CONF-9510252--1
SLAC-PUB-95-7054
November 19915

# Calculation of Muon Background in Electron Accelerators using the Monte Carlo Computer Program MUCARLO*

S. H. Rokni, L. P. Keller, and W. R. Nelson
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309 USA

*Abstract*

The program MUCARLO is a computer code developed at the Stanford Linear Accelerator Center (SLAC) to study the muon flux generated from beams of electrons and positrons on various targets. The MUCARLO program has been modified extensively in recent years; this paper describes the latest version. Preliminary results from this code are presented, and compared with results from another computer program (TOMCAT) and with experimental data.

## 1 INTRODUCTION

In high energy electron accelerators, muons are mainly produced through the coherent electromagnetic pair production process. These muons easily penetrate massive shields and could become the dominant source of radiation outside the shields, at forward angles [1,2,3]. This issue has been well recognized and is evident in massive shielding down beam of dumps and experimental areas. In experimental detectors, these muons are also the source of backgrounds that have to be reduced to a tolerable level.

There are only a few computer codes that can be used to study muon production and transport in high-energy electron accelerators. The computer program, MUCARLO version 1.0 was developed by G. Feldman [4] to study the background problem in the MARK II (later SLD) detector from muons generated in beam-halo collimators in the final focus of the SLAC Linear Collider (SLC).

## 2 MUCARLO PROGRAM

In MUCARLO version 1.0, only the coherent production of muons from nuclei, the Bethe-Heitler process (Y. Tsai [5]), was considered. MUCARLO version 2.0 was developed by L. Keller for calculating the muon background in detectors for 0.5 and 1.0 TeV designs [6,7] for the Next Linear Collider (NLC). Muon production from direct annihilation of positrons on atomic electrons was added explicitly in this version; namely,

$$e^+e^- \rightarrow \mu^+\mu^- \qquad (1)$$

The direct annihilation mechanism contributes only few percent to the muon yield. However, for the highest energy muons, this channel is comparable to pair production off nuclei. To obtain the yield of muons within an electromagnetic cascade, the differential cross section for pair production of muons $d^2\sigma/dp_\mu\, d\chi$ (Tsai [5]) is calculated. The differential cross section for each muon momentum bin $dp_\mu$ and for critical angle bin $d\chi$ is then multiplied by the photon track-length distribution as described by Clement-Kessler [8], summing over all photon energies down to a predetermined cutoff value. To obtain the yield from the direct annihilation reaction, the EGS4 code [9] was used to calculate the differential positron track length initiated by a high-energy positron beam.

The MUCARLO program randomly selects initial momenta and angles weighted by the muon yield distribution. The trajectories from various sources are then tracked through the input geometry in equal steps. Each muon is followed until the trajectory either reaches the detector or ranges out. When material is encountered, the muon scatters, bends (if magnetic fields are present) and loses energy.

For calculation of energy loss, a simple parametrization of the total energy loss for a linear two-parameter fit [10] to data of Lohmann et al. [11] is used. A muon energy-range table look-up scheme, with linear interpolation between adjacent data points, can also be used. The Lohman et al. data consider ionization, bremsstrahlung, pair-production, and nuclear interactions. Ionization loss increases slowly with energy; whereas, the other processes grow linearly with energy and dominate over the ionization process at several hundred GeV. For multiple scattering, the Gaussian approximation is used with the width given by Lynch and Dahl [12] from a fit to Moliere distribution.

## 3 RESULTS

Results from MUCARLO were used to reduce the large muon background problem in the MARK II detector by installation of magnetized spoilers in the SLC final

*Work supported by Department of Energy contract DE-AC030-76SF00515.



Contributed to the Second Workshop on Simulating Accelerator Radiation Environment
CERN, Geneva, Switzerland, October 9–11, 1995

focus transport lines [4]. MUCARLO calculations were also used in the design studies for the NLC. Keller's calculations [6,7] show that with installation of magnetized spoilers, the NLC design goal of one muon in the dectector per $10^{10}$ electrons lost in the collimation section (1% beam loss) can be met.

