Detector Models for GlueX Monte Carlo Simulation: the CD2 Baseline

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Abstract

In preparation for the CD2 review in mid-2007, the GlueX collaboration has established a baseline conceptual design for each of the detector subsystems. This design is expressed in a collection of documents, one for each subsystem, which include a description of the material and dimensions of each detector component, the readout channel segmentation and channel identification scheme, and sufficient information regarding the detector response that a credible physics simulation can be constructed for it. Particular care has been taken to account for detector materials within the detector acceptance, including signal and high voltage cables, gas and cooling distribution systems, and support structures. The purpose of this document is to bring together in one place the parts of those descriptions which are relevant to the GlueX Geant simulation, and provide a reference for the studies that will serve as a basis for the CD2 review.

The report [1] from the GlueX detector review that took place in October 2004 contained seven recommendations, the first of which was stated as follows.

> The collaboration urgently needs to take a global perspective in making design choices. Most critically, this implies that they should start as soon as possible using full GEANT MC with (a) real detector material (structural material, electronics, cables, etc) in place, (b) primary hit generation, (c) reasonable representations of noise levels (occupancy) in detectors, and (d) event reconstruction and analysis, in order to assess combined performance of all detectors. This analysis should include both signal and hadronic background. Some of the GEANT infrastructure appears to exist but it has not propagated to the detector designers, and pattern recognition and reconstruction software need yet to be written. Even rudimentary versions of a complete simulation will be helpful.

In July 2005 the DOE held a project-wide *Lehman* review, which led eventually to the awarding of CD1 2006. In its section on the GlueX detector, the Lehman review report did not mention the simulation, although it does highlight the need for simulation in the section on CLAS12. It is interesting to note that *none of the seven recommendations* from the detector review are repeated in the Lehman review report, which concentrates instead on the readout of the barrel calorimeter, presumably because the reviewers were only interested in the bottom line. Nevertheless the report does explicitly mention the detector review, which makes the above quotation immediately relevant in the preparations for the CD2 review. Even if it did not, the GlueX collaboration has made it priority to advance the simulation and reconstruction software to the point where they can be used to justify the detector design choices that drive the CD2 baseline budget.

To accomplish this, a detailed description of a baseline configuration of the GlueX detector is needed. The description is contained in a multi-part xml document that is written according to the HDDS specification [2]. It consists of one main file, a materials file, a magnetic fields file, and 11 section files describing the beam line, the solenoid, the target, the start counter, the central drift chamber, the forward drift chambers, the Čerenkov counter, the forward time-of-flight counter, the barrel calorimeter, the forward calorimeter, and the upstream veto counter. A separate section of this document is devoted to each of these, with integration issues collected in a final section. Discussion of how backgrounds are treated in the simulation is provided in a final section.

This document serves to define the standard conditions for GlueX detector simulations that will be used to prepare for the CD2 review. It is a major revision to the previous state of the simulation model which has been relatively static for about two years [3]. Ongoing detector geometry and response modifications will be documented using the CD2 release as a reference until another major milestone is reached.

1 Event sources

The HDGeant simulation supports three event sources: the single-particle gun, the coherent bremsstrahlung photon beam, and an external physics event generator. The particle gun is used by default if neither of the other two sources are specified in the input file. Using the `KINE` command, the user specifies the desired particle type, direction and energy, and position of the track origin. As an alternative to specifying the direction, the user may opt to let Geant generate the particle direction randomly over 4π sr. The particle gun simulation mode is used most often for testing the simulation and for developing reconstruction code.

Two separate simulation modes are needed to treat events coming from the GlueX target because only about 0.5% of beam interactions in the target are hadronic in nature, and for these no comprehensive model of high-energy photonuclear reactions exists. To simulate hadronic interactions, events are generated at the level of four-vectors by an external Monte Carlo generator (eg. genr8), and these are used as a starting point for the HDGeant simulation running in the third mode mentioned above. In the second mode, a coherent bremsstrahlung Monte Carlo generator within HDGeant generates coherent bremsstrahlung events in the diamond crystal and then hands the generated gammas off to Geant to follow them through the collimator cave and experimental hall. Whereas mode 3 simulations begin with an interaction vertex in the GlueX target, mode 2 supports a realistic model of actual beam conditions, including conversions in the target and beam line elements upstream, and also in detector materials near the beam axis downstream of the target.

The main reason for supporting mode 2 in HDGeant is to simulate the electromagnetic backgrounds produced by the beam in the detector. The overwhelming dominance of electromagnetic over hadronic cross sections for photons (factor of 200) means that detector backgrounds are mostly electromagnetic. Geant running in mode 2 also produces hadronic beam interactions in the target, using the crude model contained in the Gelhad package (only single and double pion production), but their rate is relatively low. Beam hadronic interactions in mode 2 mainly occur in the bulk material surrounding the beam line, eg. the primary collimator. The few beam hadronic interactions that are produced in the target primarily involve low-energy photons in the beam with 1 GeV or less, where hadronic cross sections are larger and fluxes more intense than around 9 GeV. Even though their rates are relatively low, these so-called *minimum bias* hadronic interactions (ie. those that cannot produce a physics trigger but do make hits in the detector) can be a significant fraction of the total background in certain regions of the detector, and should not be completely ignored.

