30/3-6-90 JS (3)

CONF-900343--3

SLAC-PUB--5193

DE90 008100

THE EGS4 CODE SYSTEM: SOLUTION OF GAMMA-RAY AND ELECTRON TRANSPORT PROBLEMS*

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Abstract

In this paper we present an overview of the EGS4 Code System—a general purpose package for the Monte Carlo simulation of the transport of electrons and photons. During the last 10-15 years EGS has been widely used to design accelerators and detectors for high-energy physics. More recently the code has been found to be of tremendous use in medical radiation physics and dosimetry. The problem-solving capabilities of EGS4 will be demonstrated by means of a variety of practical examples. To facilitate this review, we will take advantage of a new add-on package, called SHOWGRAF, to display particle trajectories in complicated geometries. These are shown as 2-D laser pictures in the written paper and as photographic slides of a 3-D high-resolution color monitor during the oral presentation.

Invited paper presented at the International Conference
on Supercomputing in Nuclear Applications
Mito City, Japan, March 12-16, 1990

* Work supported by the US Department of Energy under contract DE-AC03-76SF00515

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DISCLAIMER

1. Introduction

The EGS* system of computer codes is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several TeV. The current version by Nelson, Hirayama and Rogers[1] is more commonly referred to as EGS4. In addition to tracing the history of EGS, this paper will describe the physical processes that are considered and will demonstrate various problem-solving capabilities of the code by means of a variety of practical examples. We will also take advantage of a new add-on package, called SHOWGRAF[2], to display particle trajectories in complicated geometries using both laser-printed 2-D graphics and a 3-D high-resolution color graphics monitor (presented as photographic slides during the talk).

2. The History of EGS

The original version called EGS3 was developed during 1972-1978 by R. L. Ford and W. R. Nelson[3]. The sole purpose of the collaboration was to completely revamp the work started by Nagel[4] but to do it in such a way that further enhancements could easily be made as time progressed—in today's words, to create a program that was *versatile*, *upward-compatible*, and very *user-friendly*.

When it was formally introduced, EGS3 was designed to simulate electromagnetic cascade showers in arbitrary geometries and at energies up to a few thousand GeV and down to cutoff kinetic energies of 0.1 MeV (photons) and 1 MeV (electrons/positrons). Using an auxiliary code called PEGS (Preprocessor for EGS), radiation transport was achievable in any of 100 elements, or any compound or mixture of these elements. In addition to providing more efficient sampling schemes, EGS3 also included some processes that were not part of the original Nagel program.

To lend credibility to our efforts, a fairly extensive set of benchmark comparisons, representing a wide range of applications, were included in the EGS3 manual. The most important benchmarks today, however, are those that have been performed by the multitude of users of the code itself, examples of which will be presented in this paper.

Upon reflection, probably the single most important event that made EGS an everyday word in high-energy physics was the discovery of the J/ψ particle in the Fall of 1974. EGS3 was originally intended to be a tool for high-energy health physicists and accelerator designers, but the "November Revolution", as it is now referred to in the particle physics world, led to a dramatic increase in the use of storage rings and the need for sophisticated high-energy calorimetry. It is safe to say that EGS3 has played a role in the design of many, if not most, of the electromagnetic shower detectors since then.

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* Electron-Gamma Shower

3. EGS4 – A Code Greatly Influenced by Medical Physics

Since the introduction of EGS3 there has been a growing need to extend the lower limit of kinetic energy—*i.e.*, down to 1 and 10 keV for photons and electrons, respectively. Essentially, EGS3 has become more and more popular as a general low-energy electron-photon transport code that can be used for a variety of problems in addition to those normally associated with high-energy physics. While there was a collaborative effort being undertaken in 1982-1983 by Nelson (SLAC) and Hirayama (KEK) to extend the flexibility of EGS in general, particularly for use around high-energy accelerators, there was also an important low-energy benchmarking effort being done by Rogers, Bielajew, and colleagues at the NRC in Canada. The work of these three laboratories was pooled and the EGS4 Code System became the result.