In order to check the transport of muons, exclusive of the production term, results from MUCARLO calculations were compared with results of the computer program TOMCAT [13] and with data from an experiment performed at CERN [14]. In that experiment, beams of muons at 200, 240, and 280 GeV/c were incident on 300 m of earth shield after passing through 50 m of carbon. The muon fluence as a function of radial distance was measured with scintillation counters, nuclear emulsions and a silicon-diode telescope. Data taken with different detectors are consistent with each other. These experimental data are shown in Fig. 1. The solid line in this figure represents predictions from the analytic computer program TOMCAT [13], which uses the Fermi-Egyes theory for calculating the fluence at a radial distance from the axis of the muon beam. All range straggling is ignored; thus, a muon of a given momentum is assumed to have a unique range. The TOMCAT program uses the mean-square angle of scattering per unit distance, and assumes the scattering to be the sum of the Coulomb scattering from nuclei and from the orbital electrons, bremsstrahlung production from muon-nucleus scattering, and the nuclear (non-elastic) scattering process. The variation of the mean-square angle of scattering per unit distance versus energy [15] have been fitted and the empirical coefficients are used to describe the scattering from each of these processes.

Results from MUCARLO calculations were also compared with the experimental data. For carbon, in these calculations, a value of 2.3 $gm/cm^3$ was used for the density and a value of 18.0 cm was used for the radiation length. The same values for the earth shield are 2.0 $gm/cm^3$ and 12.0 cm, respectively. Gaussian distributions were used to represent the momentum and beam spot size distributions. The standard deviation for the momentum distribution was assumed to be 10% of the beam momentum. Beam spot size was represented with a Gaussian distribution ($\sigma_x = \sigma_y = 4.2$ cm). The distance from beam axis in the hole to the outside surface of the hole was assumed to be 3.5 m. A momentum bin of $dp_\mu = 1$ GeV, a critical-angle bin of $d\chi = 0.1$, and an upper critical angle limit of $3\chi$ were assumed for these calculations. The MUCARLO results are shown as histograms in Fig. 1. The features that can be noted are:

- At 280 and 240 GeV/c, MUCARLO results agree well with the experimental data at very forward angles. At larger angles, the calculations underestimate the measurements inside the hole by a factor of 3 at 280 GeV/c and by a factor of 2 at 240 GeV/c. On the other hand, TOMCAT predictions agree better with the data at wider angles, but underestimate the data at forward angles.

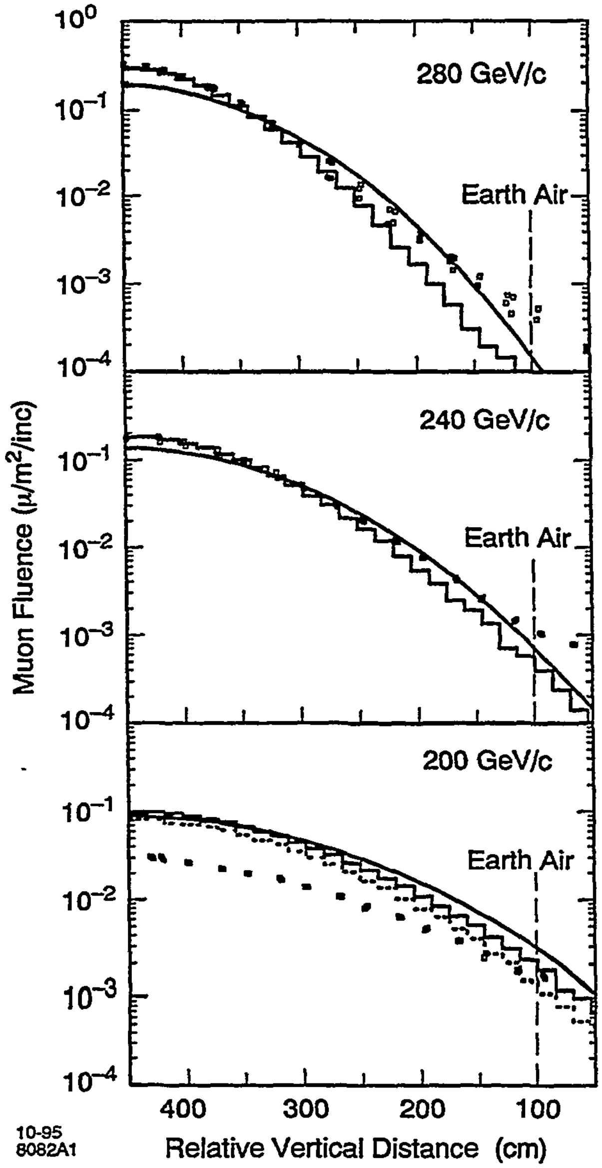


Figure 1: Radial distribution of muon fluence at a soil depth of 300 m. The muon beam axis is located at left corner at 450 cm. Experimental data are shown with symbols. The solid curves represent the TOMCAT results, and the solid and dashed histograms show results from MUCARLO calculations.