For studies of event reconstruction under realistic conditions it is actually interesting to consider how to combine simulation modes two and three. How this is done using HDGeant is described later in Sect. 14

2 Tagger

The electron beam is not a included in the HDGeant simulation. A separate Geant simulation program called *gxtwist* with its own xml geometry description and focal plane detector response package exists which covers the electron beam line from the radiator through the tagger to the electron beam dump. The gxtwist simulation was written to address questions related to the properties of the electron beam and the design of the tagger focal plane detectors. It would have been possible to combine the two geometries and perform a GlueX detector simulation starting from an electron in the electron beam. The software was not designed to do that because the two simulations address two distinct classes of questions, those that concern the photon beam (HDGeant) and those that concern the electron beam (gxtwist). For what concerns the photon beam properties (see the following section), the same Monte Carlo model is used to generate the photon spectrum in HDGeant as is used to simulate bremsstrahlung inside the diamond crystal in gxtwist. The remote location of the tagger hall and the shielding on the photon beam line are sufficient to ensure that what takes place in the tagger hall and what happens in Hall D are only correlated through beam photons that pass through the collimator.

Because there is no tagger in HDGeant, there are no tagger hits produced during simulation. This means that tagger hits need to be added artificially if the reconstruction software is to be fully exercised. The simulation produces a tagger hit consisting of one time value for each beam photon within the event gate, with a channel number corresponding to the energy bin of the tagger hit. Only hits within the energy range of the tagger microscope are reported. Events produced in simulation mode 2 mostly have no tagger hits, except if the beam photon happened to fall within the microscope energy range, in which case a single hit appears with $t = 0$. In simulation mode 3, each event is assigned a single tagger hit corresponding to the total energy of the event (assuming that it is within the microscope energy range) with $t = 0$. If background generation is enabled in mode 3 then accidental tagger hits are also produced, with non-zero t values. For more details about how accidental tagger hits are generated, see Sect. 14 below.

The tagger hit information found in the HDGeant output event stream identifies the tagger channels by their central photon energy. There are 100 tagger channels covering the range 8.20 – 9.10 GeV with equal bins of 9 MeV each. Each tagger hit is reported with a mean channel energy and a hit time (ns). The hit time of the beam photon that is considered to have trigger the event is assigned $t = 0$. All other times are multiples of the 2 ns beam pulse period. At present no smearing of this time is applied. Tagger time smearing will be applied a separate post-simulation processing step.

One small weakness of the present Monte Carlo scheme is that the physics genr8 event generator is set up to produce all events in a run with a single unique photon beam energy, eg. 9 GeV. A future improvement might be to modify genr8 to accept a range for the beam energy, within which the generator might assume a uniform distribution, or perhaps even something resembling the post-collimation coherent bremsstrahlung spectrum, although that is not important because the spectrum can be easily adjusted after the fact using a weighting scheme. The point here is that the decision on the beam energy for each event must be made in the Monte Carlo generator. The simulation can only make use of the four-vectors that it is given.

3 Photon Beam

The coherent bremsstrahlung event source is a realistic model of the photon beam in Hall D. Events begin with a single bremsstrahlung photon emerging from the 50 m pipe that runs from the tagger hall to the collimator cave upstream of Hall D. The user requests this event source in the Geant input file using the `BEAM` card, which accepts two arguments in GeV. The first argument is the electron beam energy and the second is the energy of the primary coherent edge. The coherent bremsstrahlung source model in Geant configures the diamond radiator according to these parameters and generates photons with the full angle and energy spectrum of coherent bremsstrahlung, with a low energy cut-off currently set to 1% of the end-point. The cut-off is necessary because of the low-energy divergence of the bremsstrahlung spectrum.

The Geant simulation begins at the point where the photon exits from the vacuum pipe and enters the collimator cave. At this point the beam passes into air and within a few cm reaches the primary collimator. The primary collimator is a cylinder of tungsten 20 cm in diameter and 30 cm long, with a 3.4 mm diameter hole along the central axis. Immediately in front of the primary collimator is the pin-cushion detector [4] which monitors the alignment of the photon beam on the face of the collimator. The active segment of the collimator has a clearance hole of diameter 5 mm so that it can accommodate a range of primary collimator apertures. The simulation model of this detector is detailed down to the level of the individual pins. This detail is important in simulating its response, and does not impose appreciable overhead on the beam simulation.

The part of the beam that passes through the primary collimator then enters a dipole magnet that sweeps away charged particles in the beam. The sweeping magnet has a 4 cm gap which is filled with lead except for a square 4 × 4 cm^2 hole for the photon beam. Its magnetic field integral is 0.67 kG·m. Following the sweeping magnet is a piece of iron of cross section 50 × 50 cm^2 and 200 cm long, with a 2 × 2 cm^2 hole down the central axis. After this there is a block of concrete 200 × 200 cm^2 in size and 100 cm thick, with a 2 cm square hole through the center. Following this shielding stack is a second collimator, sweeping magnet, iron and concrete sequence. The second sequence is similar to the first, but with larger transverse dimensions. The secondary collimator is a cylinder of nickel 50 cm long and 20 cm in diameter, with a 5 mm diameter of 10 mm. The secondary sweeping magnet has a gap of 5 cm filled with lead, as before, with a square hole of dimensions 5 × 5 cm^2 for the photon beam. It has a similar field integral to the first one.

Up to this point the interaction rate of the photon beam with the collimator walls is high enough that evacuating the beam line makes little difference, but after the secondary collimator this is no longer true [5]. The beam re-enters vacuum through a Mylar window 500 μm thick at the entrance to the second sweeping magnet and remains in vacuum down to a few cm upstream of the UPV. The total length of this photon beam pipe is 908 cm and it is a cylinder 3 mm thick made of stainless steel, with an inner diameter of 4.4 cm.

