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Abstract

A scintillating optical fiber calorimeter (SOFCAL) is being developed by NASA/Marshall Space Flight Center for use in balloon-borne emulsion chambers to study the spectrum of high-energy cosmic rays and gamma rays. SOFCAL will not saturate for long exposures, and the detector will be helpful for the study of primary cosmic-ray nuclei energies from 100 GeV to 1,000 TeV. For a given incident particle and energy, computer simulations of electromagnetic cascades allow computation of energy deposited in different regions of the calorimeter. For these initial simulations, a 5-cm x 5-cm x 7-cm calorimeter was used. Each subsection contained a 0.4-cm thick lead plate or two 0.2-cm lead plates and two layers of optical fibers, 90° to each other. There were 100 square fibers in a layer, and the length of an edge was 0.5 mm. For incident gamma ray energies of 0.5 to 1.5 TeV, the energy deposited in each layer of fibers was computed. Due to the limited dynamic range of the imaging electronics, a window for the energy deposition (ΣE_γ) in the fibers was explored to determine the best measure of energy deposition in the calorimeter.

Introduction

The Monte Carlo method in GEANT (CERN, 1992a) was used to simulate the photon and electron events in the Scintillating Optical Fiber Calorimeter (SOFCAL), which is under development at NASA/Marshall Space Flight Center for future applications in cosmic ray and gamma ray measurements.

Emulsion chambers employing calorimeters have been used for direct measurements of cosmic-ray composition (protons through Fe) between 10^{12} and 10^{15} eV using balloon-borne emulsion chambers (Kaplon et al., 1952; Minakawa et al., 1958; Niu et al., 1971; Burnett et al., 1986; Burnett et al., 1987; Parnell et al., 1989; Burnett et al., 1990; Asakamori et al., 1991). The emulsion chamber shown in Fig. 1 is composed of four parts: (1) a charge-determination module, (2) a target module with ~0.2 vertical interaction mean free paths for protons, (3) a spacer module, and (4) an emulsion calorimeter module with about fourteen vertical radiation lengths. In one emulsion chamber (Burnett, et al., 1986), the thickness of each part was as follows: primary charge detector, 1.78 cm; target module, 15.92 cm; drift space, 12.08 cm; and calorimeter section, 6.30 cm. The thickness was measured along an axis perpendicular to the plates. The simulations described here are for a scintillation optical fiber counterpart to the calorimeter section in the emulsion chamber.

The part of the primary energy going into gamma-rays, ΣE_γ, is the parameter most easily related to the primary cosmic ray spectrum in emulsion chamber experiments. The ability to measure energies of electron-photon cascades is one of the most important functions of the calorimeter. Following an interaction above or in the top of the calorimeter, a fraction of the total primary energy (5 - 25% of the energy released depending on impact parameters and atomic mass numbers of the colliding nuclei), will be deposited in the calorimeter in the form of photon energy, ΣE_γ. The photons originating from an interaction will develop individual electromagnetic cascades in the calorimeter. For these simulations, a calorimeter module with ten vertical radiation length of Pb was used. In the geometrical configuration shown in Fig. 2, each subsection of the calorimeter consisted of a 4-mm lead block, 100 square fibers (each 0.5-mm thick) in the x-direction and 100 square fibers (each 0.5-mm thick) in the y-direction. In these initial simulations, this lead and optical fiber combination was repeated fourteen times.

Materials and Methods

The Monte Carlo Method in GEANT.--GEANT and PAW (CERN, 1992b) are a system of detector description and simulation tools developed by CERN. The Monte Carlo simulations, which used GEANT Version 3.21, were done on DEC 5000 workstations. The principal application of GEANT in High Energy Physics are (1) the track-

Charge Detector: Measure Z by δ ray counting in emulsions and etch pit size in CR39.
Target: Interaction probability ~ 0.2 for protons and ~ 0.9 for iron nuclei.
Spacer: Primary fragments

- Produce $\pi^{\pm}$, and
- Gamma rays from π^0 decay spread out so they may be measured individually.
- θ (typical) = 2x10^{-3} radians at 10^{12} eV/amu.

Calorimeter: Gamma rays produce

- Copious e$^{\pm}$, γ's in lead.
- Number of e$^{\pm}$ counted in emulsions or X ray film.
- Optical density measured = ΣE_γ .