Although EGS is still very heavily used in particle physics, it is interesting to note that of the 260 requests for EGS4 received by SLAC in 1986, well over half were from hospitals or organizations involved in medical physics and dosimetry research. The current strong interest by hospital physicists has led to a number of EGS courses, as well as to the publication of a more general book on the subject entitled *Monte Carlo Transport of Electrons and Photons*[5]

4. General Description (and the Role of PEGS4)

EGS is basically an *analog* Monte Carlo program. That is to say, each and every particle is followed until it reaches its final destiny, usually an energy limit (cutoff) or a discard boundary. Due to the statistical nature of the Monte Carlo method, the accuracy of the results will depend on the number of histories run. Generally, the statistical uncertainties are proportional to the inverse square root of the number of histories, so that to cut uncertainties in half it is necessary to run four times as many histories. Also, for given cutoff energies, the computer time for a high-energy shower history is slightly more than linear in the energy of the incident particle. The point to be made here is that analog Monte Carlo calculations can be very time consuming.

It is for this reason that the computational task of the EGS4 Code System is divided into two parts. First, a preprocessor code (PEGS4) uses theoretical (and sometimes empirical) formulas to compute the various physical quantities needed, and prepares them in a form for fast numerical evaluation. Then EGS4 uses these data, along with user supplied data and routines, to perform the actual simulation.

5. The Physics in the EGS4 Code System

EGS4 accounts for the following processes:

- Bremsstrahlung production (corrected at low energies to agree with ICRU-37 radiative stopping powers).
- Positron annihilation in flight and at rest (the annihilation quanta are followed to completion).
- Molière multiple scattering (*i.e.*, Coulomb scattering from nuclei). The reduced angle is sampled from a continuous (rather than discrete) distribution. This is done for arbitrary step sizes, selected randomly, provided that they are not so large, or so small, as to invalidate the theory.
- Møller (e^-e^-) and Bhabha (e^+e^-) scattering. Exact rather than asymptotic formulas are used.
- Continuous energy loss applied to charged particle tracks between discrete interactions.
  - Total stopping power consists of soft bremsstrahlung and collision loss terms.
  - Collision loss determined by the (restricted) Bethe-Bloch stopping power with Sternheimer treatment of the density effect.
- Pair production.
- Compton scattering.
- Coherent (Rayleigh) scattering may be modeled using an independent-atoms approximation (non-default option in EGS4).
- Photoelectric effect.
  - Neither fluorescent photons nor Auger electrons are produced or transported in the default version of subroutine `PHOTO`.
  - However, a version of `PHOTO` is available that allows for the production and transport of K-edge photons.

In addition to the above, the user can make changes to EGS4 by means of macro commands in the driver program, called the *User Code*. For example, macros have been written to change how bremsstrahlung and or photoelectric angles are sampled—*i.e.,* to override the way EGS4 handles this by default.

6. Implementing EGS4

The flow of control and data when a user-written program is using the EGS4 code is illustrated in Fig.1 (detailed information needed to write User Codes is given in Appendix 2 of SLAC-265)[1].

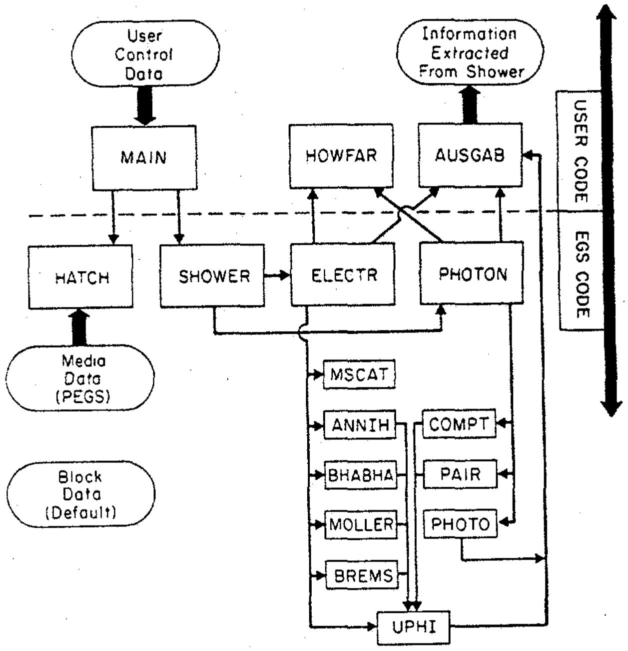

Figure 1. Flow control with user using EGS4.

The EGS4 code itself consists of two *user-callable* subroutines, `HATCH` and `SHOWER`, which in turn call the other subroutines in the EGS4 code, some of which call two *user-written* subroutines, **`HOWFAR`** and **`AUSGAB`**. The latter determine the <u>geometry</u> and <u>output</u> (scoring), respectively.

