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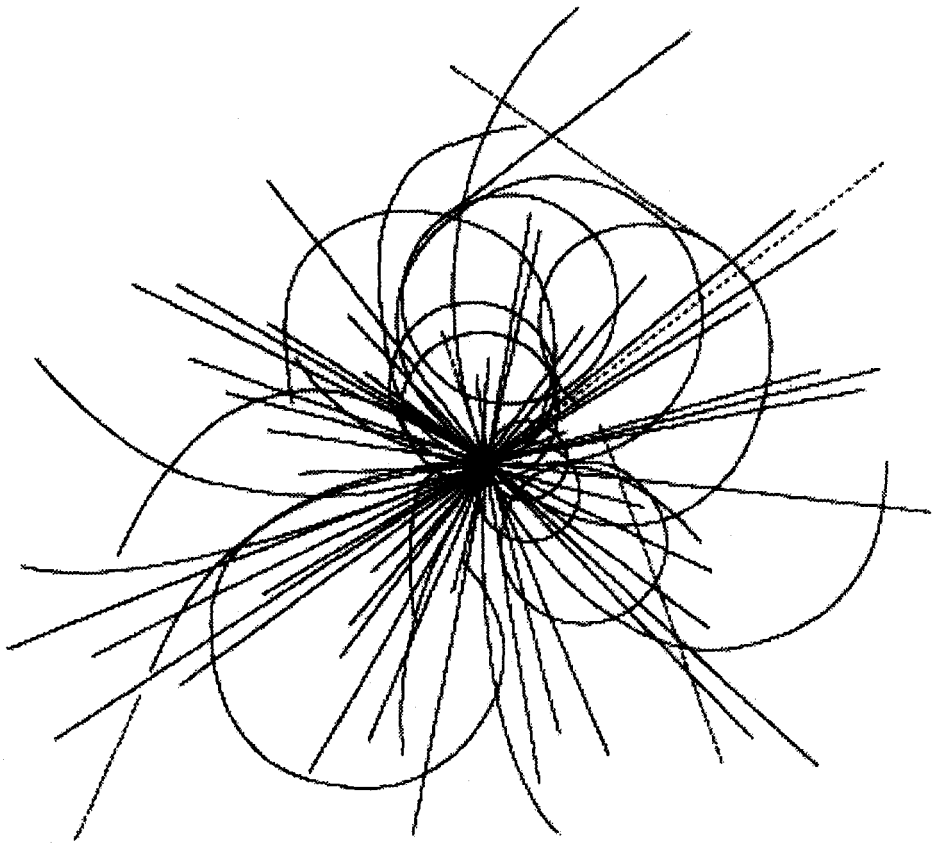

Superconducting Super Collider Laboratory

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M. V. Diwan and N. V. Baggett

Abstract

We calculate the total ionizing radiation dose in a model SSC calorimeter using well known parametrizations of electromagnetic and hadronic showers. We provide a simple method that can be applied to other calorimeter configurations.

1.0 INTRODUCTION

In this paper we quantify the ionizing radiation dose in a model SSC calorimeter. We use the idealized calorimeter parameters listed in Table 1. They roughly correspond to the GEM experiment.[1] The calorimeter is assumed to be homogeneous. Choices for materials of the calorimeter, cables, and hardened electronics will depend on the expected radiation dose.

Table 1. Parameters of a model SSC calorimeter.

	BARREL	ENDCAP	FORWARD
η Coverage	$\lvert\eta\rvert < 1.4$	$1.4 < \lvert\eta\rvert < 3.5$	$3.5 < \lvert\eta\rvert < 5.2$
Inner Radius	1 m	—	—
Inner z	—	2 m	4.5 m
Density	5.4 gm/cm^3	6.1 gm/cm^3	8.9 gm/cm^3
X_0	2.5 cm	2.2 cm	1.4 cm
λ_a	29.3 cm	31.7 cm	15.0 cm
dE/dx	6.7 MeV/cm	7.3 MeV/cm	12.9 MeV/cm

2.0 PARTICLE PRODUCTION

Reference 2 describes the gamma and charged hadron production for pp collisions at the SSC center of mass energy of 40 TeV. For both gammas and charged hadrons $dN/d\eta \approx 7.5$ particles per unit pseudorapidity. The mean $\langle P_\perp \rangle$ for gammas is about 0.3 GeV; for charged hadrons it is 0.6 GeV. We assume the luminosity of 10^{33} cm^{-2}s^{-1} for a standard SSC year of 10^7 s. This corresponds to a total of 10^{15} pp collisions at the interaction point.

