Using Geant4-based Tools to Simulate a Proton Extraction and Transfer Line

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TRIUMF

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Geant4

- Geant4 is a software toolkit for tracking and simulation of particle interactions in matter, in a 3D geometry.
- It is object-oriented, scalable to very large and diverse applications, and allows the user to plug in new or modified simulation components without any modification to the Geant4 code itself.
- The code is written in C++ and implemented as a collection of class libraries in various categories. Some "glue" classes initiate and coordinate the simulation.
- Geant4 is a world-wide software collaboration: ~100 members, 47 institutions (including CERN, SLAC, KEK, Fermilab) in 20 countries.
- Wide user base: particle physics (LHC experiments), nuclear physics, medical physics (therapy, dosimetry, imaging), space agencies and space-based experiments, and accelerator physics (e.g. collider beam delivery systems and muon cooling studies).

Accelerator and Beamline Simulations

For studying losses, particle interactions in matter and their reaction products (secondary particles) are important for:

- Safety considerations
- Loss monitoring
- Radiation damage and activation
- Geant4 is a powerful tool for such studies, but in general it requires the user to provide C++ code for (at least):
 - Defining the geometry and the particle source
 - Choosing the physics processes (interactions) and models
 - Initializing the simulation and recording the relevant data.

Using Geant4 directly requires C++ knowledge and skills.

Hence, the development of high-level tools based on Geant4:

- GATE for medical physics and SPENVIS for space physics
- BDSIM and G4Beamline for accelerator physics
- No C++ required to use these programs!

"Acceptance" Criteria

	BDSIM	G4Beamline
Web site with downloads	\checkmark	\checkmark
Source code available		
User's Guide		
Examples	\checkmark	\checkmark
Version control	\checkmark	\checkmark

BDSIM in a nutshell

- Originated at RHUL c.2000, developed by G.Blair & colleagues. It provides a subset of Geant4 functionality suitable for beam lines.
- The main motivation was to study backgrounds and other issues in the Beam Delivery System of CLIC and later ILC.
- Most interesting features:
 - Uses MAD(X) syntax and basic beam line components.
 - Uses element transfer maps for tracking in vacuum. Geant4 tracking only starts when a particle enters matter.
 - Hence, very easy transition from optics and tracking codes.
- Drawbacks:
 - User-defined geometry elements and field maps are awkward.
 - Rectangular bends are not available. An RBEND element is documented but is silently converted to SBEND. The edgefocusing of rectangular bends is important for our beam line.
 - We decided to suspend work with BDSIM until rectangular bends are available (work in progress).

G4beamline in a nutshell

- Developed by Tom Roberts starting in 2002 at Illinois Inst.
 Tech. and continued at Muons Inc. since 2004.
- Contains a wide range of beam line components with detailed specification via named element parameters, and flexible specification of fields and field maps.
- Contains extensive data-collection and output facilities, including sensitive detector planes and volumes (phantom or inside real elements), beam profiles, particle traces.
- Built-in fitting capabilities allows element parameters to be tuned for beam behaviour (via a goal expression).
- … and more.

G4beamline in a nutshell (cont'd.)

• Nice features:

- Shell-like input language with macro definition, parameter substitution, expression evaluation, looping, and conditionals.
- Input parameters can be defined or overridden on the command line that runs the program. Very nice for experimenting.
- Provides "escape" to the Geant4 command interface: useful for visualization, diagnostic output, and many other things.
- Short wish-list:
 - A conversion tool for a MAD-style beam line definition would be very useful.
 - The reference path must be defined as piecewise-linear (no arcs). Hence the coordinates inside a dipole or its fringe field, in the plane of bending, are not useful for comparison with other codes.

Visualization options

- Geant4 provides a myriad of 3D visualization drivers, both file-based and interactive.
- Examples using OpenInventor viewer (via Coin3d implementation): BDSIM
 G4Beamline



Beam line 2A



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- Supplies 500 MeV protons from the TRIUMF cyclotron to ISOL targets providing rare isotope beams for the ISAC and ISAC II facilities.
- The B3 Y-magnet switches among two "identical" lines to the targets. We model one branch with B3 treated as a simple bend in our model.
- Provides reliable and stable beam at 70µA but:
 - Difficult to tune: tight doublets and triplets, weak focusing in long straight section.
 - Performance-limited by continuous beam spill, as indicated by monitors at 38m, 45m and 56m, and by radiation damage on flange seals.
 - Losses are not well understood. It is not known whether tune modifications could reduce the losses.