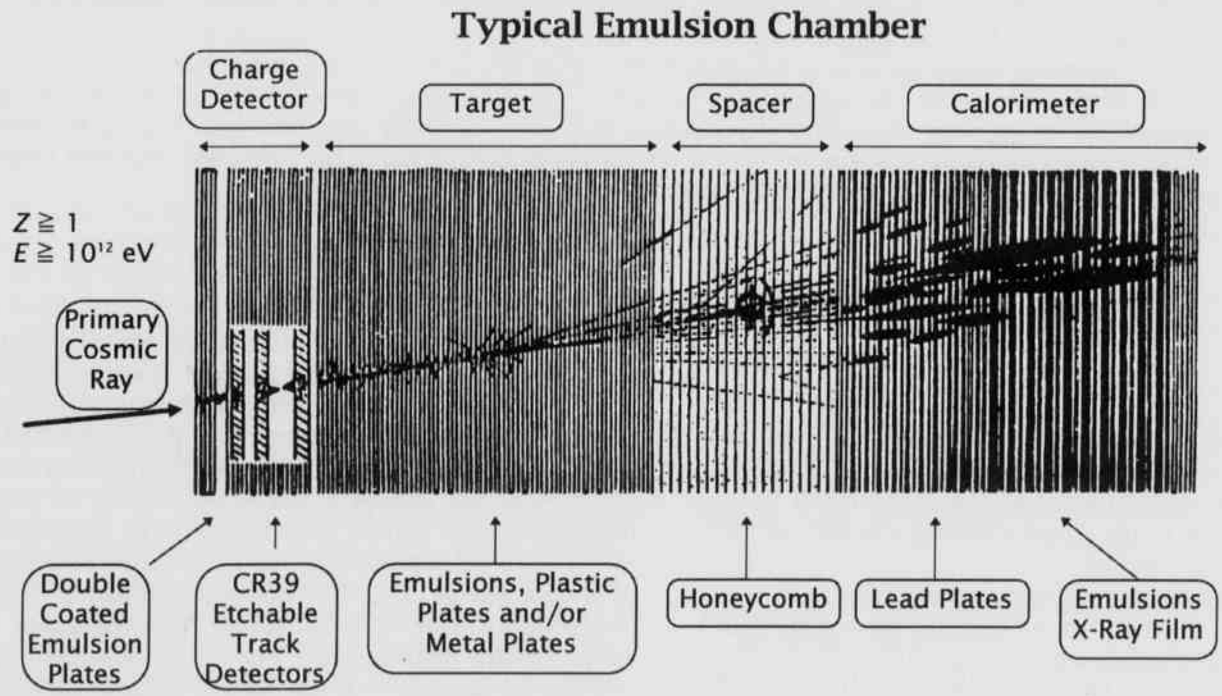

Fig. 1. Schematic diagram of an emulsion chamber.

ing of particles through an experimental setup for simulation of detector response, and (2) the graphical representation of the setup and of the particle trajectories. These two are often combined interactively in simulations.

The methods in these simulations include the following steps:

(1) ***Describe an experimental setup using geometry setup routines.*** The setup is represented by a structure of geometrical volumes. Each volume is given a medium number by the user. Different volumes may have the same medium number. A medium is defined by the so-called tracking medium parameters, which include reference to the material filling the volume.

(2) ***Accept events simulated by standard Monte Carlo generators.*** The Monte Carlo method is based on a statistical theorem which says that the distribution of a Cumulative Distribution Function is uniform. So random seeds generated by a random number generator (uniform) can be used to calculate events in a certain distribution. GEANT is interfaced with the event generator, FRITIOF. This Monte Carol program (Lönnblad, 1992) simulates events of hadron-hadron, hadron-nucleus, or nucleus-nucleus collisions at high energies.

