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New Tools for the Simulation and Design of Calorimeters *

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New Tools for the Simulation and Design of Calorimeters*

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Abstract

Two new approaches to the simulation and design of large hermetic calorimeters are presented. Firstly the Shower Library scheme used in the fast generation of showers in the Monte Carlo of the calorimeter for the D-Zero experiment at the Fermilab Tevatron is described. Secondly a tool for the design of future calorimeters is described, which can be integrated with a computer aided design system to give engineering designers an immediate idea of the relative physics capabilities of different geometries.

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The large, expensive calorimeter designs that are likely to be at the heart of future SSC and LHC experiments will require detailed simulation and modelling, both as part of the design process whereby the geometry and features of the calorimeter are arrived at, and for the purposes of Monte Carlo simulation of the finished detector to understand the response of the calorimeter and its effect on physics signatures. This contribution is in two parts, describing techniques which address both issues. Firstly the shower library scheme used in the fast generation of showers in the Monte Carlo of the D-Zero calorimeter is described. This uses a database of hadronic and electromagnetic showers instead of fully tracking the shower secondaries. Secondly a tool is described for the design of future calorimeters. It is integrated with a computer-aided engineering and design system, and enables a fast estimation of the effect of uninstrumented material (supports etc.) to be made. The goal is to enable evaluation and optimization of designs for physics capabilities at the same time as they are evaluated and optimized structurally.

1. SHOWER LIBRARIES

The full simulation of hadronic showers, while necessary for realistic evaluation of calorimeter performance, is very time-consuming of computer resources. For example, a full simulation of a single QCD two-jet event using the D-Zero Monte Carlo (where the shower is generated using the GHEISHA shower code and tracked using GEANT[1]), can take several hours of computer time to run on a VAX-equivalent processor. It is clearly necessary to be able to generate events faster than this, and various approaches are possible. Typical is the UA1 parametrisation scheme whereby the energy deposition of the particle is parametrized in longitudinal and transverse dimensions[2] in terms of interaction and radiation lengths for hadronic and electromagnetic showers. The resulting Monte Carlo is very fast but this approach fails badly when there are large scale inhomogeneities in the showering medium. It is not clear how to extend the parametrization over calorimeter boundaries going across cryostats and air into a subsequent medium.

D-Zero has adopted a more conservative parametrisation, namely to parametrise only the electromagnetic particles when they fall below a cut-off energy (set to 200 MeV). This speeds up shower development considerably (a factor of 3–5 depending on event type) and the boundary problems for low momentum electromagnetic particles can be ignored. The speed up results from the large number of low energy electromagnetic particles present in both electromagnetic and hadronic induced showers. Detector inhomogeneities prevent the raising of the threshold energy in this method to gain greater speed.

Another idea to speed up event generation, used in the simulation of electromagnetic showers in BGO in the L3 experiment[3] and in lead-glass in OPAL[4], is to use a library of 'frozen showers' for low-energy electromagnetic depositions. The showers are generated by EGS Monte Carlo and copied into the event output as required when the shower reaches the threshold energy. These frozen showers also suffer from boundary problems, since one is never quite sure how to re-shape the shower to a region of the detector that is different from the one in which the shower was generated.

In D-Zero, it is planned to generate about 10,000 events through the full showering using a multi-node MicroVAX farm. This generation will take roughly 1 month of running after the parametrisation of EM showers below 200 MeV is employed. During the generation, the energy deposition in the calorimeter cells due to individual tracks is saved individually. The summing is done later after full calorimeter response corrections not contained in GEANT are introduced. The principle of the shower library is to store these showers in a random access database and re-use them for subsequent Monte Carlo runs with great increase in speed. The axial symmetry of the D-Zero detector aids us in generating fewer tracks than would be otherwise necessary. Boundary problems are totally absent in this method since tracks simulated in one rapidity range are used for the same rapidity range. This results in a minimum of computations after the shower is fetched. The idea described here is due to R. Raja[5], and the implementation has been made by the present author.

1.1 The D-Zero Detector

The D-Zero detector for the Fermilab proton-antiproton collider is currently under construction. The principal feature of the detector is the use of a very large uranium-liquid argon calorimeter surrounding the interaction point. The detector is shown in Figure **1**. The calorimeter is enclosed in three cryostat vessels — a central toroidal vessel which surrounds the central tracking system, and two endcaps. The calorimeter is divided into an electromagnetic section (four layers, 24 radiation lengths), a hadronic section (three or four layers, out to 4–5 interaction lengths) and a leakage section (one layer, a further 2 interaction lengths). The leakage section is made of copper and steel to save cost. Projective towers are employed. To lessen the deleterious effects on energy resolution of the thick cryostat walls, thin 'massless' liquid argon readout gaps are placed in both central and endcap vessels near the transition region, and a scintillator array is mounted in the space between the cryostats.