The user communicates with EGS4 by means of various `COMMON` variables. To use EGS4, the user must write a **`MAIN`** program and the subroutines `HOWFAR` and `AUSGAB`. In general, **`MAIN`** will perform any initialization needed for the geometry routine, `HOWFAR`, and set the values of certain EGS4 `COMMON` variables which specify such things as names of the media to be used, the desired cutoff energies, and the unit of distance (*e.g.*, centimeters, radiation lengths, etc.). `MAIN` then calls the `HATCH` subroutine, which "hatches" EGS by doing once-only initialization and by reading from the data sets prepared by PEGS for the materials requested.

With this initialization completed, `MAIN` may then call `SHOWER` when desired. Each call to `SHOWER` results in the generation of one EGS history. The arguments to `SHOWER` specify the parameters of the incident particle. Therefore, the user has the freedom to use any source distribution desired.

Also included as an argument is the *particle weight*, normally assumed to be unity. This allows for the implementation of *importance sampling* and other variance reduction techniques—*e.g.*, splitting, path-length biasing, Russian roulette, leading-particle biasing, *etc.*.

7. Radiation Transport Examples Using EGS4

Several examples will be given to demonstrate how EGS4 can accurately solve electron-photon radiation transport problems at all energies. The examples will include "pictures" showing particle trajectories in a variety of geometries. For example, Fig. 2 shows the radiation induced by a single 1-GeV photon as it enters a liquid hydrogen bubble chamber and strikes a lead plate located at the center.

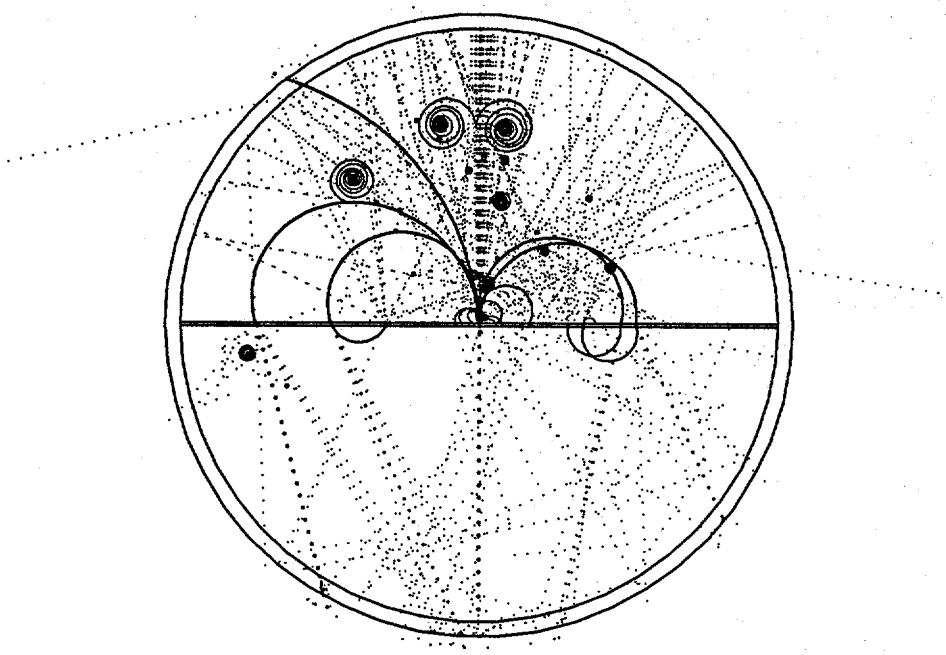

Figure 2. Hydrogen bubble chamber: A single 1-GeV photon strikes a $0.5X_0$ Pb slab from the bottom at 90°. All charged particles (solid) and photons (dots) are shown.

Photons are depicted as dotted lines in this shower picture. The charged particles (solid lines) curl up as as a result of a 20-kGauss magnetic field being applied along the axis of the cylinder (*i.e.*, out of the paper). The capability of visualizing the electron-photon transport that takes place with EGS4 is made available through an add-on graphics package called SHOWGRAF[2].

In this picture, pair production, Compton, bremsstrahlung, and other events can clearly be seen. This is an example taken from high-energy physics involving charged-particle transport under the influence of an external magnetic field in a cylinder-slab geometry. This is also a nice example to show students, since the charged particles are produced by photons—which are not visible in a real bubble chamber.