3.0 SHOWER PARAMETRIZATIONS

The electromagnetic and hadronic showers are parameterized using Reference 3. If s is the depth inside the calorimeter and s/X_0 is the number of radiation lengths, then the longitudinal development of an electromagnetic shower is given by:

$$\begin{aligned} dE &= E\frac{x^{\alpha-1}e^{-x}}{\Gamma(\alpha)}dx \\ &\equiv E\,S(x)\,dx, \end{aligned} \tag{1}$$

where E is the incident energy in GeV and $x = \beta\,(s/X_0)$. α and β are both dimensionless and depend on the energy.

$$\begin{aligned} \alpha &= \alpha_0 + \alpha_1 \log(E) \\ \beta &= \beta_0 + \beta_1 \log(E). \end{aligned} \tag{2}$$

$\Gamma(\alpha)$ is the gamma function that normalizes the above distribution. The values of α_0, α_1, β_0, and β_1 are obtained by fits to data and Monte Carlo simulation. They are given in Table 2.

Table 2. Parameters for the longitudinal shape of an electromagnetic shower.

α_0	α_1	β_0	β_1
2.284	0.7136	0.5607	0.0093

The longitudinal profiles of hadronic showers are more complex because of several sources of fluctuations. They are caused by variations in the starting position of the shower and the separation of the shower into purely electromagnetic and purely hadronic components. The longitudinal profile is parameterized by a two-component function:

$$dE = E\left[c\,\frac{p^{\alpha_E-1}e^{-p}dp}{\Gamma(\alpha_E)} + (1-c)\,\frac{q^{\alpha_H-1}e^{-q}dq}{\Gamma(\alpha_H)}\right] \equiv E\left[H_e(p)dp + H_h(q)dq\right], \tag{3}$$

where E is the energy of the incident hadron, $p = \beta_E(s - s_0)/X_0$ is the number of radiation lengths traversed since the start s_0 of the shower multiplied by a dimensionless number, and $q = \beta_H(s - s_0)/\lambda_a$ is the number of absorption lengths multiplied by a dimensionless number. c is the fraction of the energy in the electromagnetic component of the hadronic shower. α_E, β_E, α_H, and β_H are dimensionless numbers that depend on the incident energy. $\Gamma(\alpha_E)$, $\Gamma(\alpha_H)$ are the gamma functions that normalize the distribution in Equation 3.

Simultaneous fit to various data described in Reference 4 and references cited therein give the following parameters for the hadronic shower profile.

$$\begin{aligned} &c = 0.4634 \\ &\alpha_H = 0.6165 + 0.3183 \log E, \qquad \alpha_E = \alpha_H \qquad (E \text{ in GeV}) \\ &\beta_H = 0.9099 - 0.0237 \log E, \qquad \beta_E = 0.2198. \end{aligned} \tag{4}$$

Though these fits are for pure iron and pure lead calorimeters, the results should be applicable to any calorimeter within an error of 50%. Calculations of total dose do not need to be more accurate. The error is mainly due to the soft part of the hadronic shower such as protons, neutrons, and other products from nuclear breakup. The contribution from these heavily ionizing particles tends to be highly material dependent (A discussion of the neutron radiation at the SSC is given in Reference 4.). Hadron showers below 1 GeV are not described by Equation 3. This limits the applicability of our formalism to $|\eta| > 1$ for hadron showers. Since the highest dose is caused by electromagnetic showers this consideration is not a major source of error.