1.2 Library Features

When using the shower library, it is obviously impractical to have entries ready for retrieval corresponding to absolutely every possible incident momentum, rapidity and particle species. Some rescaling of energies and binning of phase space must therefore be accepted. The chosen solution for D-Zero has been to rely on the detector features to determine the bin size. Tracks are divided into electromagnetic and hadronic showers. The detector granularity being $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$, tracks are divided into 37 bins of pseudorapidity η (with $\Delta\eta = 0.1$ from 0 to 3.2, increasing therafter). There is no binning in ϕ or $\pm z$, the detector is assumed perfectly symmetric in these variables. Six bins of primary vertex position are used, for the ranges $z < -30$, $-30 < z < -15$, $-15 < z < 0$, $0 < z < 15$, $15 < z < 30$ and $z > 30$ cm (the Tevatron interaction point is spread in an approximately Gaussian distribution with $\sigma = 28$ cm). Tracks are binned according to incident momentum lying in the ranges: 100–320 MeV/c, 320 MeV/c – 1 GeV/c, 1–3.2, 3.2–10, 10–32, 32–100 and $p > 100$ GeV/c. Tracks with momenta less than 100 MeV/c are ignored entirely.

The library file uses the RZ keyed-access storage system of the Zebra memory management package[6]. This enables fast retrieval of the record corresponding to a particular bin. In the shower library, the retrieved record is a linear structure of Zebra banks, one for each stored shower. A random number determines which actual shower is chosen from the data structure to be used in event generation.

A certain space penalty must be paid for the convenience of RZ: a test library of 20k showers occupies about 50 Megabyte of VAX storage. This is perhaps one tenth of the size library that would be desirable for production running. We anticipate a dedicated disk which would contain the library.

For each shower, the information stored includes the four-momentum and particle type of the incident track, the energy deposited in uninstrumented material, the number of calorimeter tower hits stored, the calorimeter energy E_{miss} that was missed by using only the highest energy hits instead of all hits, an array of hit tower positions and a corresponding array of hit energies. The number of hits stored is restricted to some maximum in each detector, but if fewer hits encompass over 95% of the calorimeter energy for the detector then these only are stored. D-Zero currently uses maxima of 20 hits for the main calorimeter and 4 for each of the two massless gaps and scintillator.

1.3 Event Generation

When generating events, the particles are tracked normally by GEANT up to the start of the calorimetry, at which point the track is killed, and an entry is chosen at random from the library according to rapidity, energy and primary vertex position. The library shower is rotated in ϕ and/or flipped in z to match the track entering the calorimeter. The energy of each calorimeter hit is scaled by the ratio of the momentum of the incident track to that of the library entry track, so that the shower matches the new incident energy.

Table 1

Time to generate events using D-Zero GEANT, normalized to 1000 for two-jet events using full simulation.

Generation method	Minimum bias events	Two-jet events (p_T 120-160 GeV/c)
Full simulation	(not measured)	1000
Parametrize EM showers < 200 MeV	110	370
Shower library	2	5

The missing energy E_{miss} is dumped at the point where the track entered the calorimeter; in future we envisage an algorithm whereby it is sprinkled around the track direction in some appropriate manner. The energies are then smeared using the standard resolution smearing factors and copied into the calorimeter working common block.

The speed gains obtained by generating events by shower library compared to using GHEISHA are large, as shown in Table 1. Gains of 75 and 50 in speed over the parametrisation version of D-Zero GEANT were obtained for two-jet events with p_T 120–160 GeV/c, and for minimum bias events respectively.

Extensive investigations have not found any significant differences between the distributions of kinematic quantities (missing E_T, scalar E_T, x = 2(missing E_T^2)/(scalar E_T), etc.) for events generated using full simulation and those generated using the shower library. This is true both for minimum bias and for two-jet events. The shower library generated events also maintain the same degree of correlation between the calorimeter, dead material and massless gap energies as is seen in the full simulation events (see for example the plots presented in Ref. [5]).

1.4 Advantages and shortcomings of this technique

The shower library offers a way of generating events very much faster than full simulation. It handles fluctuations correctly (assuming that they were done properly in the events used to create the library) and avoids the problems with inhomogeneities that plague parametrisations. For a library that has roughly 1000 tracks per bin, one can expect to simulate jet-jet fluctuations that happen at the level of typically one part per million, if the fluctuations are due to two tracks each fluctuating at the level of one part per thousand.

Thus, this method enables us to go beyond the intial numbers used for generating the shower library.

On the negative side, the large library file must be written and stored. For an experiment such as D-Zero, or for SSC detector designs where the geometry is not yet fixed, this means that a run of full simulation events to compile a library is needed each time a substantial change is made to the geometry of the detector. In addition there are shortcomings introduced by the granularity of the library binning. The use of bins of 0.1 in η means that electromagnetic showers taken from the library may peak in the wrong cell of the third EM calorimeter layer, where the cell size is 0.05. This can however be corrected by re-distributing the third layer hits according the true position of the parent track. Tracks entering cells near cracks may also have problems, as the library entry is chosen without regard to whether its track come from near the center of a tower or from the crack region.

In general however, despite the problems listed above, the shower library simulates D-Zero events well, with a vast saving in generation time. It is planned to generate 100,000 events for D-Zero in the near future, using the shower library written from the 10,000 events generated with full simulation. The technique has obvious application to the generation of events for future detectors.

