G4 ACCELERATOR APPLICATIONS

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This paper will review GEANT4 applications and extensions for accelerator studies, both as a general framework and for the simulation of specific accelerators. G4Beamline is a Geant4-based program intended to easily simulate many different aspects of beam-line design. G4Beamline implements accelerator components via an object-oriented ASCII input format. For instance, it allows the definition of a quadrupole magnet by its physical geometry, materials, and also magnetic field (including several models for fringe fields).

The Muon Ionization Cooling Experiment (MICE) poses some challenges for simulation not normally found in a particle physics experiment. The G4MICE package is under development to allow a complete simulation of the MICE cooling channel (including the simulation of magnetic and RF fields) and instrumentation.

BDSIM is a Geant4 based code that implements fast accelerator-style tracking for particles within the beam-pipe together with the full set of Geant4 physics processes for particles that leave the beam-pipe. The program has been used to simulate and optimize the design of proposed electron positron linear colliders (ILC and CLIC). The input to the code is based on the MAD format and allows definition of geometries, fields and materials. Geometry descriptions common to those used by the ILC detector groups have enabled

common studies of the interaction region, specification of the required collimation depths and optimization of the extraction lines.

1. Introduction

It has been common to separate the simulation and optimisation of an accelerator system from that of the detectors that use the supplied beam. Research and development towards future accelerator systems (the International Linear Collider and Neutrino Factory) has resulted in the development of Geant4-based software packages that provide tools to accurately simulate the accelerator system as well as the detectors. These software tools can be used for some of the design and optimization tasks normally performed by dedicated fast accelerator simulation packages, which typically have a minimal set of material description and physics processes. These tools can also be used to simulate the interaction and passage of the beam through the relevant detector system in the more conventional manner. The merging of these abilities to design, model and simulate a beamline and detector system in one consistent package can be particularly beneficial when there is a very strong coupling between the two.

2. G4Beamline

G4beamline [1] is a general-purpose simulation program based on the Geant4 [2] toolkit that is specifically optimized for the simulation of beam lines and other systems. By implementing a large repertoire of beamline elements it relieves the user of C^{++} programming, but permits the realistic simulation of many interesting systems. G4beamline is open source and easily extensible, and users can add their own elements when necessary, via C^{++} programming.

G4beamline uses a single ASCII input file to define all aspects of the simulation, including the geometry, beam definition, physics use-case, program control parameters, output NTuples, and visualisation. As it is inherently object oriented, and beam elements include both physical materials and electromagnetic fields, describing the system is usually a matter of selecting the objects to use, setting their parameters, and placing them into the beamline.

Geant4's exampleN02 consists of ~900 lines of C^{++} code; Figure 1 shows it described in 17 lines of G4beamline input. This enormous reduction in size and complexity is common, as unlike C^{++} code the G4beamline input is no more complex than the system being simulated. Note this includes visualisation using most visualisation drivers supported by Geant4, plus histograms using HistoScope [4]; additional histogram packages are planned.

G4beamline implements "centerline coordinates" that easily permit the use of bending magnets. Figure 2 shows the MICE muon beamline in G4beamline. As it is designed for flexibility, G4beamline has been used for simulating many different systems. An example is the helical cooling channel summarised in Figure 4. The meaning of "beamline" is quite flexible, and G4beamline includes a cosmic-ray "beam" used in the simulation of muon tomography of a shipping container shown in Figure 3.

```
# select physics use-case, define materials and beam
physics QGSP
material Pb A=207.19 Z=82 density=11.35
material Xe A=131.29 Z=54 density=0.005458
beam gaussian beamZ=-200 sigmaX=0 sigmaY=0 sigmaXp=0 sigmaYp=0 \
      meanMomentum=3000 sigmaP=0 particle=proton nEvents=5
# define elements of the simulation
box Target width=50 height=50 length=50 material=Pb color=1,0,0
virtualdetector Det1 width=480   height=480   length=100 material=Xe
virtualdetector Det2 width=1344 height=1344 length=100 material=Xe
virtualdetector Det3 width=2208 height=2208 length=100 material=Xe
virtualdetector Det4 width=3072 height=3072 length=100 material=Xe
virtualdetector Det5 width=3936 height=3936 length=100 material=Xe
# place elements into the simulation "World" volume (which expands)
place Target z=0
place Det1 z=800
place Det2 z=1600
place Det3 z=2400
place Det4 z=3200
place Det5 z=4000
```