(3) ***Simulate the transport of particles through the various***

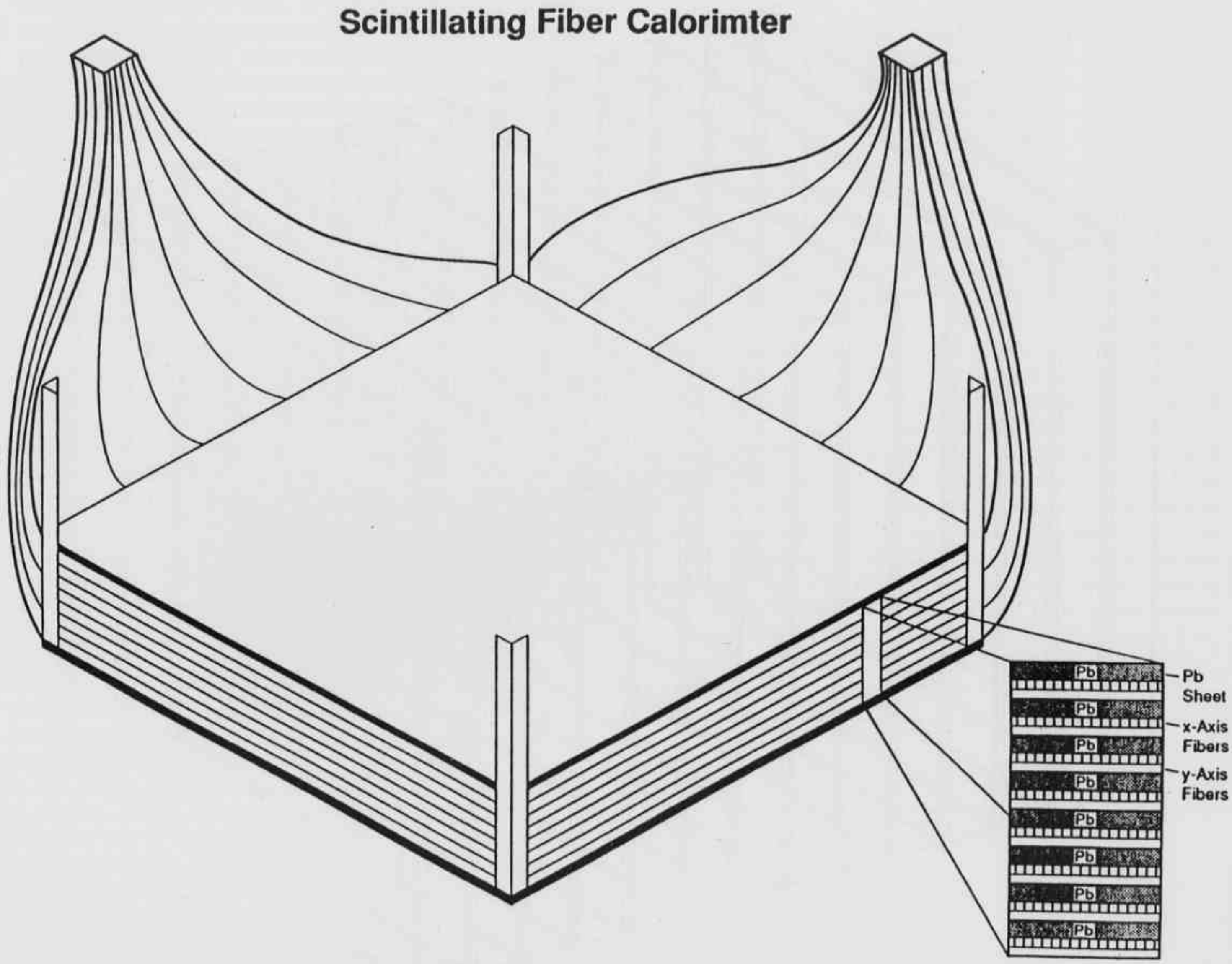

Fig. 2. Geometry of Scintillating Fiber Calorimeter (SOFCAL).

regions of the setup. GEANT can take into account the interactions of these particles with the matter and the boundary of the setup. GEANT is able to simulate the dominant processes which can occur in the energy range from 10 kV up to 10 TeV.

(4) ***Record elements of the particle trajectories and the response from the sensitive detectors.***

(5) ***Visualize the detectors and the particle trajectories.***

The Monte Carlo Program for SOFCAL Simulations (SOFCALS).--The process of optimization requires frequent design changes, so users should be able to change the geometry easily. The time required to modify GEANT programs containing geometry information about the detector can be enormous. Therefore a subroutine was developed to read in the geometrical configuration from a separate file in an ASCII format. This subroutine reads not only detector setup, but also other parameters needed for the simulation such as tracking medium parameters. The data are stored and later used for computing energy deposited by each particle in the cascade (Fig. 3) which was initially produced by a gamma ray.