We will use SHOWGRAF in many of the following examples in order to illustrate the variety of problems, both high- and low-energy, that can be solved using the EGS4 Code System.

7.1 Conversion Efficiency of Lead for 30-200 MeV Photons

An experiment to measure the conversion efficiency for 44, 94, and 177 MeV photons incident on lead was performed at CERN by Darriulat *et al*[6] using a photon *tagging* scheme. A beam of charged leptons and hadrons was momentum selected and allowed to impinge on a target so that electrons would radiate bremsstrahlung. By measuring the energy of the electron, and knowing the angles of the particles, the mean photon energy was determined to an accuracy of ±4 MeV.

The tagged photon beam was then allowed to strike a lead plate having a thickness ranging from 1 to 20 mm. A 5-mm thick scintillator was positioned immediately downbeam to detect electrons (±) produced by photon interactions in the lead converter.

To calculate the conversion efficiency with EGS4, the geometry layout shown in Fig. 3 was used, consisting of four regions separated by three semi-infinite planes.

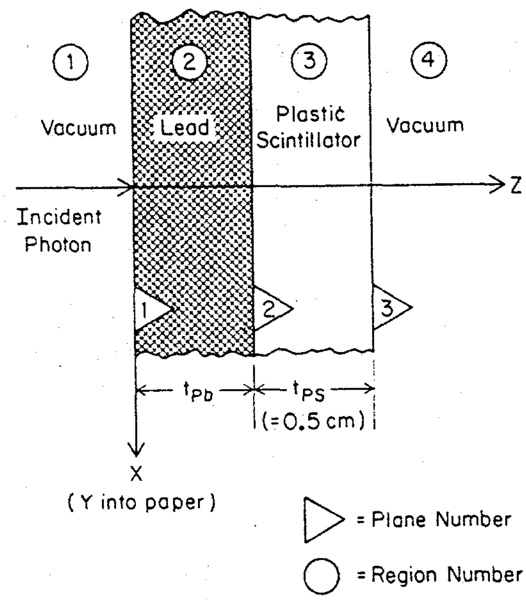

Figure 3. Geometry layout used for simulation of the photon conversion efficiency experiment.

Polystyrene (ρ = 1.03 g/cm^3) consisting of hydrogen and carbon (H/C=1.1) was used as the medium for plastic scintillator in region 3. The density of lead was taken to be 11.3 g/cm^3. PEGS4 was used to create the necessary material data with cutoff energies of 0.1 MeV and 1.5 MeV (total energy) for photons and electrons, respectively.

The scoring subroutine AUSGAB was set up to sum the energy deposition in the plastic (region 3) for each photon. An event was counted as a *conversion* if more than 60 keV, corresponding to the discrimination level established in the experiment, was deposited in the scintillator for each incoming photon.

The results of the calculation are compared with the experimental data in Fig. 4. The agreement is extremely good over the entire lead thickness range for the two energies shown.

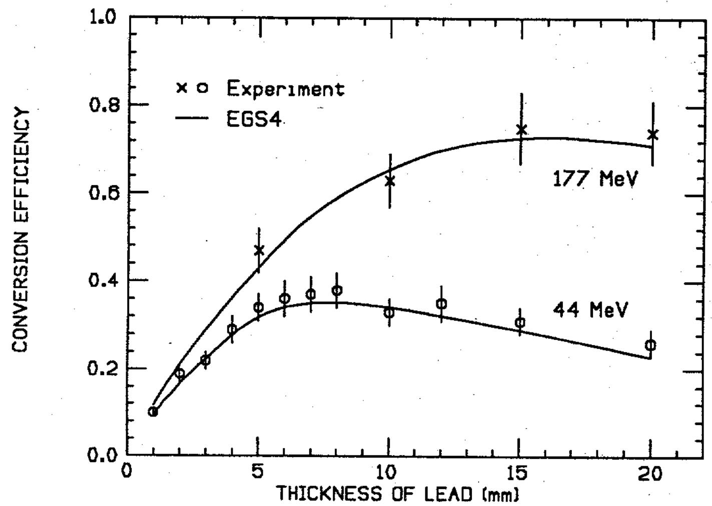

Figure 4. Absolute comparison of EGS4 simulation with a conversion efficiency experiment by Darriulat *et al*[6].