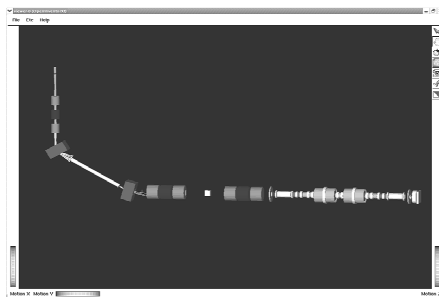Figure 1. ExampleN02 in G4beamline, units are mm and MeV.

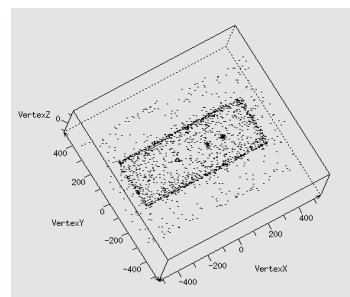Figure 2. The MICE Beamline, visualised using OpenInventor.

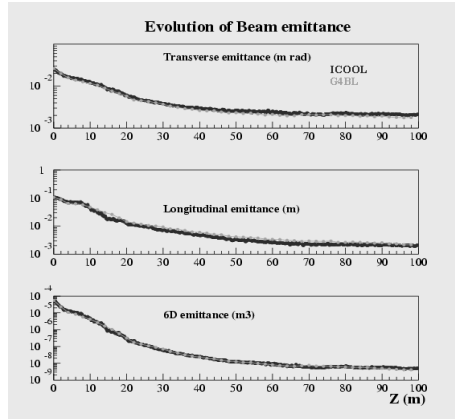Figure 3. Cosmic-Ray exposure of a shipping container.

Figure 4. Emittance reduction (cooling) along a helical cooling channel.

3. G4MICE

G4MICE is the Geant4-based software suite that provides Simulation,. Reconstruction and Analysis tools for the MICE experiment [3]. The MICE experiment requires the construction, operation and measurement of the performance of an ionisation cooling channel. The simulation of MICE therefore requires a combination of accelerator components (201 MHz RF cavities, liquid hydrogen absorbers, quadrupole triplets and solenoid magnets) and instrumentation (Scintillating Fibre tracker, Time of Flight and Cherenkov detectors and a Calorimeter), shown in Figure 5.

G4MICE provides an accurate model of the components of the downstream section of the muon beam line as well as the full cooling channel and instrumentation. Magnetic fields (including fringe fields) can be calculated directly from magnet currents (supplied as input parameters) or read in directly from an external file. An important aspect of particle tracking through the channel is the correct simulation of the time varying EM field associated with the 201 MHz RF cavities.

The simulation of the production of X-rays and electrons by the high accelerating gradient of the RF cavities has also been implemented and was crucial to the validation of the design of the tracking detector. The process of field emission from RF cavities has been studied with a high frequency cavity and the results extrapolated to the MICE cavities. The resulting extrapolation was used to create a spectrum of particles at the RF cavities which are then propagated through the experiment by GEANT4. Figure 6 shows the shower of
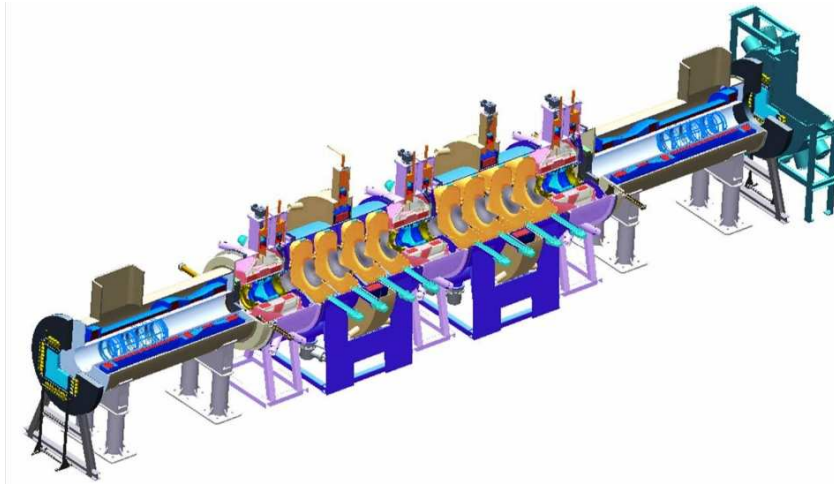
Figure 5: Muon Ionisation Cooling Experiment (MICE). Instrumentation and cooling channel comprising eight 201 MHZ RF cavities and three Liquid Hydrogen absorbers.
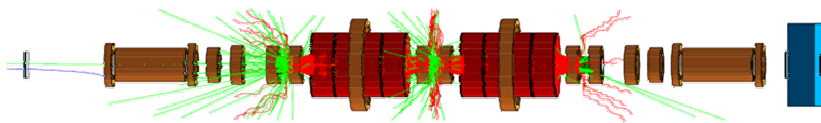