Energy deposition is calculated from the lowest level geometry. Total energy deposition is integrated using step functions. When a threshold is imposed due to limi-

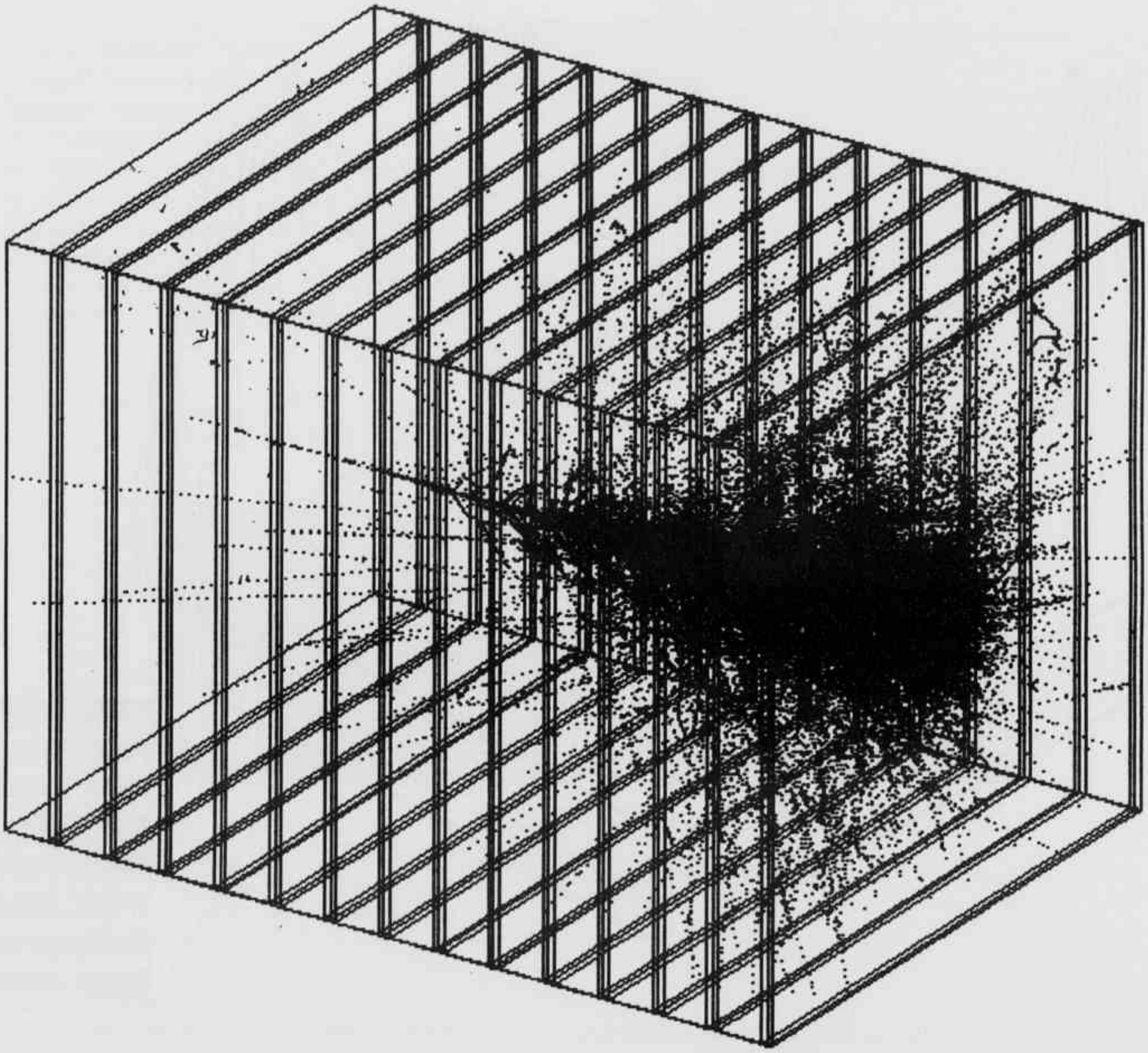

Fig. 3. The trajectories of a photon event with energy of 0.1 TeV.

tations in the electronic read out devices, then the measured energy is less than the energy actually deposited in each fiber. The program SOFCALS has interactive routines which are called to draw the trajectories of an individual gamma ray event.