After passing through the second sweeping magnet, the photon beam pipe goes through a second iron block of dimensions 100 × 100 × 100 cm^3, followed by a concrete wall of thickness 100 cm and transverse dimensions 400 × 250 cm^2. As it exits from the collimator cave, the beam pipe passes through a lead wall 15 cm thick that covers the full transverse dimensions of the cave (470 × 270 cm^2. The hole through the wall is circular, just large enough to contain the beam pipe. A second 100 μm Mylar foil terminates the vacuum pipe just upstream of the GlueX detector.

4 Solenoid

The solenoid is modeled as a solid iron cylinder extending over the full length from the upstream surface of the first coil to the downstream surface of the last coil. The total length of the solenoid cylinder is 377.80 cm, with an inner radius of 95.0 cm and an outer radius of 187.96 cm. There is an iron annulus at the upstream end of the solenoid of thickness 50.8 cm, inner radius 92.71 cm and outer radius 187.96 cm. At the downstream end of the solenoid is a second iron annulus of thickness 66.0 cm, inner radius 92.71 cm and outer radius 187.96 cm. The solenoid has no sensitive elements. No care was taken to make sure the outer radius reflects anything physical because it cannot affect the distribution of hits in any of the sensitive volumes.

Nothing in the simulation requires that the field be azimuthally symmetric, but currently it is. The field map was produced by Jlab engineer P. Brindza using the modeling program TOSCA in September, 2001. His TOSCA model includes the correct number and nominal positions of the LASS superconducting coils, with iron inserted between them, as well as the upstream and downstream annular plates. It does not include details that would break the azimuthal symmetry of the field, such as the vertical members of the spectrometer support structure or the rectangular outline of the lead glass support frame. Nevertheless it is a good representation of the field inside the region of the trackers and probably good enough to accurately measure the acceptance of downstream detectors like the Čerenkov and time-of-flight counters. The following details were supplied by P. Brindza when the field map was produced (9/2001).

> The solenoid model has all 17 superconducting coils and all the yoke modifications that I have proposed and that have been agreed to by the Hall D team as per the last collaboration meeting. The yoke also has the large hole on the upstream end that we discussed at the last meeting. I have added a 4 inch thick iron wall at Z = 280.75 inches to simulate the magnetic effect of the iron phototube frame for the lead glass detector. The physical end of the iron yoke is at 200.75 inches. The grid is on a one inch spacing because my model was done in inches. The XZ plane (Y=0) is a symmetry plane with a tangential fields boundary condition in the TOSCA model so By = 0.0000 in that plane. The X component is thus the same as an R component.

HDGeant reads the field map data from the file `solenoid.map` which contains the three components of the field sampled by TOSCA over a cylindrical grid in r, z. The original text file from which this map file was generated is also available as `dsolenoid.table` in the repository under the HDGeant project directory. The volume of the field map is a right cylinder of radius 40 inches (101.6 cm) extending from $z = 10.2$ cm to $z = 635$ cm in the standard detector coordinate system, in which the target center is at $z = 65$ cm and the front face of the forward calorimeter is around 620 cm. Azimuthal symmetry constrains the ϕ component of the field in the map to be zero at present, but this is not assumed by the simulation code that uses it. The field is interpolated over this grid using linear interpolation, and is set to zero outside the grid volume. The truncation at an outer radius of 101.6 cm may significantly distort the trajectories of charged particles that reach the outer limits of the acceptance of the Čerenkov and time-of-flight detectors. This is probably the most important defect of the field map in the current simulation.

5 Target

The structure of the target in the simulation changes substantially in this revision. The target consists of a liquid hydrogen cell with thin Kapton walls surrounded by a vacuum chamber comprised of a structural foam called ROHACELL. The elemental composition and density of ROHACELL foam has been entered in the hdds materials database. The details of the target design are given in Ref. [6]. The walls and ends of the hydrogen target container, specified as 127 μm of Kapton plus 15 μm of aluminum in Ref. [6], are replaced with are 155 μm of Kapton in the hdds geometry. The document does not give the properties of the entrance region to the target vacuum chamber. Since that is where the target plumbing is connected, there is substantially more material there than at the downstream end. The upstream cap of the target chamber is currently an aluminum plate 5 mm thick, with a 4 cm diameter hole in the center covered with a 70 μm aluminum foil in the center, similar to the downstream end.

Ref. [6] does not mention the target support arm. It is assumed that the target and start counter are supported on the same insertion arm, which is described in Sect. 6 below. The target assembly is positioned so that the axis of the target coincides with the symmetry axis of the solenoid, with the center of the liquid hydrogen cylinder located 65 cm downstream from the upstream surface of the first coil.

6 Start Counter

The start counter geometry is described in Ref. [7]. It consists of 24 planar scintillator segments which form a 24-sided polygonal cylinder 50 cm long that bends inward to form a 45 deg cone on the downstream end. The cone is formed by tapering the ends of the scintillators down to a point and then bending them inward. The bend is specified in Ref. [7] as having a bend radius of 50.8 mm. This approximated in the hdds geometry by two conical sections, the first 3.9 cm long with a half-angle of 22.5 deg, and the second 9.3 cm long with a 45 deg half-angle. This leaves a hole in the forward region for the unscattered beam of diameter 3.2 cm. The scintillator thickness is 2.15 mm.

The structural integrity of the start counter scintillators is provided by embedding them between two layers of ROHACELL. The inner layer of ROHACELL has the same density as the ROHACELL in the target vacuum vessel, and is 5.3 mm thick. It follows the inner contour of the scintillators. The outer ROHACELL layer is about 1/3 the density of the inner, and is 11 mm thick. A thickness of wrapping tape (cellulose) is added to bring the total thickness of the start counter package to 0.40 g/cm^2 at normal incidence, as specified in Ref. [6].

Ref. [7]does not specify how the start counter is supported. It is assumed that the target and the start counter are both supported on the same upstream insertion arm extending into the solenoid from a base support upstream of the UPV. The support is described as an aluminum tube of inner radius 9.5 cm (matches the start counter inner radius) and thickness 0.5 cm extending from the upstream end of the start counter active region to past the upstream face of the UPV. This cylinder is intended to account for the material in the cantilevered support arm and also for the plumbing connecting the target to its cyrostat. Wrapped around the aluminum tube is a plexiglas cylinder 1.32 cm thick that represents the light guides that connect the start counter scintillators to the phototubes located outside the magnetic field upstream of the UPV. The bend in the light guides where they couple to the phototubes and the PMT's themselves are far outside the acceptance of the detector and so are not described in hdds.

A start counter hit is produced each time a charged particle track deposits energy in one of the start counter paddles. Each hit reports a total energy and time relative to the primary interaction time. The energy value is the deposited energy corrected by an exponential attenuation factor $\exp{(z - z_0)/\lambda}$ with $\lambda = 150$ cm and z_0 representing the geometric center of the scintillator. The times are delayed by $(z - z_0)/c_{eff}$ with $c_{eff} = 15$ cm/ns. Two hits in the same paddle that occur within 25 ns of each other are combined by summing their energies and taking the energy-weighted mean of their times. The approach was taken because the majority by far of double hits take place within an interval of 1 ns or less, and in such a case the energy-weighted mean is a better model of what a constant-fraction discriminator would produce than simply taking the earlier of the two times. No statistical or electronic noise is added to the times or energies produced by the simulation. After all hits have been generated and multi-hits merged, only hits over 150 keV (1/3 minimum-ionizing deposition at normal incidence) are retained in the output record.

In addition to the hits recorded in the Monte Carlo output record, there are also so-called *truth* points which report unprocessed Monte Carlo track state data in the output stream that might be useful during the development and debugging of reconstruction code. Each time a track passes through a start counter paddle a truth point is recorded that reports the three coordinates of the mid-point of the track segment inside the scintillator material (space and time), the average dE/dx of ionization energy loss along the track segment, and the index of the track particle that generated it. A flag indicating whether the particle is a primary or secondary track is also reported.

7 Central Drift Chamber

The central drift chamber (CDC) geometry is described in Ref. [8]. It consists of 23 layers of individual straw tubes. The straws come in two lengths, short straws which are 175.0 cm long for the parallel layers and 176.0 cm long for the stereo layers. Parallel layers are those whose straws are oriented with their cylindrical axis parallel to the solenoid axis, whereas stereo layers are oriented such that the two ends of the straw are at the same radius but different azimuthal angles. The most simple description of the stereo layers is obtained by imagining a straw placed in the parallel orientation, with a axis of rotation passing through the solenoid symmetry axis at right angles and intersecting the straw at its geometric center. Rotating the straw about this axis by a small angle called the *stereo angle* defines the orientation for this layer. Layers 1-4 have zero stereo angle. Layers 5-6 has stereo angle $-6\,\text{deg}$ and layers 7-8 are at $+6\,\text{deg}$. Layers 9-13 are again zero, followed by 14-15 at $-6\,\text{deg}$ and 16-17 at $+6\,\text{deg}$. Remaining layers 18-23 are parallel. The radius and wire count of each layer have been chosen by the CDC designers such that the straws fill the circumference of each ring with minimal dead space between the straws. Azimuthal offsets have been chosen such that each layer has one straw centered at $\phi = 0$. For the stereo layers the reference place for defining the radius and azimuth of each wire is the chamber mid-plane.

Each straw is individually placed in the simulation geometry. The straws are composed of a Kapton tube of outer radius 0.80 cm and thickness 80 μm covered with a 5 μm layer of aluminum. This is replaced with a 110 μm thick Kapton straw tube wall in the hdds geometry. Along the axis of the tube is placed a tungsten cylinder of diameter 30 microns representing the wire. At the ends of the straws are placed solid cylindrical plugs 1.6 cm in diameter and 1 cm long. The upstream plug is made of aluminum, whereas the downstream plug is Delrin. The plugs are embedded in the aluminum support plates which are the main structural element of the CDC. The upstream support plate is 0.9 cm thick and the downstream 0.6 cm thick. Both plates have an outer diameter 0 120 cm and a circular hole of diameter 30 cm is removed from the center. The distance between the inner surfaces of the two plates is 175 cm. The inner cylindrical surface of the chamber is enclosed by an aluminum skin 600 μm thick. The outer surface is enclosed with a similar skin 2 mm thick. At present the space between the straws inside the chamber volume is filled with air. The chamber is placed inside the solenoid such that the downstream surface of the upstream end plate is 17.0 cm downstream of the upstream surface of the first solenoid coil.

Material has been added to the hdds geometry to account for the gas distribution system, electronics and cables. On the upstream chamber face, the hdds geometry contains a uniform disk 5 mm thick to account for high-voltage and signal cable connections. The disk is 5 mm thick and has a mixture of copper and organics that approximates the composition of electronic cables. The transverse profile of the disk matches that of the end plate. Outside the cable layer is a 3 mm layer of plexiglas with the same transverse profile that represents the gas plenum cover. A third disk composed of 3 mm of circuit board material FR-4 is added near the plexiglas cover to account for the preamplifier electronics. All of these disks lie in a region within 10 cm of the upstream plate. The downstream plate has a similar plexiglas plenum cover to the one on the upstream end. There are no cable connections on the downstream plate. A thin 1 mm layer of FR-4 circuit board was added to account for the resistor connections that enable charge-division readout.