In the text describing the experimental results, Darriulat *et al* point out that the energy distribution in the scintillator showed characteristic peaks corresponding to one, two, or three secondary electrons that are produced in the lead and lose energy as they pass through the scintillator. To check out this observation with EGS4, the total energy deposition in the scintillator per incident photon was histogrammed for a photon energy of 177 MeV. Typical results are shown in Fig. 5. Two of the three electron peaks are indeed prominent and, based on a stopping power of ~ 2 MeV-cm^2/g, at least three peaks are located where one would expect them to be.

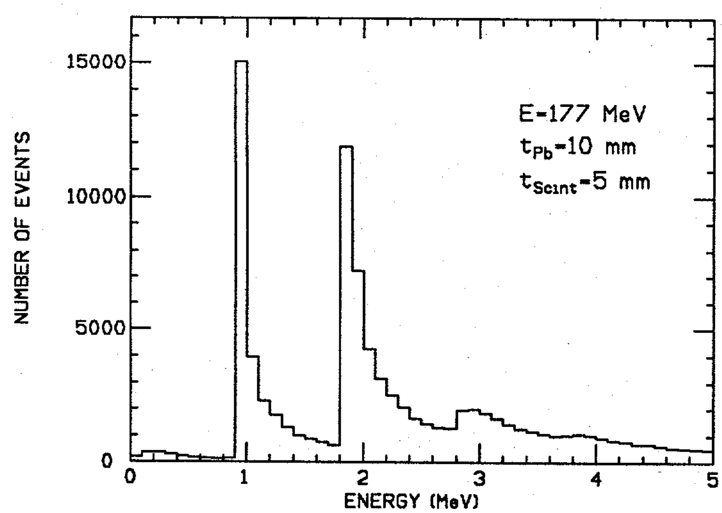

Figure 5. Energy distribution in the scintillator (EGS4 calculation).

This experiment is well-defined and, as a result, is easily simulated. One can conclude that EGS4 will predict photon conversion efficiencies rather well, at least in the energy range 30-200 MeV, and for geometries similar to the one described here.

To further aid in our understanding of the physical events taking place, we can use the SHOWGRAF package to draw particle trajectories. Figure 6 shows the electron-positron tracks created by five photons incident on a 10-mm lead converter. The photon tracks have been suppressed in order to avoid cluttering up the figure. The charged particle tracks passing through the second (scintillator) slab are consistent with the multiple-peak structure in Fig. 5.

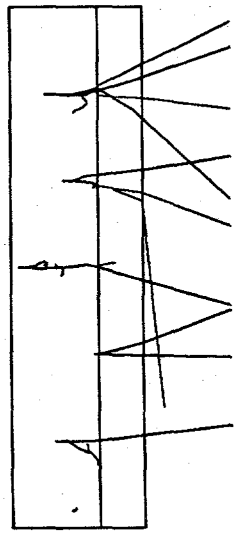

Figure 6. Electron (±) tracks produced by five 177 MeV photons (not shown) in a lead-scintillator detector.

7.2 Electron Emission in RF Cavities

The next example relates to a series of spectral measurements recently performed at SLAC after an RF cavity was tested and found to emit high levels of radiation[7]. Because the cavity was subjected to very high power levels, surface electrons were believed to be produced from two locations within the structure and accelerated to kinetic energies of 8.5 and 3.5 MeV, respectively, depending on their point of origin.

Upon exiting the cavity, they passed through a 0.015 inch copper window, where they lost energy primarily by ionization and were multiple scattered. The experimentalists attempted to measure the spectrum of the electrons using a magnet, a lead slit, and a Faraday cup. A strong peak corresponding to the 8.5-MeV group was observed, but the 3.5-MeV peak was not observed.

The object of the EGS4 simulation was to try to understand these observations, particularly with the help of graphics showing particle trajectories. Figure 7 shows the EGS4 geometry designed for this problem.