Results

Energy Deposition Transition Curve and the Shower Event.--The typical detector (emulsion chamber) shown in Fig. 1 has a "target section" and "calorimeter section" designed for measuring produced charged particles and gamma rays, respectively. The target section includes many layers of nuclear emulsion plates to measure the charge of the incident particle and the emission angles of the produced charged particles with high accuracy (0.01 mrad). The spacer section is a drift space that permits closely collimated gamma rays from an upstream vertex to diverge from each other before cascade development in the downstream calorimeter. The calorimeter includes layers of nuclear emulsion and X-ray film among lead plates to measure the electron distributions from the electromagnetic cascades initiated by gamma rays from π^0 decay. The calorimeter is used to measure the spectrum of energy deposition ΣE_γ from which the primary energy spectrum is derived.

It is difficult to measure the momenta of produced charged particles in emulsion chambers. However gamma rays from the π^0 decay are observed in the calorimeter and the emitted angles and energies can be measured individually if they are well separated. For high multiplicity events, they overlap in the forward region.

The incident energy of the cosmic ray projectile is not measured directly, but it can be estimated from the total gamma ray energy. The angular distribution and energy distribution of gamma rays from each π^0 decay are needed. Isospin symmetry is assumed so the number of π^0s which decay into pairs of gamma rays is about half that of the charged π mesons.

Figure 3 illustrates the cascade of electrons and photons produced by an incoming gamma ray with incident energy of 0.1 TeV. Figure 4 shows the energy deposited in each x-layer of fibers as a function of distance through the calorimeter. The incident particle is a gamma-ray with energies of 0.5, 1.0, and 1.5 TeV. The three curves are based on ten events each.

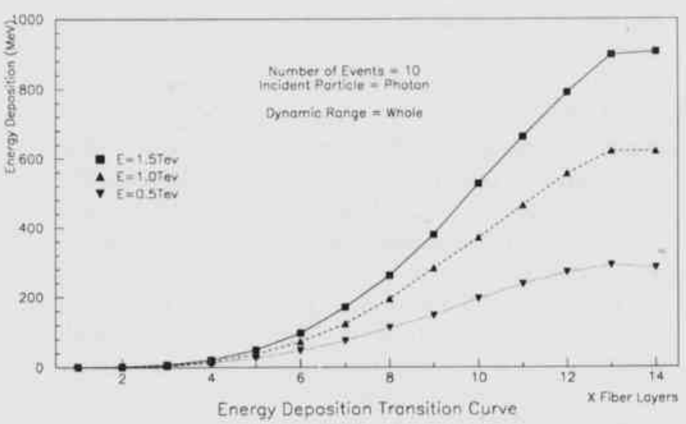

Fig. 4. The energy transition curve of a photon with energies of 0.5 TeV, 1 TeV, and 1.5 TeV.

Discussion

In these simulations of gamma rays incident on the SOFCAL detector, the direction of the incoming photon lies along the z-axis which is normal to the plane of each lead plate and layer of fibers. The energy transition curves show the energy deposited in each layer of optical fibers. They are used to determine parameter settings of the data acquisition devices.

The dynamic range is one limitation of the output image intensifier CCD electronics. Typical devices are limited to a dynamic range of approximately 256. For example, if the threshold energy is set to 1 MeV, then the highest energy which can be measured is only 256 MeV. Due to this limitation, a specific threshold and window may be needed to optimize the measurements. For these initial simulations of SOFCAL, a dynamic range of 100 was used. In Fig. 5, a threshold of 2 MeV appears to be optimal. Figures 5 to 8 show that the 2-MeV to 200-MeV range differentiates between gamma ray energies from 0.5 to 1.5 TeV better than other ranges. These figures should be compared with the energy deposition curve in Fig. 4, for which no threshold or range limitation has been imposed. For simulations of the primary cosmic rays, calculations must be performed with event generators, such as FRITIOF, to predict the distributions in ΣE_γ and then use GEANT for associated optimum "window" settings.