2. PARTICLE TRACKING IN ENGINEERING DESIGN SYSTEMS

A detailed simulation of the response of a proposed detector to particles is also a necessary part of the design process. This is particularly true in the case of calorimeters. At the SSC and LHC, large hermetic calorimeters are likely to be the most important component of each detector proposed or built. They provide the only way of measuring missing transverse energy, which will be an important signal for new processes, and enable electron identification by shower shape. Given this importance, it is crucial to understand the effects of features such as magnet coils and their supporting structures, tracking chamber components, liquid argon cryostats or warm-liquid vessels, and uninstrumented regions, on calorimeter resolution and response.

Traditionally, this task has been performed either by greatly simplified "back-of-the-envelope" calculations (with obvious attendant risks of an expensive blunder) or by painstakingly modelling the detector volumes and structures, using for example programs such as GEANT [1]. The problem with the latter approach is that it involves many man-months of effort to model a large hermetic detector. The physicists typically scale dimensions from engineering drawings. This results in a time lag of months or even years between the development of a design which is structurally sound, and its evaluation for physics potential. By the time problems are found, it may be too late to change the design. The location and thickness of a magnet coil, and the details of interfacing of liquid vessels in a liquid argon or warm-liquid calorimeter, are examples of situations where the timely avaliablility of simulation tools to understand the effects of uninstrumented ("dead") material is crucial.

When energy is deposited in dead material rather than in the live calorimeter, there are two effects. Firstly the mean response is reduced. This can relatively easily be corrected, using a calibration factor to multiply the observed energy. Fluctuations in the energy deposited in the dead material, however, result in a broadening of the energy resolution. This may be estimated as outlined below.

2.1 Estimation of Resolution Non-uniformites

The thicknesses (in interaction lengths λ and radiation lengths X_0) of each live and dead layer of material are evaluated using the computer-aided design, modelling and analysis system on which the geometry is being designed. Rays are traced from the interaction point over any desired range of azimuthal angles (at arbitrary intervals). Using rays effectively means setting the widths of showers to zero. This makes areas of bad resolution appear too narrow in pseudorapidity, but makes the actual value of resolution attained appear worse than it should. The area of a peak in a plot of resolution vs. pseiudorapidity is therefore roughly correct. A shower parametrization equivalent to that of Bock et al. [2] is then used to compute the average energy lost in each dead layer. The energy desposited as a function of distance through the detector, s, is as follows.

For electron induced showers:

$$dE = E\frac{x^{a-1}e^{-x}}{\Gamma(a)}dx$$

where $x = bs/X_0$, $a = 2.4215 + 0.4847\ln E$ and $b = 0.4250$.

For pion induced showers:

$$dE = E\left\{w\frac{y^{\alpha_E-1}e^{-y}}{\Gamma(\alpha_E)}dy + (1-w)\frac{z^{\alpha_H-1}e^{-z}}{\Gamma(\alpha_H)}dz\right\}$$

where $y = \beta_E(s-s_0)/X_0$, $z = \beta_H(s-s_0)/\lambda$, $\alpha_E = \alpha_H = 0.6165+0.3183\ln E$, $\beta_E = 0.2198$, $\beta_H = 0.9099 - 0.0237\ln E$, $w = 0.4634$, and s_0 is the coordinate of the start of the shower which is generated randomly according to $e^{-s_0/\lambda}$.

The energy resolution is then calculated using the ansatz that, provided the mean energy $\langle E_d\rangle$ deposited in a layer of dead material is small compared to the incident energy

E, E_d is distributed with a variance $\sigma_d^2 \sim \langle E_d \rangle^2$. The fluctuations of E_d lead to an increase in the fractional energy resolution $R = \sigma_E/E$, which becomes:

$$R = \left\{ R_0^2 + \Sigma_{\text{Dead layers}} \left(\frac{\langle E_d \rangle}{E} \right)^2 \right\}^{1/2}$$

where R_0 is the fractional resolution obtained without any dead material. The incoherent sum over dead layers assumes that the energies in the various dead parts of the detector are uncorrelated: this is reasonable if they are an interaction length or more apart. Leakage from the rear of the calorimeter is also included, as if it were just another dead layer.

The ansatz is not unreasonable, since $\sigma_d^2 = \langle E_d \rangle^2$ is rigorously true (in the limit of large multiplicity) for thin layers of material in an electromagnetic shower evolving according to a Furry distribution [8]. The major justification for the ansatz however lies in its success. The following situations have been tested:

— 50 GeV test beam electrons incident on a D-Zero central calorimeter electromagnetic module. If the first layer (2 X_0), or the first two layers (4 X_0) of the calorimeter are switched off, this technique successfully predicts the worsening of resolution, as indicated in fig. 2(a).

— 25 to 150 GeV test beam pions incident on a D-Zero end calorimeter hadronic module. If the first layer (1 λ), or the last layer (from 4 λ to 8 λ) of the calorimeter are switched off, this technique successfully predicts the worsening of resolution, as indicated in fig. 2(b).

— The effect of adding an aluminum dead layer upstream of a lead-liquid argon electromagnetic calorimeter module of the H1 experiment. This technique successfully reproduces an EGS calculation[7] of the worsening of resolution for 1–3 X_0 of aluminum, for electrons from 1 to 35 GeV, as indicated in fig. 3.

