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USING THE EGS4 COMPUTER CODE TO DETERMINE RADIATION SOURCES ALONG BEAM LINES AT ELECTRON ACCELERATORS[a]

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ABSTRACT

The EGS[b] computer code, developed for the Monte Carlo simulation of the transport of electrons and photons, has been used since 1970 in the design of accelerators and detectors for high-energy physics. In this paper we present three examples demonstrating how the current version, EGS4,[1] is used to determine energy-loss patterns and source terms along beam pipes (*i.e.*, including flanges, collimators, *etc.*). This information is useful for further shielding and dosimetry studies. The calculated results from the analysis are in close agreement with the measured values. To facilitate this review, a new add-on package called SHOWGRAF,[2] is used in order to display shower trajectories for the three examples.

INTRODUCTION

The EGS4 Code System[1] is a set of programs designed to simulate electromagnetic cascade showers at energies up to a few thousand GeV and down to cutoff kinetic energies of 1 keV (γ) and 10 keV ($e^{\pm}$). Using an auxiliary code called PEGS4,[c] radiation transport is achievable in any of 100 elements, or any compound or mixture of these elements. Because of its versatility and relative ease-of-use, and because it has been checked against many experiments, EGS4 has been used rather extensively by the particle physics community in the development of shower counters and related detectors. There has also been a growing use of EGS4 by the medical physics community for modeling the transport of electrons and photons down to a few keV in complex geometries, including the human body.

The user is expected to write an EGS4 User Code in an extended FORTRAN language known as Mortran3.[3] The User Code is primarily a MAIN (driver) program and two subroutines—AUSGAB and HOWFAR—but, it can include user-auxiliary subprograms as well. Subroutine HOWFAR allows the user to specify the geometry for any given problem, and to assign media data (created by PEGS4) to various regions in the geometry. The user scores and outputs information by means of subroutine AUSGAB. Transport can be initiated from sources having spatial, angular, or energy distributions. Efficiency and variance reduction techniques are not built into EGS4 *per se*, but can be implemented[4] by means of a macro facility available through Mortran3.

PHYSICS PROCESSES IN THE EGS4 CODE SYSTEM

The following physics processes are taken into account by the system:

- Electron (±) bremsstrahlung.
- Positron annihilation at rest and in flight (annihilation quanta followed to completion).
- Multiple Coulomb scattering of electrons (±) from nuclei (Molière model).
- Delta-ray production by means of e^-e^- (Møller) and e^+e^- (Bhabha) scattering.
- Continuous energy loss applied to electron (±) tracks between discrete interaction sites using a restricted stopping power (*i.e.*, Bethe-Bloch formula including Sternheimer density-effect correction).
- Pair production.
- Compton scattering.
- Coherent (Rayleigh) scattering.
- Photoelectric effect (including K-edge fluorescent photon production).

GRAPHICS CAPABILITIES IN EGS4

EGS4 has been coupled with the SLAC Unified Graphics System (UGS77)[5] for displaying particle tracks on UGS77-supported devices.[6] It has also been modified to display the distribution of induced radioactivity in beam targets.[7] This is accomplished by inserting the SHOWGRAF package[2] into the User Code and then making the CALL statements in the appropriate places in AUSGAB.[d] The graphical output may be displayed directly onto an IBM 5080 color terminal which supports three-dimensional rotations, translations, and zooming. SHOWGRAF can also output graphics into files for printing on a PC display using a post-processor system called EGS4PL.[2] In the remainder of this paper we will make use of SHOWGRAF to graphically demonstrate radiation source distributions along accelerator beam pipes.

[a] Work supported by the DOE, contract DE-AC03-76SF00515.

[b] Electron Gamma Shower.

[c] Preprocessor for EGS.

[d] A similar package called MORSGRAF[8] has also been created for use with the MORSE-CG code.

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EXAMPLES OF EGS4-GENERATED SHOWER SOURCES

A. Multiple Scattering and Bremsstrahlung Production by a 220 MeV Positron Beam.

The SLAC Linear Collider is an electron-positron machine system designed to accelerate and collide two 50 GeV beams. Electrons are emitted from a thermionic gun and accelerated by the SLAC Two-Mile Accelerator. In order to produce positrons a pulse of electrons is extracted at the 2/3 point of the Two-Mile Accelerator and is incident on a target. Low energy (2-20 MeV) positrons are produced in the shower, captured, accelerated to 220 MeV and returned to the front section of the Two-Mile Accelerator for further acceleration. Figure 1 shows a schematic of the Positron Return Line (PRL) and the front section of the Two-Mile Accelerator.