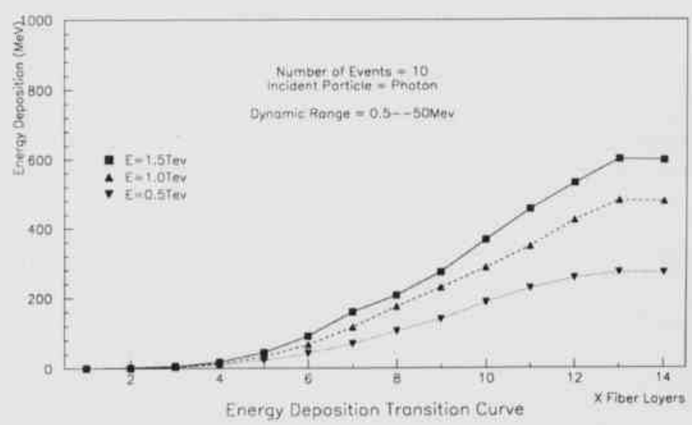

Fig. 5. The energy transition curves of photons with different energies. The dynamic range is 0.5 MeV to 50 MeV.

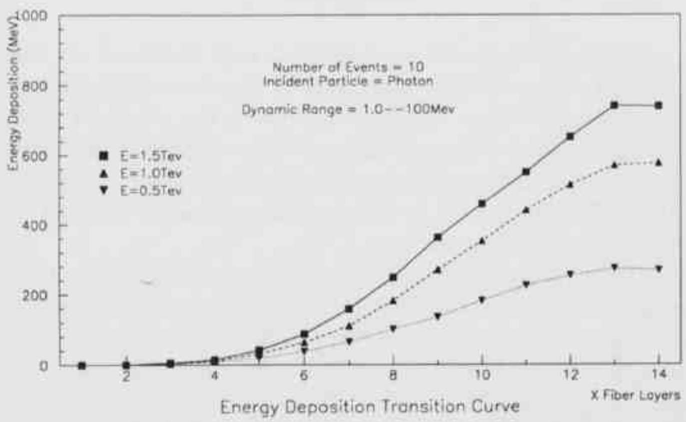

Fig. 6. The energy transition curves of photons with different energies. The dynamic range is 1 MeV to 100 MeV.

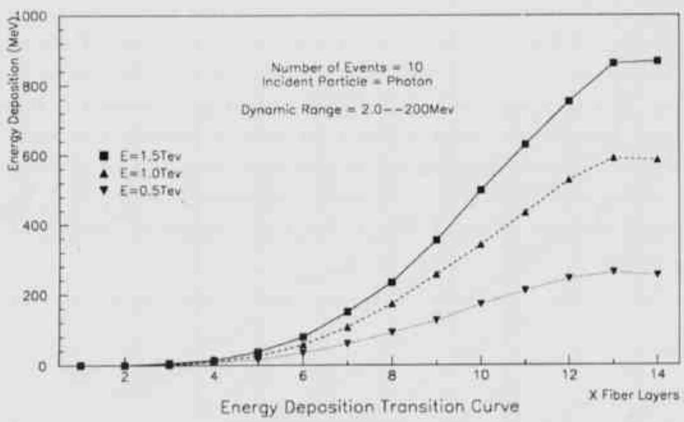

Fig. 7. The energy transition curves of photons with different energies. The dynamic range is 2 MeV to 200 MeV.

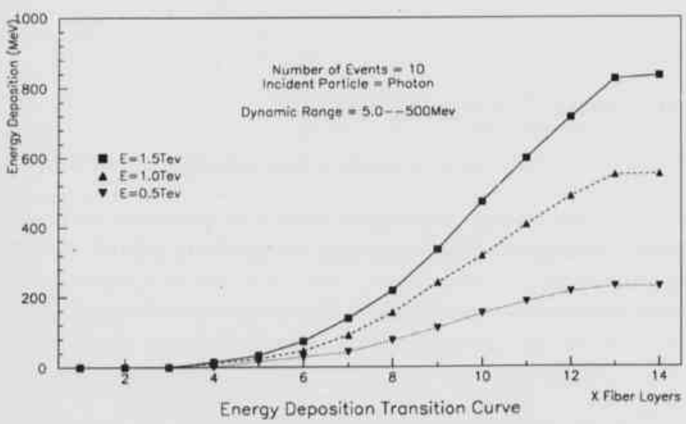

Fig. 8. The energy transition curves of photons with different energies. The dynamic range is 5 MeV to 500 MeV.

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