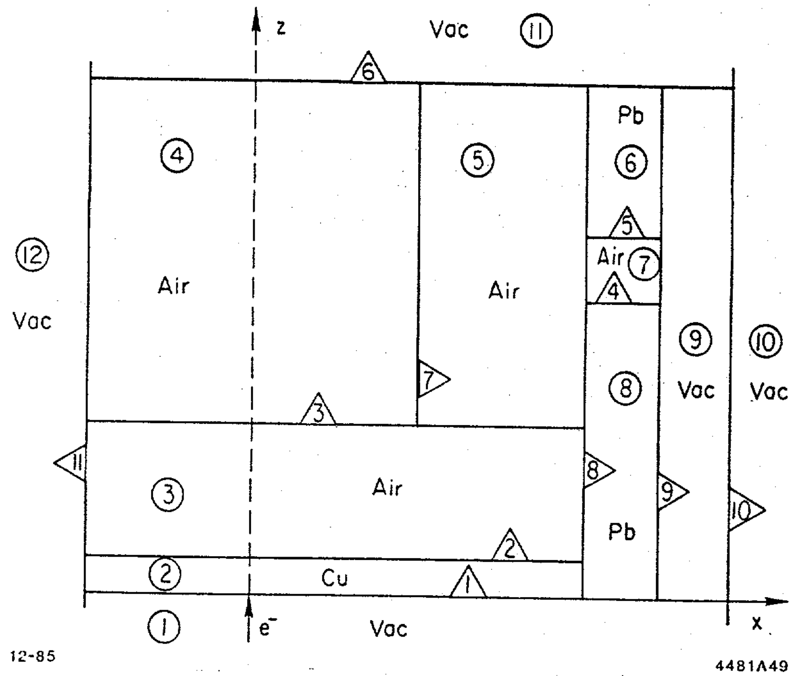

Figure 7. EGS4 geometry diagram used in the RF cavity simulation (not to scale).

Electrons start from the origin (at plane 1), transport through the copper window (Region 2), emanate out into the air (Region 3), and pass through the magnetic field, which is constant and along the positive y-direction (in Region 4 *only*). They are then bent in the direction of the lead wall (Regions 6 and 8) where some of them pass through the slit (Region 7) and get scored (at Plane 10). By varying the field strength of the magnet, one should be able to re-create the observations for both 3.5 MeV and 8.5 MeV.

The result of running this EGS4 simulation at 8.5 and 3.5 MeV is shown in Figs. 8 and 9, respectively, for 100 incident electrons. It becomes clear from pictures such as these that it is easier to focus the 8.5-MeV electrons through the slit than the 3.5-MeV ones.

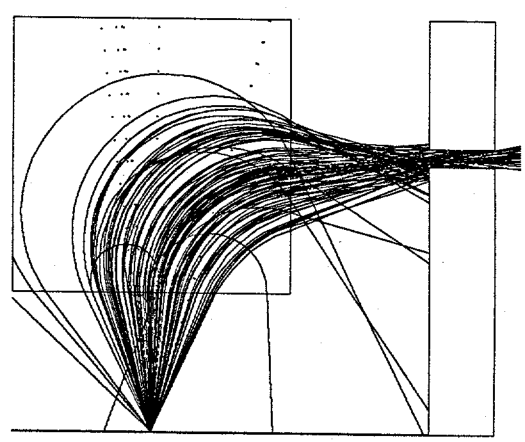

Figure 8. 8.5-MeV electrons (solid lines) scattering in a 0.38 mm copper foil, bending in a 2.6 kG focusing field, and passing through a lead slit.

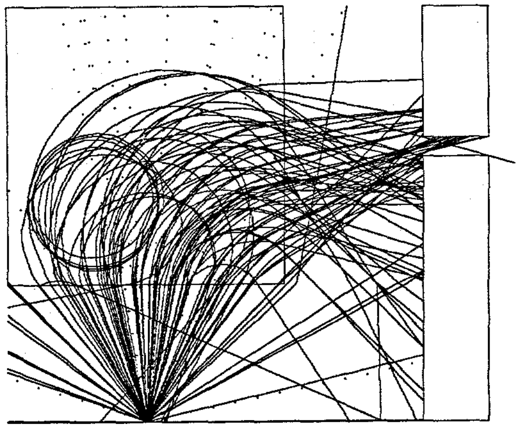

Figure 9. Same as Fig. 8, but energy is 3.5 MeV and magnetic field is 1.0 kG.

A number of EGS4 "experiments" can be performed rather easily once the basic geometry and magnetic field transport is established. For example, one can replace the air regions and/or the copper window with vacuum in order to determine what effect they have. What was discovered by doing this is that the copper window has the greatest effect on the transmission through the lead slit.

Figure 10, incidentally, demonstrates what happens when the magnetic field is turned off.

