to model beamstrahlung at a collider intersection region.

NEW SOFTWARE FEATURES

The new build system for G4beamline is modeled after the new build system introduced in Geant4 release 9.5. It is entirely contained in a single file, the *configure* script, and includes building all non-system libraries and G4beamline itself. This is considerably more robust than the old system, and is also more efficient (the total build time on my machine was reduced from 60 to 30 minutes).

In Geant4 9.5, more data sets are required than in previous releases, which made including them in the G4beamline distribution problematical. So a new helper program, *g4bldata*, was written to assist users in downloading and installing these data sets. It presents the user with a graphical interface to select which datasets to download, with a brief description of each one (including when they are needed).

The new *fieldlines* command will draw the field lines of either the electric or the magnetic field. They are drawn in 3-D using any supported viewer, so the user can use the Open Inventor viewer to explore, rotate, and pan the system with the field lines.

The *material* command can now implement a filter for tracks; this is similar to the *particlefilter* command, except any element can use a material that filters. This is especially useful in a neutrino factory, where all magnets and beam pipes can be constructed of a material that kills all particles except neutrinos; the new neutrino interaction interface to Genie can then be used to model neutrino fluxes at far detectors, without wasting CPU time tracking other particles over large distances.

All visible objects can now be made fully or partially transparent by specifying the 4^{th} value in any color. This is especially useful when looking at field lines.

There are some new features that improve the ability to debug the program:

- The –debug flag to *configure* will compile the libraries and G4beamline in debug mode, making it easy to use debuggers such as gdb, ddd, or the VC++ debugger.
- Any fault or exception now generates a stack trace, which indicates the function in which execution was aborted.

SUMMARY

G4beamline continues to be under active development, with new features requested by users.

ACKNOWLEDGMENTS

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