As an example of the usefulness of this algorithm, the implementation which has been made in the computer-aided design, modelling and analysis system used at Martin-Marietta Astronautics will be briefly described. It is being used in conjunction with their design study for a hermetic liquid argon calorimeter for the SSC (R&D project of M. Marx, H. Gordon and N. DiGiacomo). This work is still in progress and will be reported on fully later, but Fig. 4 shows a section through one quadrant of this calorimeter as the design stood at the time of writing. A detailed three-dimensional model of the design has been created, as shown in Fig. 5. Rays are traced through this model of the calorimeter, and resolutions are then calculated by a post-processor program according to the algorithm described earlier. Results such as those shown in Fig. 6 are obtained. In this implementation, it has been assumed that $R_0^2 = 0.16^2/E + 0.003^2$ for electromagnetic showers and $R_0^2 = 0.49^2/E + 0.02^2$ for hadronic, based on D-Zero test beam results [9]. (Other resolutions may of course be substituted.) Such curves have already proved useful in establishing that an 'endcap', rather than an 'endplug' or a hybrid design, would be pursued, and are an important tool in the ongoing work to refine and optimise the design.

In conclusion, the technique described can be integrated with CAE/CAD systems to estimate the effect of dead material on calorimeter resolution. This enables optimization of calorimeters for physics at the same time as they are being designed structurally. A great deal of time and duplicated effort may be saved by using this approach, and the ultimate design of calorimeter should be better. Extensions of the technique are can clearly be made: incorporation of the transverse development of showers, simulation of jets and full *pp* events, and estimation of missing transverse energy resolution are all possible enhancements.

Acknowledgments

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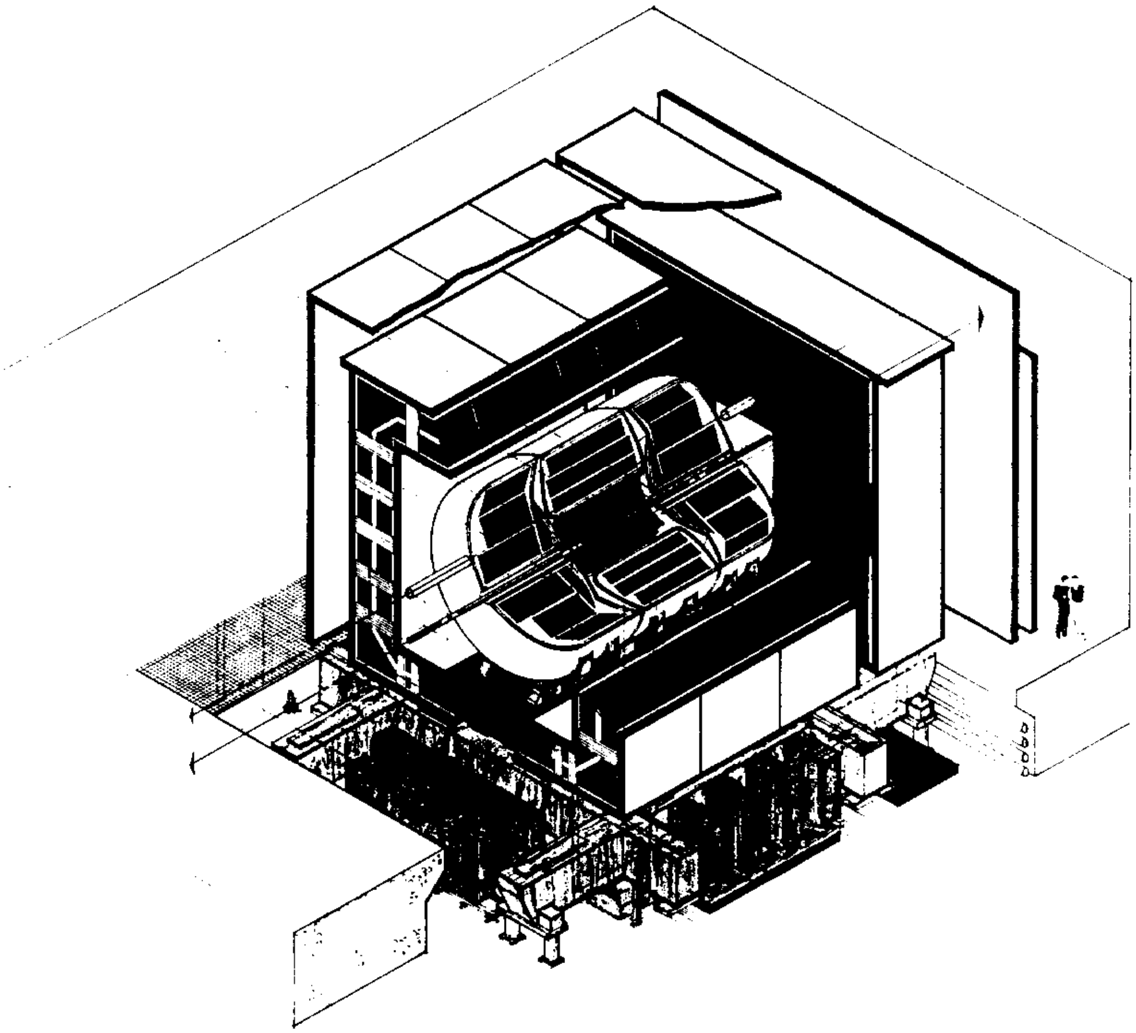

Figure 1

The D-Zero detector for the Fermilab Tevatron collider.