Figure 6: Visualisation of the passage of one muon through the MICE experiment with the production of X-rays and electrons by the RF cavities.

X-rays and electrons produced by two RF cavities overlaid with a single muon passing through the channel.

The simulation of the tracking and particle identification detectors in G4MICE is as detailed as can be reasonably achieved. An example is the scintillating fibre tracker model, which includes the active core and two layers of cladding for each fibre. Each fibre is explicitly represented and is contained inside a layer of glue and supported by a carbon fibre frame. The digitisation parameters have been taken from previous experience and updated in light of the results of test-beam experience as part of the ongoing research and development efforts for the experiment.

G4MICE has been used to simulate the performance of the full experiment with a realistic set of accelerator components and a range of input beams. Ten

different beams (each matched to the cooling channel and of a given transverse emittance) were simulated passing through the experiment. The digitised events were reconstructed and analysed using one potential analysis technique under study. The results show the expected performance of a transverse cooling channel and are summarised in Figure 7.
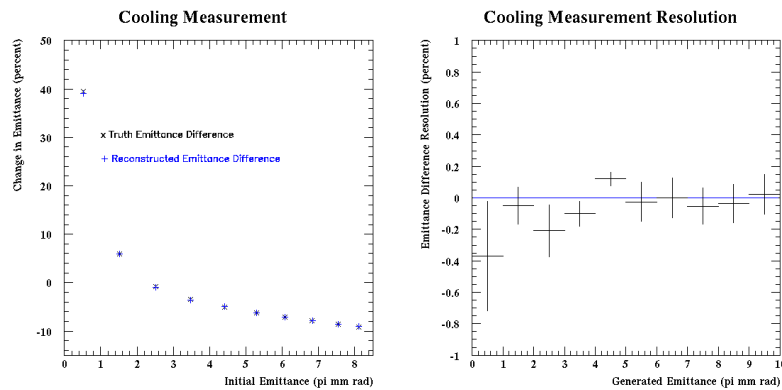

Figure 7: Left: The reconstructed (+) and simulated (x) change in emittance as a function of the input beam emittance. Cold beams are seen to be heated (positive change) and hot beams are seen to be cooled (negative change). Right: The difference between the reconstructed and simulated change in emittance is plotted as a function of the input beam emittance.

4. BDSIM

BDSIM is a Geant4-based program created originally to simulate the beam delivery system (BDS) of the International Linear Collider (ILC), with early application to the CLIC [5]. However BDSIM is designed flexibly in order to track particles through any beam-line and includes particle interactions and production of secondary particles in materials. The accelerator input to the program is controlled by a file that is based on the MAD format, but also includes additional descriptions of geometries, apertures and materials [6]. The code is maintained under CVS and is available freely [7].

Inside the beam-pipe a new approach is adopted. Rather than track the particles using a locally defined magnetic field strength, the approach more commonly adopted by accelerator tracking codes is followed, using an analytic solution to the equations of motion. By using the analytic solutions directly within a G4Stepper, a significant time saving is obtained over the more usual Geant approach of solving locally for each step in a magnetic field. In addition, an

interface to full field maps has been implemented for the specialised magnets such as are needed in the ILC interaction region and extraction line.