4.0 RADIATION DOSE

We consider deposition of ionization energy in a volume element $dv = r^2\,dr\,d\Omega$ inside the calorimeter. The element dv is located at distance r and polar angle θ from the interaction point and subtends a solid angle of $d\Omega$. The number of particles into this solid angle is given by

$$\left(\frac{dN}{d\Omega}\right)_{\gamma,h} = \left(\frac{dN}{d\eta}\right)_{\gamma,h} \frac{1}{2\pi\sin^2\theta}, \tag{5}$$

where the subscripts γ, h refer to gammas or charged hadrons, respectively. The mean energy of these particles is given by:

$$E_{\gamma,h} = \left(\frac{\langle p_\perp \rangle_{\gamma,h}}{\sin\theta} \right). \tag{6}$$

Therefore, the energy deposited in volume element $dv = r^2\, dr\, d\,\Omega$ by electromagnetic showers produced by gammas from the interaction point is given by:

$$dE = \frac{1}{r^2} \left(\frac{dN}{d\Omega} \right)_\gamma E_\gamma\, S(x) \frac{dx}{dr} dv$$

where

$$E_\gamma \approx \frac{0.3\, GeV}{\sin\theta}; \quad \frac{dx}{dr} = \frac{\beta}{X_0}. \tag{7}$$

Similarly, the energy deposited in the same volume element by charged hadrons is given by:

$$dE = \frac{1}{r^2} \left(\frac{dN}{d\Omega} \right)_h E_h \left[H_e(p) \frac{dp}{dr} + H_h(q) \frac{dq}{dr} \right] dv$$

where

$$E_h \approx \frac{0.6\, GeV}{\sin\theta}; \quad \frac{dp}{dr} = \frac{\beta_E}{X_0}; \quad \frac{dq}{dr} = \frac{\beta_H}{\lambda_a}. \tag{8}$$

In the case of hadronic showers, the depth at which the shower begins can fluctuate according to an exponential distribution with a characteristic length λ_a. To be exact, therefore, we would need to convolute this exponential with the shower shape defined in Equation 3. Instead, we choose to take the beginning of the hadronic shower at the entrance to the calorimeter. This choice causes a small overestimate of the dose due to hadrons.

We use the geometry described in Table 1 and Equations 7 and 8 to compute the energy deposited in the calorimeter. If $\vec{r}$ is the location of the volume element, then the distance along $\vec{r}$ inside the calorimeter is computed and used in the computation. The radiation dose in rad is computed by dividing dE/dv by the density and using the conversion factor:

$$1 \text{ rad} = 6.24 \times 10^4 \text{ GeV/g}. \tag{9}$$

Finally, a factor of 10^{15} events/year is used to get the yearly dose. The result is displayed in a contour plot in Figure 1.

The highest dose levels are due to electromagnetic showers, concentrated in the front of the calorimeter. The hadronic dose spreads out over a much larger volume. The highest dose, of about 100 Mrad in our geometry, occurs in the forward calorimeter.

In the above calculation we have ignored the transverse spread of the showers. For the electromagnetic showers, which are responsible for the highest dose levels, the transverse size is characterized by the Moliere radius, which is much smaller than the size of the calorimeters that we are considering. Therefore

ignoring the transverse spread of the showers should result in a small overestimate at high pseudorapidities. Similarly the dose at the edges of the calorimeters is also overestimated because we have ignored the transverse leakage.