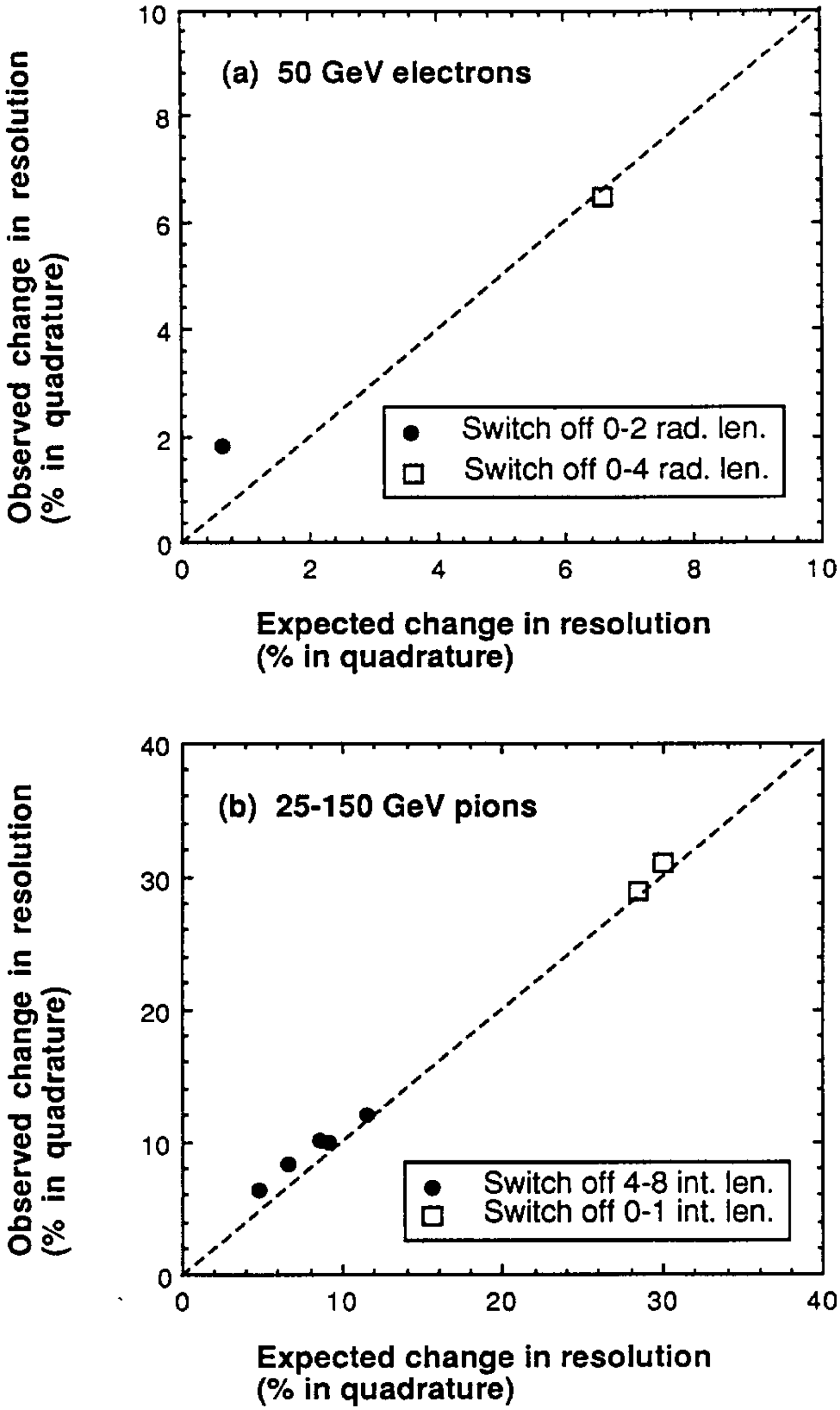

Figure 2

Comparison of predicted and observed effect of dead material on calorimeter resolution. (*a*) D-Zero central calorimeter EM module, using 50 GeV electrons and switching off the first layer (0 to 2 X_0) or two layers (0 to 4 X_0); and (*b*) D-Zero end calorimeter hadronic module, using pions from 25 to 150 GeV and switching off the first layer (0 to 1 λ), or the last layer (4 to 8 λ) of the calorimeter.

