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SOLENOIDAL DETECTOR NOTES

IONIZING RADIATION ENVIRONMENT IN SSC DETECTORS

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Ionizing Radiation Environment in SSC Detectors *

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Estimates of ionizing dose and neutron fluence have been made for typical SSC detector configurations exposed to radiation from p-p collisions. Ionizing dose from direct particle flux from the interaction point depends only upon the inverse square of the distance from the beam line. Using a description of "average events" in conjunction with simulations of secondary processes, it is found for calorimetry that the ionizing dose rate can be adequately expressed as

$$\dot{D} = \frac{A}{r^2 \sin^{2+\alpha} \theta} .$$

Here A depends on the process and exposure time, α is slightly less than unity, and r is the distance from the interaction point. Under nominal operating conditions, an calorimeter element 2 m from interaction point and 6° from the beam line is subjected to an annual dose of 30 kGy at electromagnetic shower maximum.

This report includes provisional correction of an error in electromagnetic dose discovered in the Task Force Report.‡

1. Introduction

An SSC Central Design Group task force was formed to assess radiation levels to be expected in SSC detectors. Its findings are available in a thick report[1], and short versions have also been published[2]. Radiation *effects* were addressed by a separate task force[3]. In this report we present a very brief discussion of radiation levels.

This particular report is for a workshop on radiation damage to plastic scintillator. According to current wisdom[6], primary neutron damage to such materials in the environment of high-energy hadron colliders is totally insignificant as compared with the effects of ionizing radiation. *Secondary* effects exist, of course, because neutron recoil products are often ionizing. To the best of our knowledge such effects are relatively minor and are readily explained. Accordingly, all discussion of the neutron flux is omitted from this report.

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* This report is based on a version published in the *Proceedings of the ECFA Conference on Future Accelerators*, Madrid, Spain (Sept. 1989), but differs from it in three important respects: Table 1 in that report was wrong, and has now been corrected, the electromagnetic dose has been corrected (see the footnote below), and two figures specific to the detector being proposed by the Solenoid Detector Collaboration have been added.

† For the SSC Central Design Group Task Force on Radiation Levels in the SSC Interaction Regions: F. S. Alsmiller, R. G. Alsmiller, Jr., S. Ban, J. E. Brau, K. W. Edwards, A. Fassò, H. Fesefeldt, T. A. Gabriel , M. G. D. Gilchriese (Chairman), D. E. Groom, H. Hirayama, H. Kowalski, H.W. Kraner, N. V. Mokhov, D. R. Nygren, F. E. Paige, J. Ranft, J. S. Russ, H. Schönbacher, T. Stanev, G. R. Stevenson, A. Van Ginneken, E. M. Wang, R. Wigmans, and T. P. