Detector Models for GlueX Monte Carlo Simulation: A Status Report

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June 8, 2006

Abstract

The physics Monte Carlo simulation of the GlueX detector is based upon an abstract model of the experimental geometry and fields expressed in the form of a hierarchy of xml documents. This geometry is converted to the internal representation of whatever simulation package is used in MC production (currently Geant3), which propagates tracks through the detector, generates hits in sensitive materials, and collects the hits at the end of each event into an output record. Representing the detector geometry in a form that is suitable for accurate and efficient simulation requires a model for each detector subsystem. Models have been assembled for each subsystem which satisfy the minimum requirements that they have the correct sensitive area coverage, the right amount and type of material at a level of detail better than the detector position resolution, and at least as much segmentation as required by the readout. This report provides a brief description of the models used for each subsystem, and describes how the detector response is simulated.

The GlueX geometry is described in a multi-part xml document consisting 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 Cerenkov counter, the forward time-of-flight counter, the barrel calorimeter, the forward calorimeter, and the upstream veto counter. The model for the beam line is the most detailed part of the geometry at present, but it is less relevant for detector performance and reconstruction studies and so is not considered further in this report. The remaining components in the list are covered in the following sections.

1 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 in making sure the outer radius reflects anything physical because it cannot have much effect on the distribution of hits in any of the sensitive volumes.

2 Target

The target is modeled as a tube within a tube. The outer tube represents the outer wall of the target vacuum chamber. The inner tube is an aluminum can filled with liquid hydrogen. The walls and ends of the can are 100 microns thick. The outer radius of the can is 2.5 cm and its outer length is 30 cm. The outer tube is made of beryllium with walls 1 mm thick. It is 9.5 cm in radius and 183 cm in length, starting upstream of the upstream veto counter and extending beyond the downstream end of the target can. The downstream end of the target vacuum chamber is a hemispherical dome of 1 mm beryllium. The entire assembly is positioned so that the axis of the target can coincides with the symmetry axis of the solenoid and with the center of the can located 65 cm downstream of the upstream surface of the first coil. There are no hits or truth information reported from the target.

3 Start counter

The start counter consists of 40 rectangular scintillator paddles 50 cm long and 1.58 cm wide, 2 mm thick. The long axis of the paddles are aligned with the target axis and the mid-line of the inner surface of the paddles are all 10.0 cm from the axis. The paddle width is about 100 microns larger than $2\,(10.0\sin(2\pi/80))$ so there is a bit of overlap between the counters at the inner edges at present. The Detector Review Design Report Fig. 4.55 shows the counters overlapped along their long edges like shingles on a roof, which has essentially the same effect as the (unphysical) overlaps in the Monte Carlo geometry. The text in the design report says that "the downstream side [end] of the scintillators will be bent toward the beam line in order to increase the solid angle coverage while minimizing multiple scattering." No such bent sections appear in Fig. 4.55, however, and none are present in the MC geometry. It is not trivial to imagine how the tapered ends of the scintillators must be cut and bent to maintain full single-thickness coverage in the conical region while being shingled in the cylindrical region. At present the Monte Carlo geometry has only a cylindrical section er, with no end cap, that ends 17.75 cm past the downstream end of the target. Note that the text of the Design Report calls for start counter scintillators to be 5 mm thick rather than the 2 mm that is currently in the simulation.

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 800 keV 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.

4 Central drift chamber

The central drift chamber (CDC) consists of 23 layers of individual straw tubes. The straws come in two lengths, short straws which are 200.00 cm long for the longitudinal layers and 201.10 cm long for the stereo layers. Longitudinal 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 longitudinal 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 $-6\,\mathrm{deg}$ and layers 7-8 are at $+6\,\mathrm{deg}$. Layers 9-13 are again zero, followed by 14-15 at $-6\,\mathrm{deg}$ and 16-17 at $+6\,\mathrm{deg}$. Remaining layers 18-23 are longitudinal. 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 straw are composed of an aluminum tube of outer radius 0.80 cm and thickness 80 microns. Along the axis of the tube is placed a tungsten cylinder of radius 30 microns (diameter 60 microns, might be an oversight) representing the wire. The ends of the straws pass through aluminum support plates. The upstream plate is 2.0 cm thick and the downstream late is 1.0 cm thick, both with inner radii 15.0 cm and outer radii 60.0 cm. The plates are solid except for where the straws punch through, replacing aluminum plate with tube, chamber gas and wire. The plates are placed such that the outer dimensions of the chamber are length 200.0 cm and diameter 120.0 cm, including support structures. The inner cylindrical surface of the chamber is enclosed by an aluminum skin 600 microns 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 upstream surface of the upstream end plate is 17.0 cm downstream of the upstream surface of the first solenoid coil.

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 time relative to the primary interaction 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 mid-point of a track segment 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. This mid-point is taken to be the point of closest approach to the wire. 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 22 μm/ns. The drift time is then added to the particle time-of-flight mentioned above to 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.

Although above treatment of the track mid-point as the point of closest approach to the wire works well most of the time, there are rare cases where it fails. One case is where the track passes through the wire itself. In such a case there are two track segments generated which get merged by the double-hit procedure into one hit with a drift time corresponding to the half-radius of the straw (instead of zero). Other cases occur when a track stops inside the straw volume or starts inside a straw due to some interaction which produces secondaries. The fact that the material represented by the gas is relatively thin compared with the straw tubes and surrounding support structure makes these effects relatively rare.

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.

5 Forward drift chambers

The forward drift chamber (FDC) tracker consists of four identical planar drift chamber packages. The first package is positioned just downstream of the CDC, with subsequent packages spaced out every 55 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 cylindrical boundaries at inner radii of 3.5 cm and outer radii of 61.0 cm. The region between $r = 60.0$ and $r = 61.0$ cm is filled with aluminum to represent the chamber support structure. No material is included at present to represent the high voltage distribution, preamps and cables. The inner hole of 7.0 cm diameter is filled with air, with cathode planes and wires terminating in thin air at that point. The lack of chamber material in the forward beam region is a major deficiency of the geometry at present.

Cathode planes are separated from their corresponding anode plane by 5.0 mm. A space of 1.0 cm separates adjacent chambers in a package. 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 cathode strip layers are represented by 59 microns of a copper and Kapton mixture in the ratio 11%,89% by weight, respectively. In comparison with this material, the anode wires do not represent a significant amount of additional material and so are not explicitly included in the geometrical description.

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 forward chambers. 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 mid-point of the track segment in the chamber gas and the nearest anode wire. 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 22 μm/ns. The hit energy is just the energy deposited in the gas volume in the simulation. In the present FDC model there is no case in which a track creates a signal in more than one adjacent anode wire cell, as must happen in a more realistic model for tracks far from normal incidence.

Each anode hit is used to generate eleven cathode strip hits centered on the strip on 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. 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 $u_0 \rightarrow -\inf$ and $u_1 \rightarrow +\inf$. 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.

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.

6 Cerenkov counter

The model for the Cerenkov counter in the GlueX geometry is essentially an empty box filled with freon gas. The outer surface of the enclosure consists of a shell of 1 mm thick aluminum shaped like two stacked coaxial cylinders around a beam pipe of radius 5.0 cm. The first cylinder has an outer radius of 58.0 cm and extends 54.0 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 only exception to the 1 mm thickness is the planar entrance surface where particles enter the Cerenkov gas volume after exiting from the last FDC package, where the Cerenkov wall is only 0.5 mm thick.

The entire interior volume of the Cerenkov counter is filled with a sensitive gas, currently nitrogen. It is divided into 16 equal azimuthal sectors. The velocity of a charged track passing through the Cerenkov volume is computed as the ratio of the momentum to the total energy of the particle averaged between its values at entrance and exit from the volume. Cerenkov radiation is generated using the standard Cerenkov formula with a refractive index of 1.0017 and a N_0 parameter of 60. At least two photoelectrons are required in a given sector in order to produce a hit. Cerenkov hit information includes an integer photoelectron count and a hit time. The same double-hit merging algorithm is applied to multiple hits in a Cerenkov sector as described above for CDC straws, except that a minimum double-hit resolution of 50 is used. Truth points in the Cerenkov counter report the coordinates (space and time) of the track mid-point in each Cerenkov sector, as well as the average particle momentum and energy, and the index of the track that caused it.

7 Forward time-of-flight counter

The forward time-of-flight detector (FTOF) 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 × 1.27 cm. In each layer there is one short bar 126.0 cm in length on either side of the 6×6 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 so that there is no dead space between them in the simulation geometry.

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.

8 Forward calorimeter

The forward calorimeter (FCal) consists of a square wall of 53 × 53 blocks. This is not intended to represent 2809 actual lead-glass blocks, but rather the rectangular outer limits of a quasi-circular array. The dimensions of the blocks are $4 \times 4 \times 42$ cm^3. A circular array of radius 106 cm would comprise approximately 2200 active blocks. The simulation generates hits in all of the blocks within the square array, even those that are outside the limits of the circular bounds. The unphysical blocks that appear in the corners of the FCal in the simulation are behind the shadow of the BCal and so do not have line-of-sight access to the target. Nevertheless there are occasionally events in which secondary gammas and charged particles deflected in the fringe field of the solenoid create showers showers in these blocks. It is the job of the dead-channels elimination step that filters the Monte Carlo hits list prior to reconstruction to eliminate hits corresponding to non-existent electronics channels.

Note that the current size of the FCal in the simulation is significantly smaller than the 2500 active block calorimeter described in the Detector Review Design Report. The increased size was required in order to eliminate a hole in the photon acceptance in the vicinity of 12 deg in lab polar angle. It has not yet been propagated into the production Monte Carlo geometry. A hole of 12×12 cm^2 (3×3 blocks) at the center is present to allow the unscattered photon beam to exit the back of the detector. The entrance surface of the FCal is located 622.8 cm downstream from the upstream surface of the first coil in the solenoid, 557.8 cm from the center of the target.

Producing individual hits for each changed particle track in the FCal, as was done in the sensitive detectors described above, is impractical owing to the large number of individual particles in an electromagnetic shower. Instead, when a particle enters the FCal through one of its exterior surfaces then that track and all of its descendants in the secondaries tree is tagged with a single shower identifier. At most one hit is created in each block for a single shower. The hit information for a block includes the total ionization energy loss of all tracks within the sensitive lead-glass volume of the block. In the case where more than one shower contributes energy to a given block, the result depends on the time difference between the two showers. If the showers occur within 75 ns of each other then the block energies are summed and the hit time is taken to be the energy-weighted average of the two shower times. If the showers are separated in time by more than 75 ns then two separate hits are produced in the output for the given block. Blocks receiving less than 30 MeV of energy are dropped from the hit list in the output record.

Truth information is stored for each 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.

9 Barrel calorimeter

The barrel calorimeter (BCal) consists of a cylinder of inner radius 65.0 cm, outer radius 90.0 cm, and length 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 lead (85% by mass) and plastic (15% by mass). The microstructure of the fibers is not described in the geometry because the readout is more coarse-grained. The segmentation of the readout begins with an azimuthal segmentation into identical 48 modules subtending 7.5 deg each in azimuth. The modules are read out by an array of photodetectors coupled to the fibers at either end. The following scheme is currently used to further segment the readout from the end of a single module. The module is divided radially into 12 layers, the first 8 of which are 1.875 cm thick and the last 4 of which are 2.5 cm thick. The inner 8 layers are further segmented into 4 equal azimuthal cells, and the 4 outer layers into 3. The total number of electronics channels in this scheme is 44 per module per end, for a total of 4224 channels.

The BCal simulation uses a similar shower identifier scheme as described above for the FCal to aggregate track segments from a single shower into a single hit per readout channel. The entire BCal volume is treated as a sensitive material, and the total ionization energy loss in a shower is summed in each readout cell to produce the hit energy. 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.

The deposited energy from each track segment in a particular BCal readout cell is corrected for attenuation at each end using an exponential attenuation length of 150 cm. The attenuation factor is normalized such that depositions that appear at the geometric center of a module have an attenuation factor of unity for both ends. For the hit time, the propagation delay for the light inside the fibers (15 cm/ns) is added to the time-of-flight and accumulated at each end using an energy-weighted algorithm. After all tracking has been completed for a given event, multi-hit merging is performed on all hits in a given readout channel that occurred within a minimum two-hit resolution window of 50 ns. All end-hits over 10 MeV are saved in the output record.

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.

10 Upstream veto counter

The upstream veto counter (UVC) is a lead-scintillator sandwich calorimeter located upstream of the CDC. 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 UVC with dimensions 25.5×25.5 cm^2 through which the target vessel is inserted. The downstream face of the UVC 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. There is currently no representation of this material in the simulation geometry.

The UVC 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 UVC 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 UVC 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 UVC volume.

This material is based upon work supported by the National Science Foundation under Grant No. 0072416.