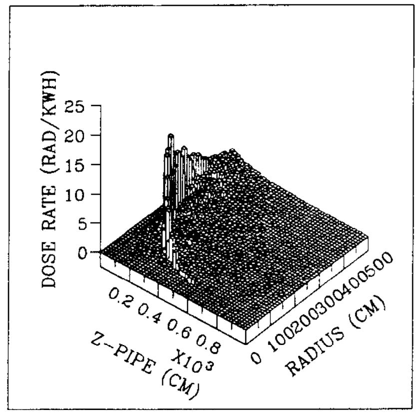

Fig. 2. Photon dose rate at shielding wall location, as a function of both the distance (radius) from the beam pipe and the tagging distance (Z-pipe) along it.

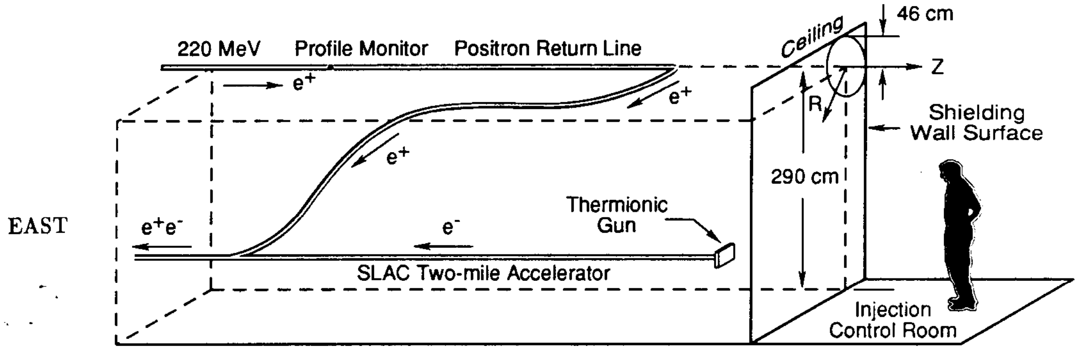

Fig. 1. Positron Return Line: A 2-inch O.D. (0.065-inch thick) stainless-steel beam pipe runs along the ceiling of the tunnel, makes a 180° turn, and joins the Two-Mile Accelerator.

A recent radiation survey in the injector control room showed radiation levels as high as 10 mSv/hr (1 Rem/hr), in small localized areas, whenever a beam profile monitor was inserted. This profile monitor (0.323 cm CsI) was located 60 meters upbeam (East) of the shielding wall. The high-radiation levels at the injector control room were caused by multiple scattering of 220 MeV positrons in the profile monitor, leading to electromagnetic showering in the PRL beam pipe itself. As a result, the shielding for the injector control room was not adequate. In order to understand the spatial distribution of the shower along the beam pipe, EGS4 was used together with a tagging scheme to score where particles exit the beam pipe; that is, this position (Z-pipe) was noted and carried along with the other particle properties (*e.g.*, energy, direction cosines, etc.) in the subsequent Monte Carlo transport. Figure 2 was then obtained by scoring the dose rate as the photons cross the shielding wall location as a function of both the distance (radius) from the beam pipe and the tagged distance along the beam pipe (Z-pipe).

A contour slice of Fig. 2 is provided in Fig. 3, which clearly shows that radiation reaching the shielding wall 60 meters downbeam comes from showers produced along the PRL beam pipe within 500 cm of the profile-monitor target. This provides insight as to how to best shield the source; *e.g.*, as opposed to constructing a thick shielding wall down beam.

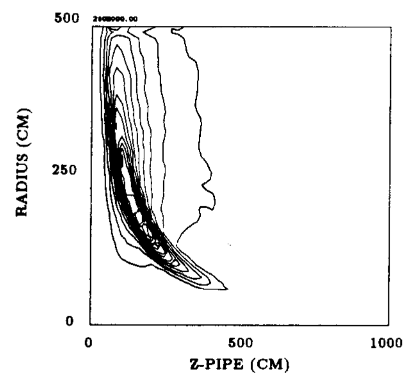

Fig. 3. Contour plot (slice) of Fig 2.

For example, adding a relatively thin layer (0.5 inch) of lead around the first 500 cm of beam pipe results in the contour plot shown in Fig. 4, corresponding to a dose rate reduction factor of about 1/1300.

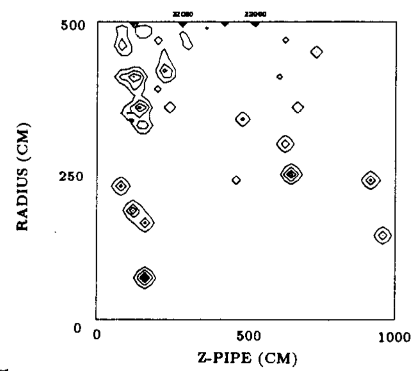

Fig. 4. Contour plot after adding 0.5-inch layer of lead around the beam pipe.