Extraction from the TRIUMF cyclotron



Extracted beam characteristics



However, the vertical tune in the cyclotron cannot be predicted accurately and the betatron phase at the foil is not accurate.

Hence we use another method to generate the Y-Py coordinates at the foil.

Optical model

The beam optics code TRANSOPTR has been used (Baartman & Rao PAC09) to develop a model of BL2A fitted to profile measurements. This provides:

> •A best fit of a parameterized model of the cyclotron fringe field, via the exit angle from the cyclotron magnet.

•The beam sigma-matrix at the foil.

Two beam generators are used:

- 1. COMA for X-Px and P (total momentum)
- 2. ACCSIM (another simulation program) for Y-Py according to TRANSOPTR fitted ellipse.

The beam data are merged and a consistent Pz is derived.





Modelling the cyclotron field and edge angle

G4Beamline has rectangular (edge angle = $\frac{1}{2}$ bend angle) and sector bends. It does not allow an arbitrary edge angle to be specified. To simulate the exit edge angle, we used a rectangular bend and worked out its displacement and rotation by "dead reckoning".

In the time available we were unable to obtain horizontal and vertical edge focusing consistent with the optical model (and hence with measurements).

The G4Beamline fringe-field treatment uses Enge functions and is difficult to match with the simple edge-matrix approach of the optical model.

Altering the fringe field depth, or any other adjustments, requires lengthy manual retuning.

This problem needs further study.



Pre-Tracking with ACCSIM

Interim solution: use another simulation code ACCSIM to track the beam through the foil and through the cyclotron to the beam line entrance.

- Advantage:
 - ACCSIM's edge focusing in the cyclotron field can be easily matched to TRANSOPTR.
- Disadvantages:
 - Treatment of extraction foil (multiple scattering, energy loss, nuclear interactions) is less advanced than Geant4.
 - Geant4 can produce secondary particles and more extremely scattered protons, however most of these would not survive the first arc.

Simulation with ACCSIM front-end

The COMA+ACCSIM+G4Beamline solution was used to track 100000 particles through the line and RMS beam sizes were determined at frequent intervals.

This scheme yields beam sizes that conform well to to the optical model (with *identical quad settings*) and with measurements (within ~1mm).



Role of extraction foil scattering

- When the foil was introduced in G4Beamline (or in Accsim pretracking) no losses due to foil scattering were observed. In Accsim the multiple scattering distribution is known to cut off at ~3mrad for a 5mg foil.
- Using a single-scattering model in ACCSIM we investigated the distribution of large-angle coulomb scattering. For statistics of 10^6 protons the halo of θ > 3mrad comprises a fraction 4.2×10^{-4} of the incident protons, with an average of ~125 scatters per proton traversal.

Forcing the single-scatter model, we used ACCSIM to generate a "halo beam" for tracking in G4Beamline.



3mrad Halo tracking

- Tracking the halo in G4Beamline reveals proton losses of 35%, or a fraction of 1.4x10⁻⁵ of the total beam. For 70µA operating current, this is near the measurable spill rate of 1nA.
- Most of the non-accepted halo is cleaned in the first 12m, but about 1% of the halo survives until ~45m where it is lost in the next 7m (Q13/14 region). This region is of interest due to downstream radiation damage observed on flange seal near final arc and somewhat elevated spill monitor readings at 56m.







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Conclusions

- With input methods similar to those of beam optics and tracking codes, BDSIM and G4Beamline can be used to construct 3D simulation models of a beam line, with a comprehensive treatment of particle interactions in matter.
- The programs greatly ease the process of developing a full-fledged Geant4 simulation, without any need for C++ programming.
- In G4Beamline we were able to validate the model against measured beam envelopes and to investigate beam loss characteristics.
- We observed a baseline loss rate due to foil scattering of ~1.4x10⁻⁵ of the total beam intensity for a 5mg foil. The G4Beamline model will be used to explore other possible loss mechanisms, such as field and alignment errors.
- These programs are significant achievements in bringing the power of Geant4 to accelerator and beam line studies.