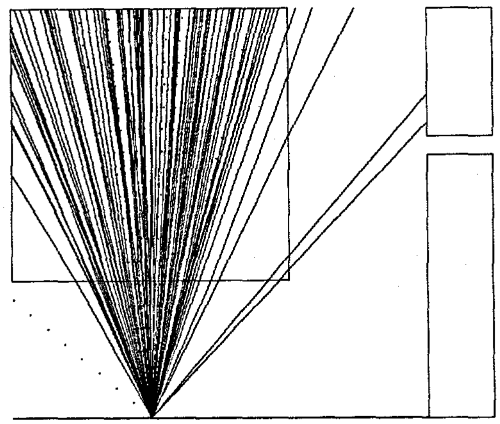

Figure 10. Same as Fig. 8 (*i.e.*, 8.5 MeV again) but magnetic field *turned off.*

7.3 Nuclear Fuel Rod Irradiation

In addition to using geometry methods intrinsic to EGS4, one can also create rather complex geometries using the Combinatorial Geometry (CG) package that is available with the MORSE-CG program[8]. User Codes are available to make this task very easy. Furthermore, a special version of SHOWGRAF, called CGSHOWGF, allows for the visualization of the particle trajectories in the CG geometry.

We recently set up a CG geometry to simulate the irradiation of nuclear fuel rods by electron accelerator x-ray beams (*e.g.*, to study the possibility of reducing the concentration of a select group of very long-lived radioisotopes).

Figure 11 shows a system consisting of five iron rods (10 cm long, 1 cm diameter) suspended in a cylindrical vacuum tank. Three 100-MeV electrons strike the center rod and produce a cascade shower. This example is included here to demonstrate that one can use Combinatorial Geometry as well as CGSHOWGF with EGS4.

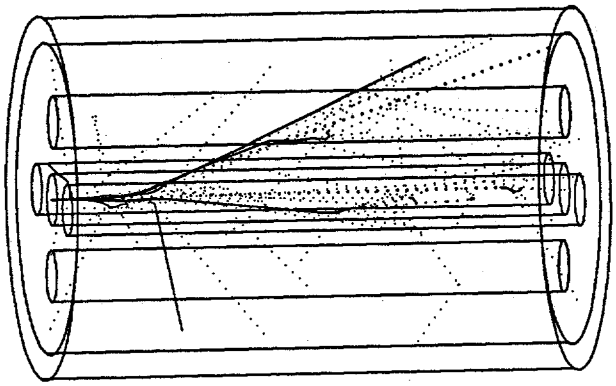

Figure 11. EGS4/Combinatorial Geometry example. Three 100-MeV electrons strike the center rod.

7.4 Photoproduction and Induced Radioactivity

EGS4 can be used to simulate photonucleon production and the resultant induced radioactivity. This is most easily done by scoring within subroutine `AUSGAB` of the User Code. In particular, whenever a photon with energy k is transported a distance ℓ in the medium, an estimate can be made of a specific reaction (*e.g.*, $^{182}W(\gamma, n)^{181}W$) using ℓ/λ, where λ is the mean-free-path for the reaction at that energy.

A calculation of this type was recently performed by Donahue and Nelson[9] for electron beams showering in *natural* tungsten. Figure 12 shows the distribution of induced radioactivity within a 9-cm long (10-cm diameter) cylinder of tungsten struck by 100-MeV electrons.

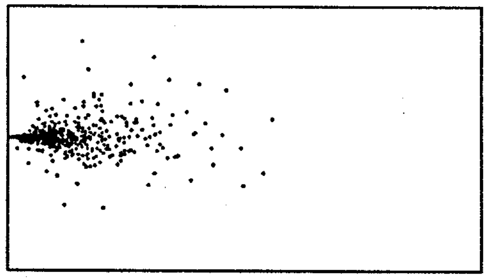

Figure 12. Activity produced in natural tungsten by 1000 incident electrons at 100 MeV/e^-.

The activity is not uniformly distributed, but tends to follow the higher-energy photons—*i.e.*, the shower profile. Whereas with relatively low-energy incident electrons the activity is produced near the front surface, the more energetic the primary beam the deeper into the target the maximum activity concentration is found.

Calculations of this type can be very useful in radiation protection where estimates must be made of the expected dose rate from devices (*e.g.*, targets, collimators, dumps) struck by electrons beams.