B. Radiation Source Produced by Multiple Scattering With 2-10 GeV Electrons

Recently the SLAC End Station A (ESA) beam line has been used to study deep-inelastic electron-proton and electron-deuteron scattering. The layout of ESA is shown in Fig. 5.

2-10 GeV electrons from the Two-Mile Accelerator are incident on various targets which are located at a common pivot point. Spectrometers in ESA measure both the angle and the momentum of various particles coming from the target. Electrons hit the target, produce bremsstrahlung, scatter and spread out, producing electromagnetic showers in beam pipes, flanges and collimators downstream. General radiation shielding is provided by the thick walls and the roof of ESA, as well as stacked concrete shielding blocks around the beam pipes.

To control the radiation levels around ESA and the SLAC boundary, the amount of beam that strikes the beam pipes can be limited by means of a current comparator. The current comparator consists of two average current monitors, I_1 and I_2, that measure beam currents entering the pivot and going to the dump, respectively. The beam-loss pattern varies with beam energy and target thickness, and EGS4 was used to determine this. Based on calculations and initial measurements, the total allowable beam loss had to be kept below 10 kW for the ESA experiments. The comparison of the amount of beam loss calculated by EGS4 with measured data is listed in Table 1.

Table 1. Beam loss between average current monitor I_1 and I_2

Beam energy (GeV)	Target thickness (r.l.%)	Beam loss calculated by EGS4	Measured values
4.3	6% Fe 12% Au	7.6% 24.5%	8.0% 27.0%
6.3	6% Fe 12% Au	2.9% 8.8%	4.2% 9.7%

A 500 kW collimator (9 feet long, 16-inch O.D., 10-inch I.D.) located near the beginning of the tunnel (see Fig. 5) helps keep target-scattered radiation from striking the pipe downbeam of the collimator. Very high radiation levels in the occupied areas opposite the tunnel are therefore prevented. However, since electrons impinge at such small glancing angles upon the inside surface of the collimator, it is still very easy for high-energy shower particles to escape down the pipe. These secondary particles themselves produce showers in the downstream pipe, which then cause radiation levels to increase in the occupied areas opposite the tunnel. This is clearly demonstrated in the SHOWGRAF plot given in Fig. 6, where shower radiation from a single high-energy (< 5.1 GeV) electron is observed to leak out of the collimator section and re-shower in the downstream pipe. Only 14-ft of about 100-ft of beam pipe between the well-shielded collimator and the beam dump is shown in this figure.

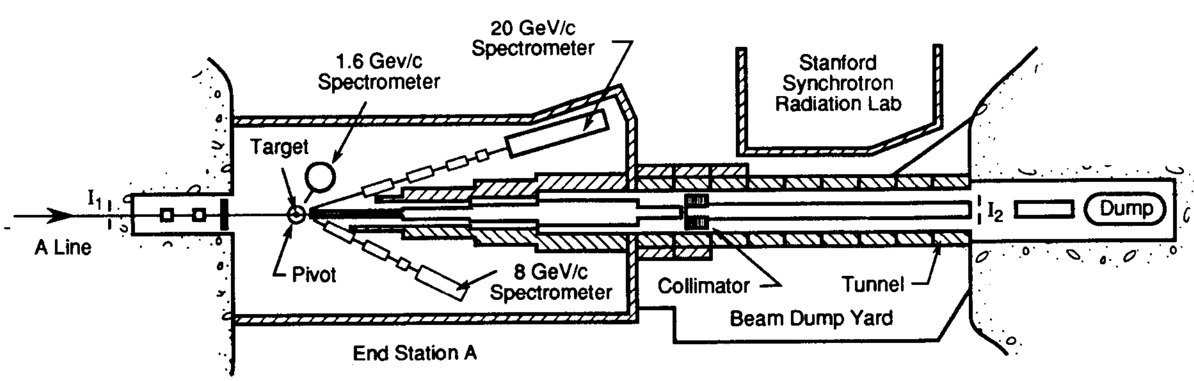

Fig. 5. Plan view of End Station A showing beam line, shielding, and tunnel to the beam dump.

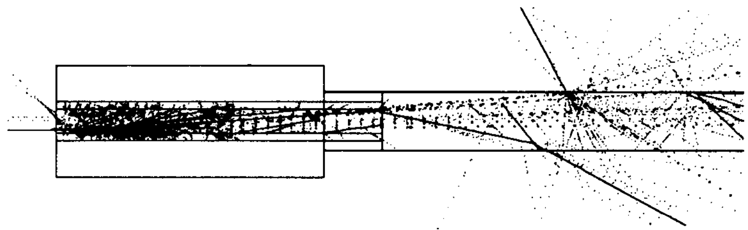

Fig. 6. A single (target-scattered) electron strikes the collimator from the left. Additional showers are produced in the beam pipe from leakage of the high-energy component.