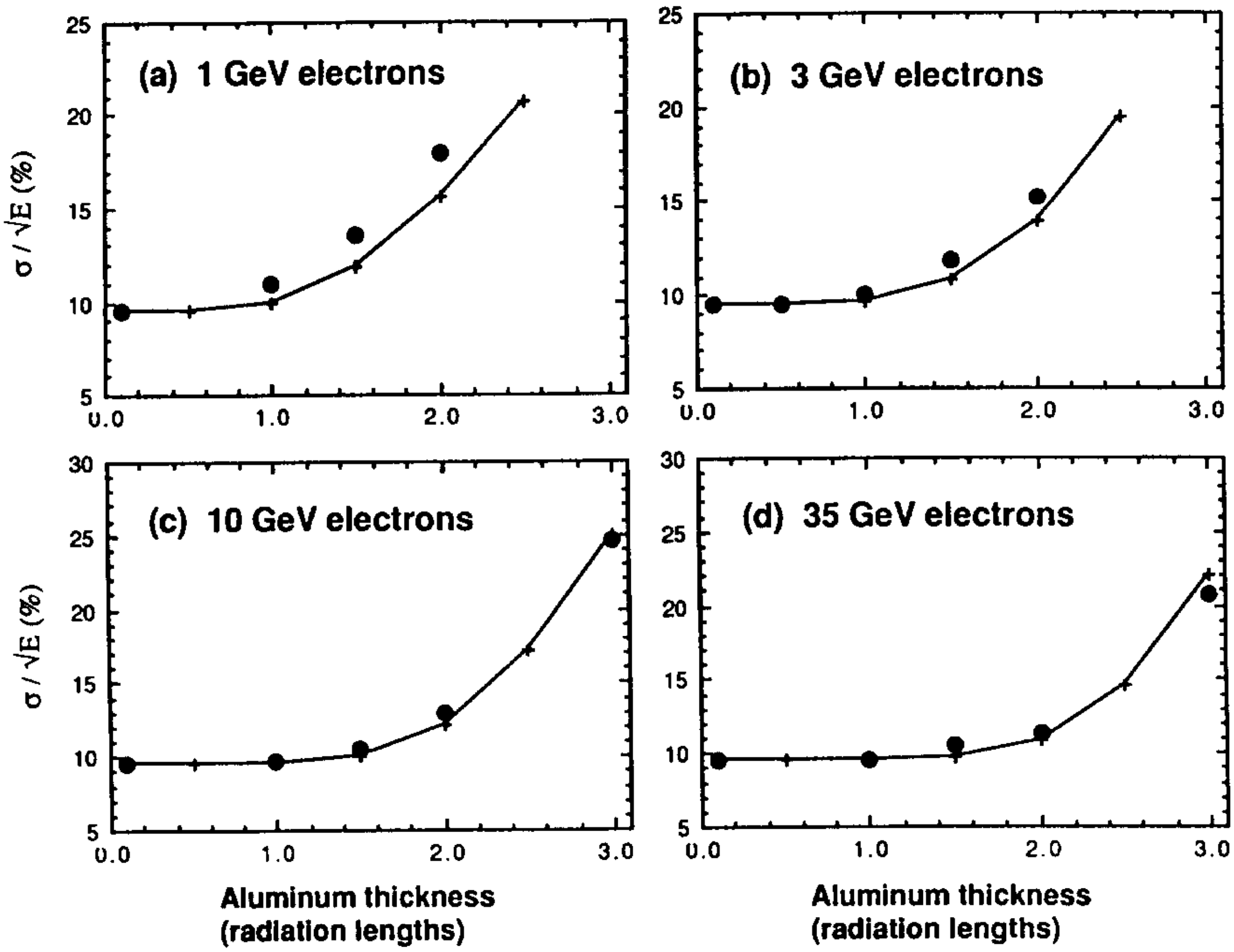

Figure 3

Effect of dead aluminum block upstream of the calorimeter on resolution, for H1 EM calorimeter [7] using electrons from 1 to 35 GeV and 1 to 3 X_0 of aluminum. The line shows the prediction of this technique, the data points that of a full EGS simulation.