7.5 Positron Target Design

The basic scheme behind the newly commissioned SLC project at SLAC is to produce and collide a beam of 50-GeV positrons with a beam of 50-GeV electrons, the purpose of which is to observe and measure intermediate vector bosons (Z^0, W^+, W^-) near the center-of-mass energy of 100 GeV.

This requires producing low-energy (2 to 20 MeV) positrons by directing a 33-GeV electron beam onto a 2.4-cm tantalum alloy target. These positrons are then "collected", re-injected into the machine, and accelerated to the required energy of 50 GeV.

EGS4 was used in order to determine the size and nature of the target necessary to accomplish the task. Fig. 13 shows an EGS4 shower generated by a single 33-GeV electron striking the target.

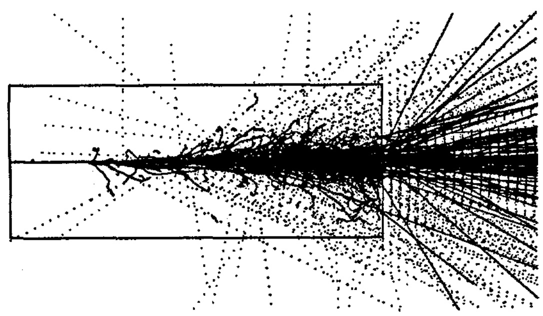

Figure 13. Shower produced in 2.4 cm-tantalum alloy target struck by one 33-GeV electron: solid ($e^{\pm}$), dots (γ).

Clearly, not only are a lot of positrons and electrons created by a single electron, but there is a central core of energy deposition that can lead to serious engineering problems, particularly target heating, melting, and stress (this core is primarily due to the small angles associated with bremsstrahlung and pair production, convoluted with multiple scattering).

EGS has been useful in determining not only the optimum positron yield, but also to point out some of the difficulties involved in running small beam spots into thick targets, generally leading to premature target failure[10].

7.6 Electron-Beam Irradiation of Wire and Tubing

EGS4 has recently been used to predict the absorbed dose distribution in wire and tubing[11]. Figure 14 is an example showing the irradiation of a thin (1-mm diameter) copper wire by 3-MeV electrons. One is interested in the absorbed dose pattern in the surrounding insulation (2-mm O.D.).

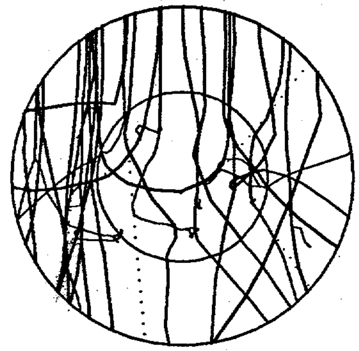

Figure 14. Simulation of 3-MeV electron beam irradiation of an insulated copper wire (25 particles).

Note the difference in electron scattering between the lower-density insulator, where the paths are nearly straight, and the copper in the center. The overall effect of irradiating from only one side is that the copper conductor *shadows* the insulator on the far side, producing a very non-uniform dose distribution as shown by the isodose contour plot in Fig. 15.

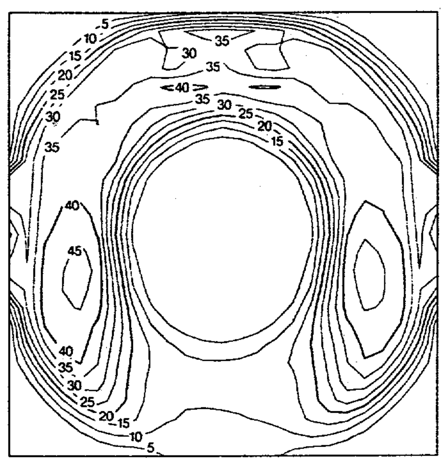

Figure 15. Isodose contours for 3-MeV electron irradiation of one side of an insulated copper wire (taken from McIntyre *et al*[11]).

8. Concluding Remarks

In this paper we have provided a brief glimpse of the capability of the EGS4 Code System to simulate electron-photon transport at all energies. The versatility of the system has been demonstrated by a myriad of examples that represent practical problems of interest to high-energy physics, radiation protection, medical physics, and industry.

EGS4 runs on all computers that have the 1977 ANSI Fortran. Recently the system has been successfully run on personal computers, most notedly those based on the 80386 microprocessor. This trend is expected to continue as PCs become faster.

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