C. Spatial Distribution of Induced Radioactivity

The induced activity produced in high-energy accelerator beam devices (*e.g.*, targets, stoppers, collimators, etc.) is largely due to photonuclear reactions, primarily through excitation of the giant resonance. When a photon in the EM shower interacts with a nucleus via the giant resonance mechanism, it may knock out one or more charged and/or uncharged nucleons. Typical giant resonance reactions are (γ,n), (γ,2n), (γ,pn), etc. While it is true that these nucleons may then interact with other nuclei, creating additional activity in the target, the majority of the induced activity is assumed to be created in the initial interaction. Based on this assumption, EGS4 was used to estimate the spatial distribution of the induced activity by scoring the yields and the locations of giant resonance neutron production.

The giant resonance neutron yield can be determined analytically for each reaction using

$$Y_{GRN} = \frac{6.02 \times 10^{-4} \rho f N_n}{A} \int_{E_{th}}^{E_{max}} \sigma(k) \frac{dl(k)}{dk} dk \quad (\mathrm{n/e^-}) ,$$

where

σ = giant resonance cross section (mb),[9]

$\frac{dl}{dk}$ = differential photon track length (cm/MeV),

ρ = density (g/cm^3),

A = atomic weight (g/mol),

f = isotope abundance,

N_n = number of neutrons per reaction,

E_{max} = upper limit of resonance cross section (MeV),

E_{th} = threshold energy (MeV).

This integration can also be done using the EGS4 Monte Carlo code, which will provide not only the total yield, Y_{GRN}, but also the spatial distribution of the interactions within the target. The differential yield is calculated within EGS4 using an estimator determined by multiplying each photon track length by the appropriate GRN cross section. This is done for photons with $E_{th} < k < E_{max}$ using a rejection scheme to properly account for the cross section shape.

Table 2 compares the neutron yields calculated by EGS4, using (γ,n), (γ,2n) and (γ,3n) cross sections, with experimental results presented by Swanson.[10]

Table 2. Neutron Yields from Thick Targets (34 MeV) (10^{12} n/kWs)

Target	Swanson[10] (Table XV)	This paper [EGS4]
Al	0.2	0.2
Fe	0.5	0.5
Ta	1.2	1.4
W	1.5	1.7
U	3.5	1.3*

*Note: Photo-fission not included.

Except for uranium, the EGS4 results are well within the ±20% experimental uncertainties. The photofission cross section was not included in this EGS4 calculation, but it could have been.

The spatial distribution of the induced radioactivity can also be easily determined. The activity is assumed to be produced randomly along each photon track, but is only scored if the photon energy is within the giant resonance energy limits.

Figures 7 and 8 show representations of the induced activity produced in a 4 cm long by 2 cm radius cylinder of tantalum. Electromagnetic shower theory[11] tells us that the number of particles produced in a shower is directly proportional to the incident electron energy. Therefore, going from 1000 incident electrons at 34 MeV/e$^-$ to 10 incident electrons at 3.4 GeV/e^- is expected to give approximately the same induced-activity yield. However, the spatial distribution of the induced activity changes with different incident energies because the shower profile changes. This is clearly shown in these figures.

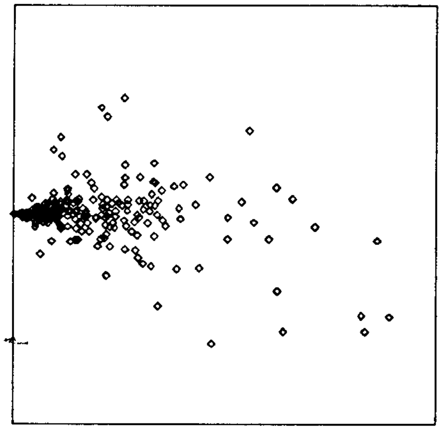

Fig. 7. Activity produced by 1000 incident e^- at 34 MeV/e^-.

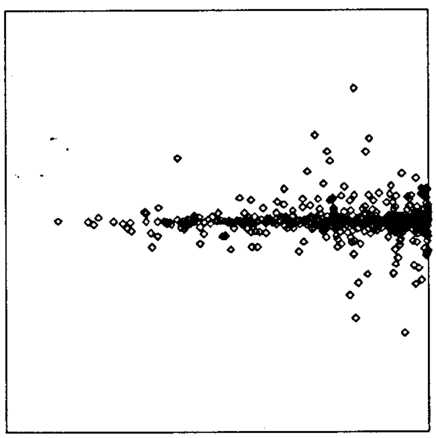

Fig. 8. Activity produced by 10 incident e^- at 3.4 GeV/e^-.

CONCLUSIONS

In this paper we have provided a brief glimpse of the capability of the EGS4 code to determine radiation sources along beam lines at electron accelerator facilities. The versatility of the system has been demonstrated by a few examples that represent practical problems of interest to high-energy physics, medical physics and industry, as well as radiation protection in general.

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