- At 200 GeV/c, MUCARLO calculations overestimate the data at all angles, and the same general pattern is also evident in the TOMCAT results.

One reason for the difference between the results from MUCARLO calculations and the experimental results at wide angles could be due to processes that have not yet been added to the scattering model; namely, scattering from bremsstrahlung, nuclear interaction, and pair-production processes that could result in rare, but large, angle scatters.

Another possible cause of the wide-angle discrepancy between MUCARLO and experimental data could be due to the uncertainty in the input geometry as modeled in MUCARLO. Based on comparison of the results of TOMCAT and MUCARLO for the geometry used in the MUCARLO calculations, a shift of up to 15 cm for the data near the surface at 280 GeV/c could be ascribed to the difference in the actual geometry and that simulated with MUCARLO program.

Straggling was suggested as a possible explanation for the disagreement between TOMCAT and the 200 GeV/c experiment [14]. Muon range straggling was included in MUCARLO, and the results still overestimate the data, as shown by the dashed line in Figure 1.

## 4 SUMMARY

MUCARLO is a Monte Carlo computer program developed at SLAC for production and transport of muons in high-energy electron accelerators. In order to test the muon transport term exclusively, preliminary results from MUCARLO are compared with results from the computer program TOMCAT and with experimental data taken at CERN. The MUCARLO calculations agree well with data at forward angles at 280 and 240 GeV/c, but underestimate the experimental results at wider angles. Low probability processes that contribute to the angular distribution at wide angles (e.g., bremsstrahlung, nuclear interaction) and uncertainties in the geometry as simulated in the program could be the sources of this discrepancy. At 200 GeV/c, both MUCARLO and TOMCAT underestimate the experimental data at all angles.

## 5 REFERENCES

[1] W. R Nelson et al., "The Shielding of Muons around High Energy Electron Accelerators: Theory and measurement", Nucl. Instrum. Methods, vol. 66, no. 2, pp. 293–303, 1968.

[2] W. R. Nelson, K. R. Kase, and G. K. Svensson "Muon Shielding Around High Energy Electron Accelerators: Part II. Theory," Nucl. Instrum. Methods, 120, pp. 413-429, 1974.

[3] W. R. Nelson and K. R. Kase, "Muon Shielding Around High Energy Electron Accelerators: Part I. Theory", Nucl. Instrum. Methods, 120, pp. 401–411, 1974.

[4] G. Feldman, "Muon Background at the SLC," SLC Collaboration Internal Presentation, March 1988.

[5] Y. Tsai, "Pair Production and Bremsstrahlung of Charged Leptons," Rev. Mod. Phys., vol.. 46, no. 4, pp. 815–851 October 1974.

[6] L. P. Keller, "Calculation of Muon Background in a 0.5 TeV Linear Collider," SLAC–PUB–5533, April 1991.

[7] L. P. Keller, "Muon Background in a 1.0-TeV Linear Collider," SLAC–PUB–6385, October 1993.

[8] G. Clement and P. Kessler, "Electroproduction of Very High–Energy Muons," Nuovo Cim., vol. 37, no. 3, pp. 876-887 June 1965.

[9] W. R. Nelson, H. Hirayama, and D. W. O. Rogers, "The EGS4 Code System," SLAC–265 December 1985.

[10] A. Fasso et al., Shielding Against High Energy Radiation, Berlin: Springer–Verlag, pp. 368–381, 1990.

[11] W. Lohmann et al., "Energy Loss of Muons in the Energy Range 1-10000 GeV," CERN 85-03, 1985.

[12] G. R. Lynch and O. I. Dahl, "Approximation to Multiple Coulomb Scattering", Nucl. Instrum. Methods, B58, pp. 6–10, 1991.

[13] G. R. Stevenson, "A Description of the TOMCAT Muon Transport Program" CERN Internal Report, HS–RP/IR/81–28 April 1981

[14] W. R. Nelson et al., "Transport of High Energy Muons in a Soil Shield," Nucl. Instrum. Methods, 215, pp. 385–396, 1983.

[15] R. G. Alsmiller et al., "Muon Transport and the Shielding of High-Energy Proton Accelerators," CERN 71–16, pp. 601–640, 1971.

*Refer questions to:*
**Sayed Rokni** – MS 48
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309 USA
Tel. +001 415 926 3544
Fax +001 415 926 3569
E-mail. ROKNI@SLAC.STANFORD.EDU

## DISCLAIMER