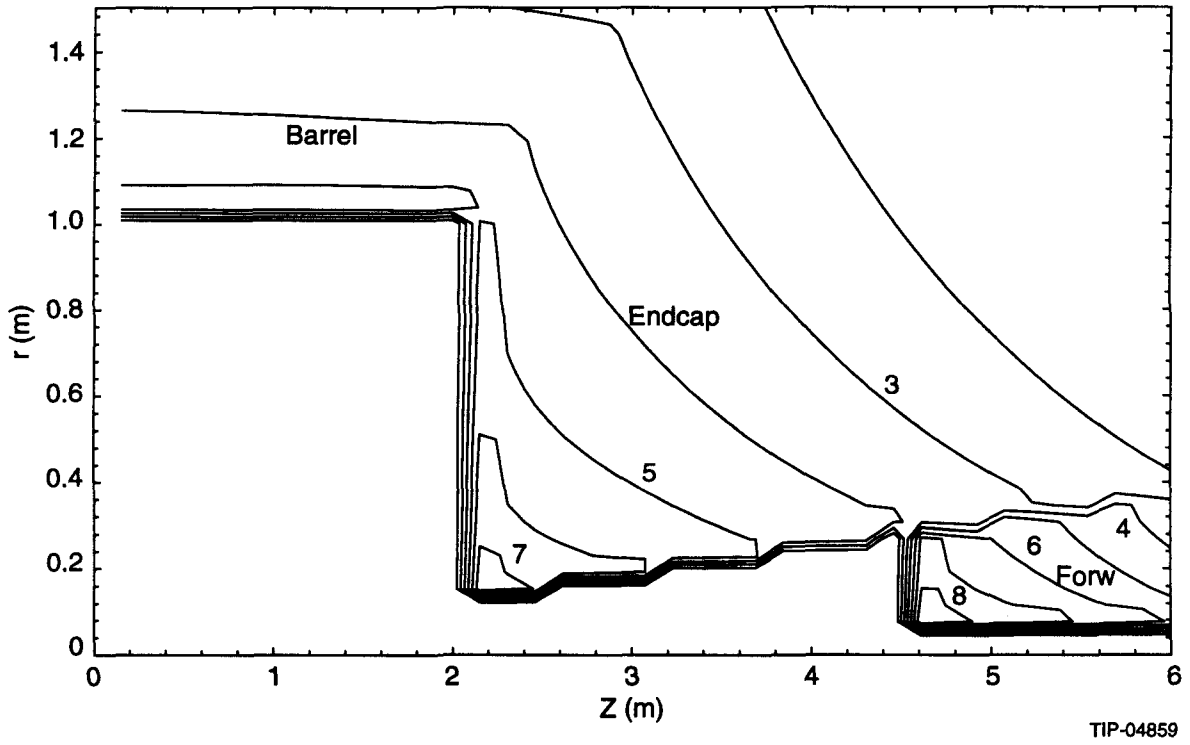

Figure 1. Contour plot of the yearly radiation dose to a model SSC calorimeter. The dose is given in 10^n rad. The contours are labeled by the exponent n. Table 4 shows the dose in some specific locations.

5.0 DOSE TO COMPONENTS AND CABLES

The dose to electronics components, cables, and other embedded materials will be different from the dose to the calorimeter because of the differences in density and *dE/dx* for minimum ionizing particles. Suppose we replace a small volume of calorimeter material by another object. Introduction of this object does not affect the development of the shower and therefore the same number of minimum ionizing particles traverse the volume element of the object. Since the density and *dE/dx* for the object are different from those for the calorimeter, the dose is given by the following:

$$(Dose)_{obj} = (Dose)_{cal} \frac{d_{cal}}{d_{obj}} \frac{(dE/dx)_{obj}}{(dE/dx)_{cal}} \tag{10}$$

where d_{cal}, d_{obj} are the densities of the calorimeter and the embedded object respectively, and $(dE/dx)_{cal}$, $(dE/dx)_{obj}$ are the ionization energy losses for minimum ionizing particles in the calorimeter and the embedded object, respectively. Table 3 lists densities and *dE/dx* for several common materials in the calorimeter. Using Tables 1 and 3 we find that the dose to the lighter materials listed in Table 3 can be about 50% higher than the dose to the calorimeter.

Finally, in Table 4 we list the expected yearly dose at several ρ, z positions in the calorimeter. ρ is the transverse distance from the beamline and z is the distance from the interaction point along the beamline. Table 4 also contains the dose for silicon and organic cable insulation.

Table 3. Density and *dE/dx* for several common materials.

MATERIAL	DENSITY gm/cm^3	*dE/dx* MeV/cm
Si	2.33	3.87
Polyethylene*	0.93	1.94
Mylar	1.39	2.58
G10	1.70	3.18

*Cable insulation

Table 4. Yearly dose at several ρ, z positions inside the calorimeter.

ρ (m)	z (m)	cal	Si	Cable
1.10	0.50	21 krad	28 krad	34 krad
1.10	2.00	25 krad	33 krad	40 krad
0.50	2.10	190 krad	250 krad	300 krad
0.30	2.10	0.9 Mrad	1.2 Mrad	1.5 Mrad
0.15	2.10	7.1 Mrad	9.5 Mrad	12 Mrad
0.10	4.60	44 Mrad	60 Mrad	72 Mrad
0.25	4.60	2.7 Mrad	3.6 Mrad	4.3 Mrad

ACKNOWLEDGMENTS

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