The accurate tracking performance was tested in detail as part of a comparison of a wider set of tracking codes [8] and showed that the BDSIM technique has comparable accuracy to other accelerator trackers. The magnitude of the step length is provided by Geant4 and depends on which processes are present. For most cases, the step length is equal to the length of the beam-line element because the particles are traveling in high vacuum. Scattered particles, or halo particles in outer positions of phase-space, can leave the beam-pipe; once outside the beam-pipe the tracking defaults to the usual Geant approach.

BDSIM naturally has access to all the impressive range of processes that are included in the Geant4 toolkit. These processes include multiple scattering off beam-gas particles or in detector elements and the usual electromagnetic shower processes such as electron-positron pair creation and bremsstrahlung. The beam-gas is specified by a normal Geant4 material with a pressure that can be defined by the user. Neutron generation from photo-production can also be included using the Geant4 photo-nuclear processes.

Synchrotron radiation (SR) from electrons in the magnet elements can be generated and tracked down the beam-line. An example is shown in Fig.8 (Left) where the subsequent absorption of the SR is obtained as a function of position in the CLIC BDS.
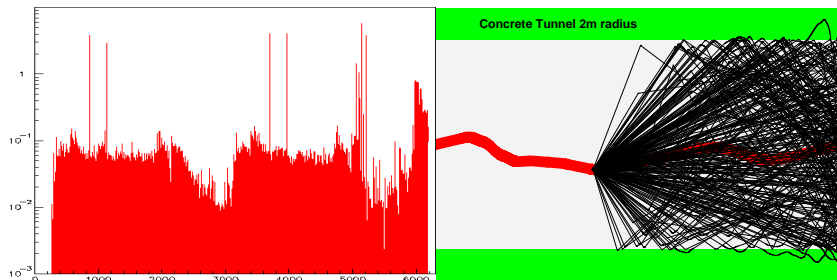

Figure 8: Left: The SR absorption in GeV/m as a function of length along the CLIC BDS showing impacts on limiting apertures such as collimators.
Right: muons created in electro-magnetic showers in the (TESLA) collimation system are transported down the tunnel to the interaction point (IP). Only the tracks of those muons that actually reach the IP are shown.

Additional processes can also be included as options. One example is tracking of beam halo and its collimation in the spoilers and absorbers of the ILC. The resultant generation of muons within electromagnetic showers in the collimation

sections, and the tracking of these muons down the accelerator tunnel, is illustrated in Fig.8 (Right).

BDSIM is particularly useful for the detailed design of accelerator components and layouts. A common interface has been set up with the ILC detector groups so that detector geometries can be included rapidly for performance studies and optimisation. An example is shown in Fig. 9 (Left) where the ILC interaction region has been modeled and is currently being studied [9] to quantify and minimise the backgrounds in the detector from reflection of SR off downstream components (Fig. 9,Right).
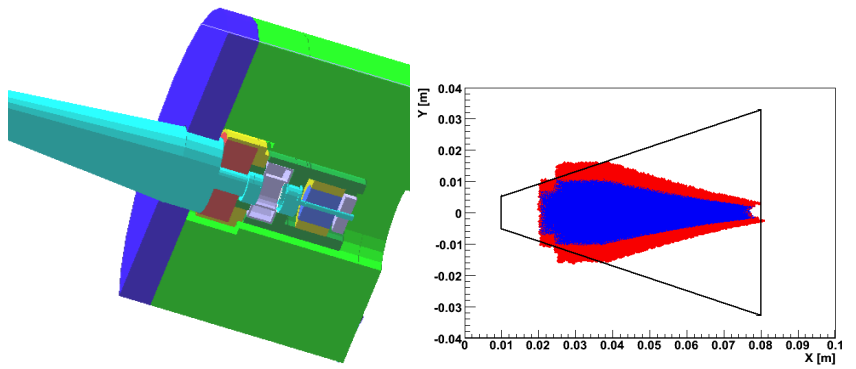

Figure 9. Left: The Interaction Region for one of the ILC detectors ("LDC") as modeled in BDSIM, the IP is beyond the left of the figure.
Right: The SR impinging on the first quadrupole downstream of the IP for various collimation depths; the black outline is the air-pocket of the quadrupole.

References

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