A tapered cone of cable material starting at zero thickness at 15 cm radius and increasing to 3 cm thickness at 60 cm is placed upstream of the upstream end of the CDC to represent the electronic and gas connections. The cone tapers out in the upstream direction until it reaches a radius of 68 cm, where it forms a cylinder 3 cm thick that passes upstream through the hole in the mirror plate and then radially outward in the space between the mirror plate and the UPV. This material principally affects the performance of the UPV.

A CDC straw hit is produced each time a charged particle track deposits energy in the gas-filled interior of one of the straws. Each hit reports a total energy and avalanche time relative to the event reference time. The energy value is the deposited energy (GeV) produced by the simulation without any correction. The time of a hit is computed in the following way. First the approximate point-of-closest-approach of a track segment to the wire inside the straw is computed by averaging the track coordinates (space and time) at the points where it enters and exits the gas volume of an individual straw. The perpendicular distance of this point from the wire is computed and converted to a drift time by dividing by a constant drift speed of 2.2 cm/μs. The drift time is then added to the particle time-of-flight at the straw position produce a measured time for this hit. If two hits in a single straw appear within 250 ns of one another they are combined into one hit by summing their energies and taking the energy-weighted average of their times. After all hits have been generated and multi-hits merged, only hits with deposited energy over 1 KeV are retained in the output record. For comparison, the average energy loss for a minimum-ionizing pion in the present simulation chamber gas (85% Argon, 15% CO_2) is about 3 KeV/cm.

Each time a hit is produced by a track segment inside a straw, a truth point is also recorded. Truth points record the coordinates (space and time) of the mid-point of each track segment inside a straw, the computed distance of closest approach, the dE/dx and the index of the track that caused it. Truth points are not merged by the multi-hit merging algorithm.

8 Forward Drift Chambers

The forward drift chamber (FDC) geometry is described in Ref. [9]. It consists of four identical planar drift chamber packages. The first package is positioned just downstream of the CDC, with subsequent packages spaced out every 63 cm. Each package consists of six identical chambers placed in a variety of orientations. Each chamber exists as an independent self-contained tracking element, consisting of a single plane of parallel anode wires enclosed on either side by a plane of cathode strips running at ±45 deg with respect to the wire direction. Both anode and cathode planes have outer cylindrical boundaries at a radius of 53.6 cm. A central disk of diameter 7 cm is deadened to make it blind to the unscattered beam.

The region between $r = 53.6$ and $r = 60.0$ cm is filled with circuit board material FR-4 (like G-10 but non-flammable) representing the chamber planes support structure. Just outside the 60 cm radius is a cylinder 1.1 mm thick made of a plastic/silicon/FR-4 composite that represents the preamplifier boards. Material representing the signal and HV cables is placed in the region between the outer FDC boundary at 61 cm radius and the barrel calorimeter inner surface at 65 cm. Support rods between the chambers are also included. Ref. [9] contains a detailed prescription for how all of this is represented in hdds.

The six chambers in a package are oriented with an azimuthal offset that advances by 60 deg for each chamber, so that the first and fourth, second and fifth, and third and sixth have parallel wires and strips. The anode wire planes consist of 96 sense wires (20 μm diameter tungsten) and 97 field wires (100 μm diameter aluminum) placed alternately on a pitch of 0.558 cm, corresponding to a drift cell 1.116 cm wide. The tungsten wires comprise only 0.07% and the aluminum wires only 0.26% of the total material in the active region of the chambers. Because of these minuscule amounts, the wires are not explicitly included in the hdds geometry, but the FDC readout code takes into account their locations in computing the avalanche positions. Cathode planes are separated from their corresponding anode plane by 5.0 mm filled with chamber gas, currently the same Argon-CO_2 mixture as is used in the CDC.

The cathode planes are 50 μm of copper-coated Kapton mounted on a rigid backing composed of low-density ROHACELL (0.32 g/cm^3). The ROHACELL planes are 5 mm thick, with a circular hole 7 cm in diameter cut out of the middle to reduce the material in the path of the beam. On one side of the ROHACELL plane is glued the cathode plane and on the other is a ground plane consisting of 25 μm aluminized mylar. The glued plane is represented in hdds by adding an epoxy component into a composite material containing mylar or Kapton and copper in appropriate ratios, and adding 25 μm to the foil thickness. The total material seen by a charged particle traveling through the active region of all 4 FDC modules is 1.78 g/cm^2, except in the region of the beam where it is reduced to 1.04 g/cm^2, not including the air.

One FDC anode wire hit and several cathode strip hits are produced each time a charged particle track deposits energy in the gas-filled interior of one of the FDC anode planes. Separate hit information is generated for each anode wire and cathode strip, and multi-hit merging is performed on each channel before the hit information is written in the output record. The drift time in the FDC is computed by measuring the perpendicular distance between the point of closest approach of the track segment in the chamber gas to the nearest anode wire. If a track segment intersects more than one drift cell then multiple avalanches are created and read out by the simulation. The anode hit time is taken as the track time-of-flight at the anode plane plus the drift distance divided by drift velocity of 2.2 cm/μs. The hit energy is just the energy deposited in the gas volume in the simulation.