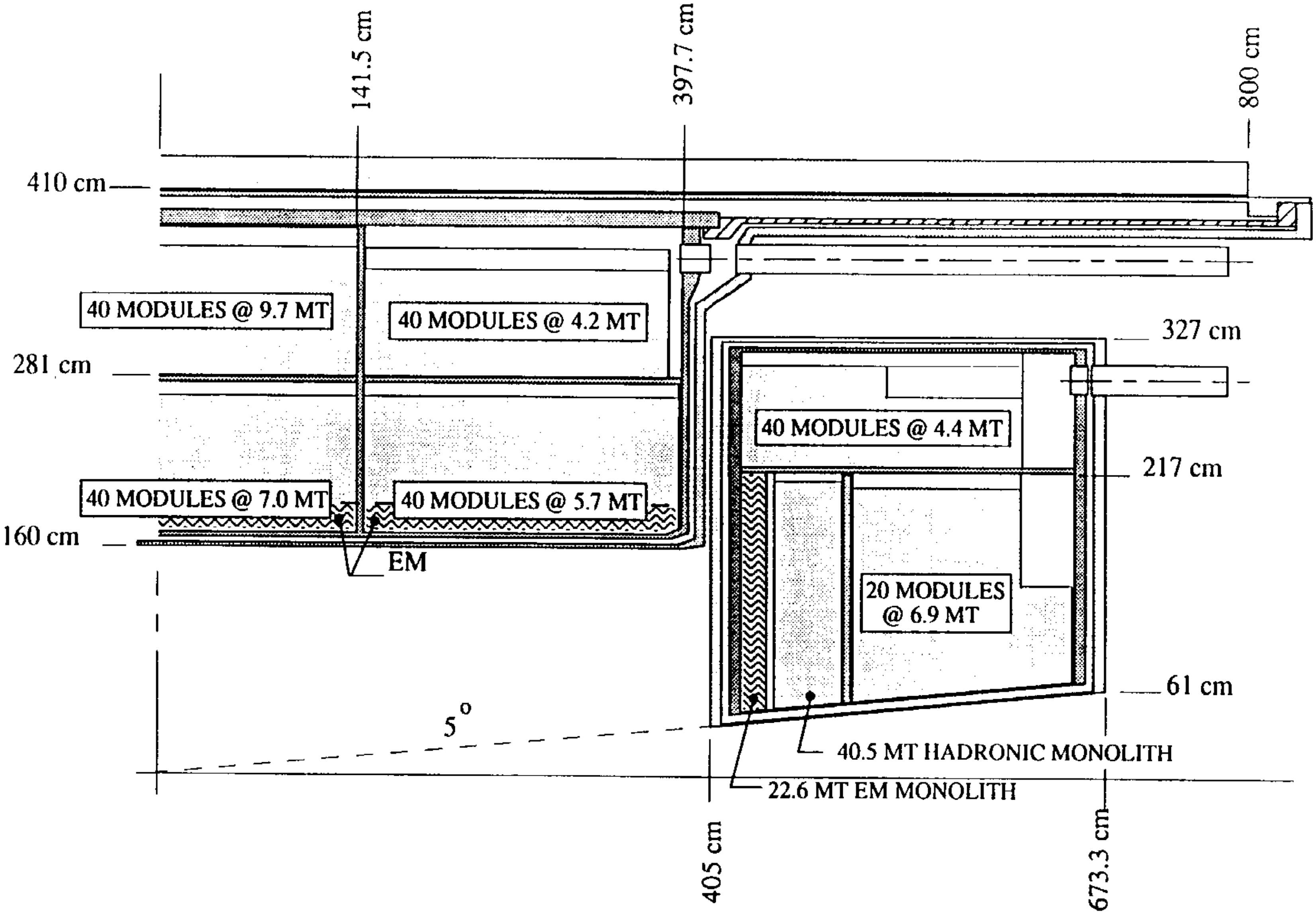

Figure 4

Cross section through one quadrant of the hermetic liquid argon calorimeter design for the SSC, developed at Martin-Marietta for M. Marx, H. Gordon and N. DiGiacomo. This work is still in progress, and the figure is only intended to be illustrative of the general appearance of the design at the time of writing.