Each anode hit is used to generate seven cathode strip hits centered on the strip in each of the two adjacent cathode planes nearest to the position of the avalanche. The time value from the anode wire is copied to each of the cathode strips for each hit. However strips may have different times after multi-hit condensation has been applied. The energy value V_i of the cathode strip hits is computed according to the following formula,

$$V_i = \frac{1}{2} V_0 \left[\tanh(0.9\lambda_2(i)) - \tanh(0.9\lambda_1(i))\right]$$

where $\lambda_1(i) = (u_0(i) - u)/s$ and $\lambda_2 = (u_1(i) - u)/s$, u is the position of the avalanche in the strip coordinate, $u_0(i)$ and $u_1(i)$ are the lower and upper limits of strip i in the strip coordinate, and s is the anode-cathode plane separation distance. The strip coordinate refers to a position along the axis in the plane of the strips perpendicular to the strip direction. The total induced pulse height V_0 is obtained in the limit of one continuous cathode plane where $u_0 \to -\inf$ and $u_1 \to +\inf$. This prescription is derived from the Mathieson function for the case of pure Argon gas, and is scaled to correspond approximately to the height of the pulse maximum at the output of the chamber preamplifiers in units of mV. The usual multi-hit merging prescription is applied here as well prior to final event output, using a minimum two-hit resolution of 250 ns. Strips with less than 5 mV for their energy value are eliminated from the output, resulting in an average of five cathode strip hits per FDC anode hit. Anode hits must have at least 1 KeV of energy deposition to be included in the readout.

Each time a hit is produced by a track segment inside an anode plane, a truth point is also recorded.

Truth points record the coordinates (space and time) of the mid-point of each track segment inside a FDC tracker layer, the computed distance of closest approach of the track to an anode wire, the dE/dx and the index of the track that caused it. Truth points are not merged by the multi-hit merging algorithm.

9 Čerenkov Counter

The Čerenkov counter is described in Ref. [10]. The outer enclosure consists of a shell of 1 mm thick aluminum shaped like two stacked coaxial cylinders around a beam pipe. The first cylinder has an outer radius of 58.0 cm and extends 54.3 cm along the beam direction. The second section has an outer radius of 280.4 cm and extends a further 155.0 cm along the beam direction, for a total depth of 209.3 cm. The beam pipe is aluminum 1 mm thick with an inner radius radius 5.0 cm. It is currently filled with air, which could be replaced with helium if background rates in the forward region require it. The entrance window to the Čerenkov volume is a 40 μm thick Tedlar foil.

The interior volume of the Čerenkov counter is divided into 16 equal azimuthal sectors. Each sector contains two mirrors and a photomultiplier tube for the readout. The mirrors are represented in the hdds geometry as planar wedges. The inner set of mirrors form a 16-sided polygonal cone. The outer set lie similarly on a 16-sided polygonal cone, but only cover the central 50% of the azimuthal range in each sector. The details of this arrangement are described in Ref. [10]. The PMT's and mounting rails are represented by an annular ring of borosilicate glass. This description overestimates the amount of material represented by the PMT's, but this should not matter because it is outside the acceptance of the forward detectors.

A few simple changes have been incorporated into the hdds geometry relative to the simple prescription in Ref. [10]. The first change is the half-angle of the first mirror cone, which has been increased from the specified value of 37.3 deg to 62.5 deg. Before this change, none of the Čerenkov photons associated with tracks coming from the target would hit the second mirror. Care was taken when making this change to leave the upstream limit of the mirror wedges against the beam pipe and the downstream limit against the back wall of the gas volume. The thickness of the mirror backing material is unchanged at 5 mm. The second change is to square off the edges of the mirror and PMT volumes. This is easy to do in the hdds geometry description and makes the shapes more realistic for ease in interpreting event graphics displays.

If the `CKOV 1` directive appears in the HDGeant input file `control.in` then Čerenkov photons are generated by particles traveling through the freon gas. These photons are followed through the volume, reflecting from any mirrors in their path, and any photons reaching the PMT annulus are detected with the efficiency function of a bialkali photocathode. The current Čerenkov energy window is $1.0 - 5.0$ eV, but the efficiency curve limits the effective window to something closer to $2.0 - 4.5$ eV. The total detected photoelectrons in each sector is summed at the end of the event, and hits reported for any signal with 2 or more photoelectrons. If more than one hit occurs in a given channel within a 50 ns window, they are merged together into one hit. The Čerenkov simulation is of limited use at present because the mirror optics have not yet been optimized, but the functionality is present and will produce realistic estimates of the Čerenkov response once a realistic mirror geometry has been defined. Truth points in the Čerenkov counter report the coordinates (space and time) of the track at entry to the Čerenkov counter, as well as the particle momentum and energy at that point, and the index of the track that caused it. The recording of truth information at the entry point is different from the previous behavior. The change was made because but it produces results that are of more straight-forward use for PID studies.

10 Forward Time-of-Flight Counter

The forward time-of-flight (FTOF) counter is described in Ref. [11]. It consists of two layers of scintillator bars covering on a square area immediately in front of the forward calorimeter. Each bar is 258.0 cm long with a rectangular cross section of dimensions 6.0 cm × 2.54 cm. In each layer there is one short bar 126.0 cm in length on either side of the 12×12 cm^2 beam hole. The long bars are read out by a single phototube on each end. The short bars are read out only on one end. The bars are packed together without a gap between them in the simulation geometry. The bar numbering scheme from Ref. [11] was imported into the hdds geometry, and the hddm FTOF hits structures were changed to use the terms “bar” and “north/south” instead of the less clear “paddle” and “left/right” identifiers that were formerly used.

A hit is generated each time a charged track creates a track segment inside the sensitive scintillator volume of the FTOF counters. The hit energy is based on the ionization energy loss deposited by the charged particle, corrected for attenuation of light along the length of the bar using the exponential attenuation length 150 cm. The attenuation factor is normalized such that hits that occur at the geometric center of the bar receive a correction factor of unity. For bars with readout on both ends, the attenuation is applied separately to the two ends. The hit times are computed from the time-of-flight of the particle track at the mid-point of its track segment in the scintillator bar plus the propagation time of the light as it travels down the bar at an effective speed $c_{eff} = 15$ cm/ns. Multi-hit merging is performed on each end of each scintillator, using a minimum double-hit resolution of 25 ns. Energies must be greater than 800 keV in order to be included in the output record, a cut which is applied separately to each end of each bar. Truth points are recorded for each charged track passing through the scintillator, regardless of whether it produced one or two hits, or none. No statistical or electronic noise is added to the simulated hit data for the time-of-flight counter.

11 Forward Calorimeter

The forward calorimeter (FCal) is described in Ref. [12]. It consists of a square wall of 59 × 59 blocks. This is not intended to represent 3481 actual lead-glass blocks, but rather the rectangular outer limits of a quasi-circular array. The dimensions of the blocks are $4 \times 4 \times 45$ cm^3. Ref. [12] explains how the outer limits of the active region are determined: fill the entire plane with squares of area 4×4 cm^2 with one square centered on the origin, and then remove all squares whose distance from the origin to their center is greater than 120 cm. This leaves 2809 squares. Removing the central 3 × 3 blocks gives a total of 2800 active blocks. The outer radius of 120 cm corresponds roughly to the shadow cast by the downstream edge of the barrel calorimeter onto the back plane of the FCal, illuminated by a point source at the downstream end of the target. Blocks are identified by a row and column index. The row index starts with zero at the bottom and increases to 58 at the top. The column index starts with zero at the north end and increases to 58 at the south end of the calorimeter stack. The entrance plane of the calorimeter is moved to $z = 628.0$ cm in order to make a little more room for the FTOF.

For the sake of efficiency, the hdds geometry contains lead glass blocks over the entire 240×240 cm^2 surface, except for the central 12×12 cm^2 which is filled with air. However hits are generated only for the active blocks. This is a change from the previous behavior of the simulation, in which hits were being generated over the entire 3472 blocks in the square array. The magnetic field is switched off inside the lead glass in the simulation for the sake of efficiency, but it is present in the region upstream of the FCal. Each time a charged shower particle deposits energy in a FCal block, that energy is added to the hit list for that block. Multiple hits within a 75 ns time window for a single block are accumulated as a single pulse. The time of the pulse is recorded as the energy-weighted average of the accumulated hit times. Light attenuation inside the block is taken into account using an attenuation length of 100 cm. Hit times are also corrected for light propagation delays inside the block, computed using 15 cm/ns for the effective speed of light. Blocks receiving less than 30 MeV of energy are dropped from the hit list in the output record.

Truth information is stored for each neutral particle or charged track that enters the FCal, regardless of whether it produces a shower or not. Truth information includes the incident position time and momentum of the track at the point where it enters the FCal, as well as the track index and primary track flag.

12 Barrel Calorimeter

The barrel calorimeter (BCal) is described in Ref. [13]. It consists of a cylinder of inner radius 65.0 cm, and outer radius 90.0 cm with the back 2.54 cm occupied by an aluminum support bar. The length of the BCal is not specified in Ref. [13]. It was assumed to be unchanged at 390.0 cm. The material is a matrix of scintillating fibers embedded in lead and epoxy, which is represented in the simulation geometry as a homogeneous mixture of scintillator, lead, and epoxy, with a composition detailed in Ref. [13]. The microstructure of the lead/epoxy/fiber matrix is not described in the geometry for tracking efficiency reasons; the scale for details in the simulation is set by the segmentation of the readout. The ends of the calorimeter are divided into 48 equal azimuthal segments called modules. Each module is segmented radially into layers and azimuthally into sectors. Ref. [13] proposes two alternative light collection schemes, which differ in the segmentation of the final layers. The "non-uniform readout" choice has been implemented in the hdds geometry. That choice corresponds to 9 layers and 32 sectors per module, for a total of 1636 channels per end of the BCal.

The readout and electronics on the ends of the BCal modules has been implemented in the hdds geometry in the following way. The area of each sector is covered with a trapezoidal plexiglas light guide that tappers from the approximately square sector footprint on the end of the BCal module down to a square 1.3×1.3 cm^2 face that attaches to the SiPM module. The areal reduction factor is about 2.5 for the inner sectors, and 6 for the outer. The corresponding Winston cone heights of 5 cm and 10 cm were used to determine the length of the light guides, even though they have planar instead of parabolic surfaces. The SiPM modules with attached electronics and coolers are represented by a solid aluminum cube of dimension 2 cm that is attached to the end of the light guides.

A cylinder of thickness 3 cm has been added to represent the signal cables. On the upstream end, the cylinder flares outward to pass between the upstream mirror plate and the UPV. On the downstream end the cables pass outward between the end yoke of the solenoid and the Čerenkov counter. This material principally affects the UPV, because the downstream cables are hidden in the shadow of the BCal modules.

The simulation treats the entire active BCal volume as a sensitive material. As in the case of the

FCal, a hit is recorded each time a charged track deposits energy in a sector. The partial pulse height from each hit is propagated to the two ends of the module with an attenuation length of 150 cm, using 15 cm/s as the effective speed of light. Multiple hits within 50 ns are merged together, with times computed as the energy-weighted average hit time. The merging is done separately on the two ends of the module, so that the effects of pile-up in a realistic background environment are reproduced in the simulation. All end-hits over 10 MeV (after attenuation) are saved in the output record.