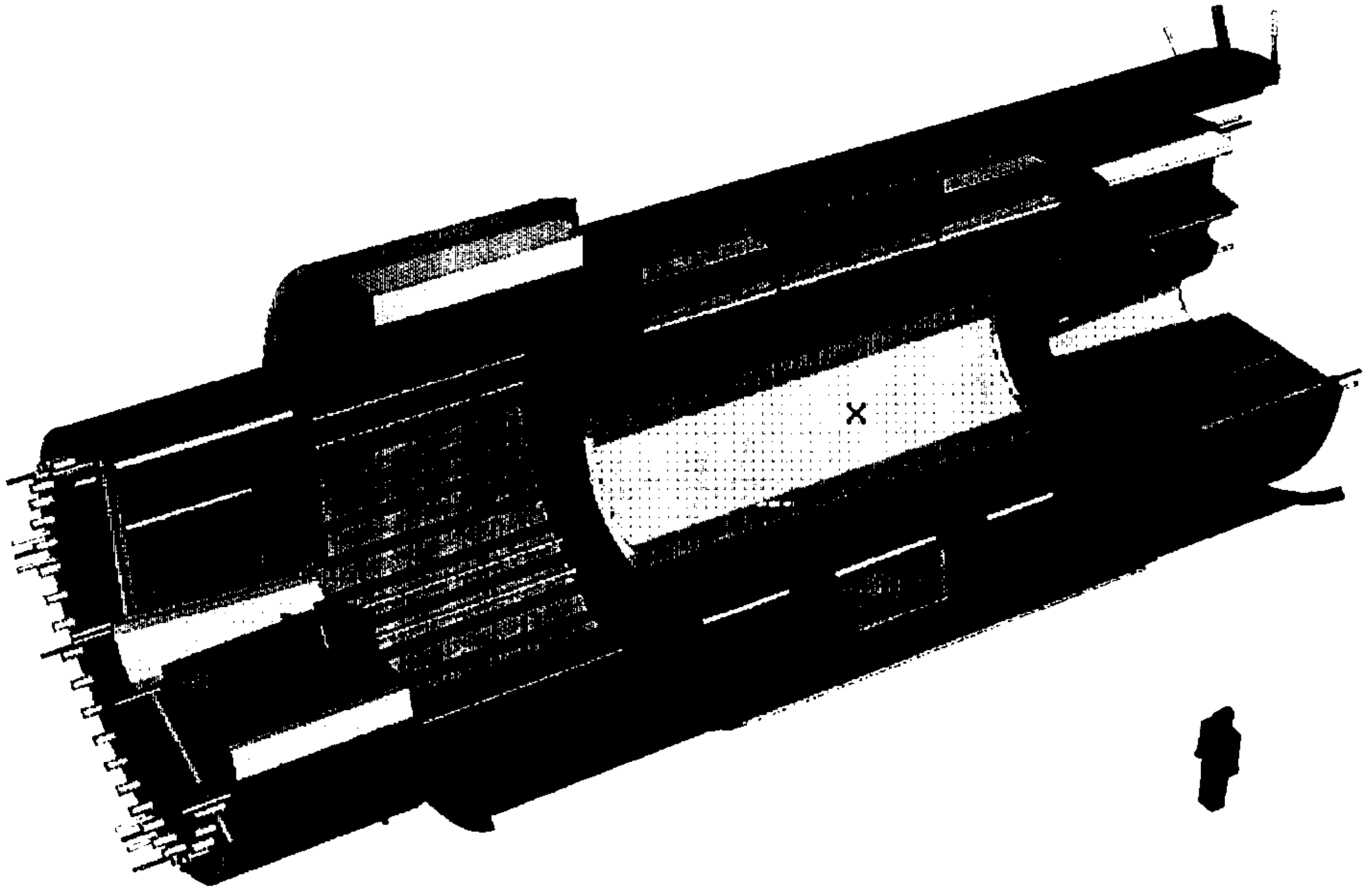

Figure 5

Perspective view of the three-dimensional model of the calorimeter design shown in Fig. 4.

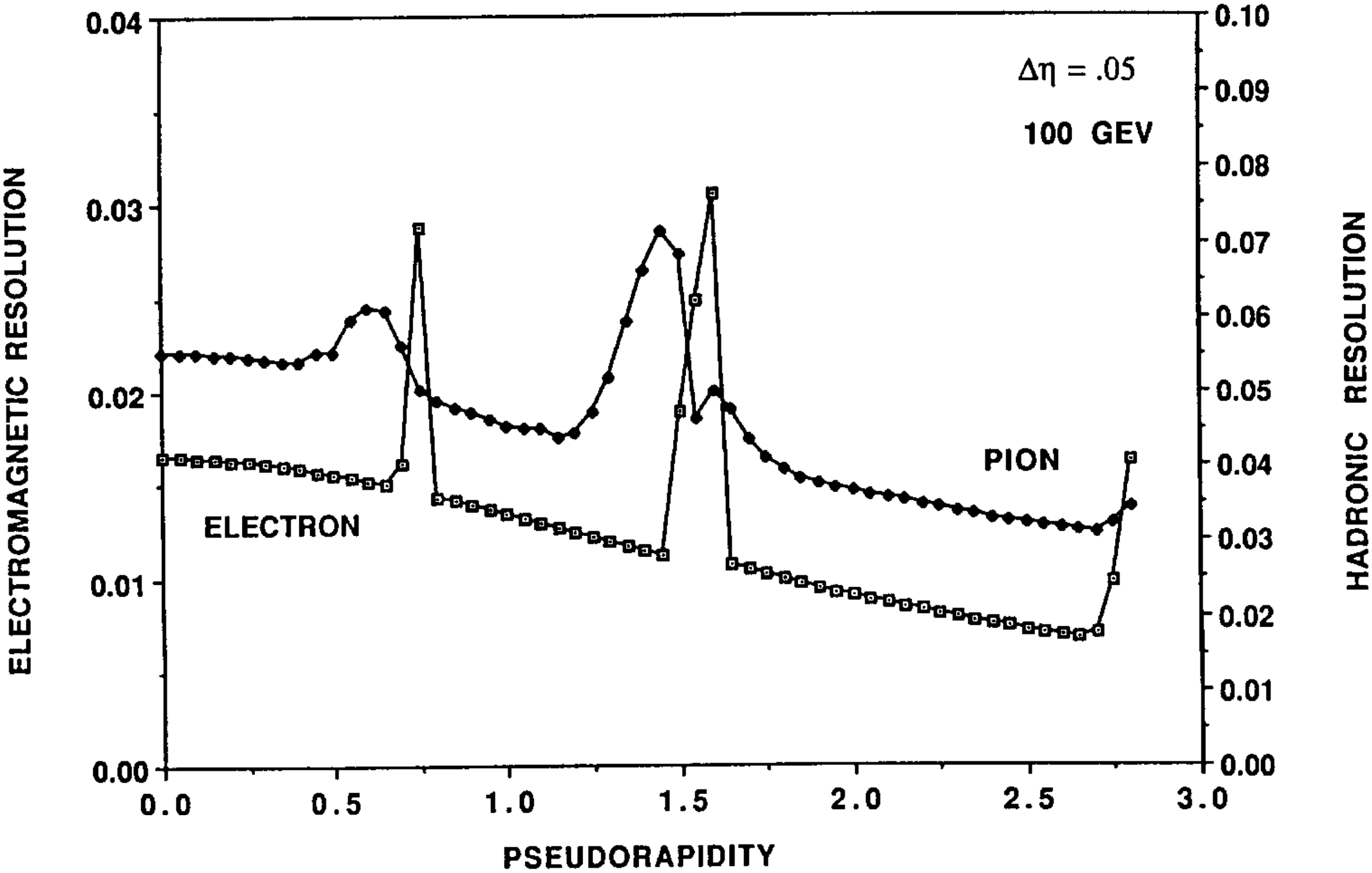

Figure 6

Resolution as a function of pseudorapidity, for pions and electrons at a transverse energy of 100 GeV, calculated for the calorimeter geometry shown in Fig. 4.