This model is able to describe accurately the mean shower response in the BCal but not the resolution that is limited primarily by sampling fluctuations. Energy and time smearing according to resolution functions determined using a microscopic simulation or beam test data must be applied to the simulation data prior to reconstruction in order for the Monte Carlo data to provide a realistic estimate for final BCal resolution.

Truth information is stored for each track that enters the BCal, regardless of whether it produces a shower or not. Truth information includes the incident position time and momentum of the track at the point where it enters the BCal, as well as the track index and primary track flag.

13 Upstream Veto Counter

The upstream veto counter (UPV) is described in Ref. [14]. It consists of a lead-scintillator sandwich calorimeter located upstream of the LASS spectrometer. It is contained within a rectangular box of transverse dimensions 240×240 cm^2 by 26.0 cm thick. A square hole exists in the center of the UPV with dimensions 25.5×25.5 cm^2 through which the target vessel is inserted. The downstream face of the UPV is 60.8 cm from the upstream face of the first coil, of which 50.8 cm is occupied by the upstream iron “mirror plate” leaving 10.0 cm of space for BCal connections, CDC cables and gas system tubing to enter at the solenoid volume at the upstream end.

The UPV sandwich structure consists of 18 layers of alternating lead and scintillator planes. Ordered from inside out (nearest the target to furthest) the first 12 layers of lead are 2.5 mm thick and the last 6 layers are 5.0 mm thick. Between each lead sheet is a plane of scintillator paddles 4.25 cm wide and 1.0 cm thick. Each plane contains 50 long paddles and 12 short ones, the short ones being cut off at in the middle by the beam hole. The long paddles are read out by photodetectors on both ends. The short paddles are modeled in the same way, assuming that the light from a paddle on one side of the beam hole is somehow coupled across the hole into the corresponding paddle on the other side. Such a scheme is plausible if the readout employs embedded wave-shifting fibers.

Hits are formed in the UPV essentially the same way as in the case of the BCal. Light propagating to either end of a paddle is attenuated using an attenuation length of 150 cm and a propagation delay given by $c_{eff} = 19$ cm/ns. A particle entering the UPV is grouped together with its secondaries in accumulating hits so that a single shower produces no more than one hit per readout channel. Hits merging is performed using a double-pulse resolution of 50 ns. A threshold of 5 MeV is applied to each end-hit when the final hit list is stored in the output record. Truth points record the position, time and momentum of particles at the point where they enter the UPV volume.

14 Backgrounds

In Sect. 1 above it was explained that HDGeant supports three event sources: the particle gun, the photon beam, and the external Monte Carlo generator. The photon beam is the source of interest to background studies. To run in mode 2, simply omit (or comment out) the line in *control.in* beginning with `INFILE` and make sure the `BEAM` line is enabled with the correct values for the electron beam energy and coherent edge energy (GeV) provided as its two arguments. Under standard collimation conditions, one photon in the beam within the tagged energy range of 8.4 – 9.0 GeV reaches the GlueX target for every 125 events generated in mode 2. In other words, a mode 2 simulation consisting of 30 million triggers would represent 240,000 tagged photons on target, or 24 ms of beam at an intensity of 10^7 tagged γ/s. This simulation mode is most useful for estimating singles rates in detector elements.

As of November, 2006 the possibility also exists to inject background into the simulation of physics events (mode 3). This is done using two new directives in the *control.in* file called `BGRATE` and `BGGATE`. The `BGRATE` directive takes a single argument, which is the rate of beam photons (GHz) to add to the event. The `BGGATE` card takes two arguments, a start time and an end time (ns) for the interval during which beam photons might produce something that could be seen in one of the detector elements when that event is read out. In reality, the gate interval is differs for different detector systems, with the drift chambers being the slowest, but that is not a problem. The background gate should be set for the slowest detector element; the irrelevant hits will be suppressed during analysis because their hit times will not allow them to be matched to the reconstructed event. This mimics the real situation with a live beam. The present values for the background gate in the example *control.in* file in the repository are -200,200 ns which should fully cover anything that might produce a straw hit within a drift chamber gate of 0,200 ns. This might be reduced somewhat, once we know better what is the actual width of the drift time distribution.

The rate one should specify using the `BGRATE` directive depends on the running intensity of the experiment. It is found by multiplying the desired beam intensity in tagged γ/s by the factor 125. The same beam generator is used to generate background in mode 3 as is used to generate events in mode 2. The only difference is that several beam photons are superimposed on the physics event in mode 2, whereas each photon is a separate event in mode 2.

Simulating physics events with background is costly in terms of compute time. For example, a $\gamma p \to \rho^0 p$ simulation at 9 GeV requires 0.11 s/event on a Athlon MP 2800+ processor with `BGRATE 0`, but costs 0.55 s/event on the same processor with background turned on using 400 ns gate and a tagged intensity of 10^7 s^{-1}. The background overhead is the same regardless of the final state, so the overhead for more complex final states will be a smaller fraction of the total event processing time than this factor 5. A factor 3 may be a more typical value. Regardless of the cost, the capability of simulating events under realistic background conditions is essential.

Now for the first time we have the simulation tools we need to carry out the number one recommendation from the detector review, "full GEANT MC with (a) real detector material (structural material, electronics, cables, etc) in place, (b) primary hit generation, (c) reasonable representations of noise levels (occupancy) in detectors, and ... include both signal and hadronic background."

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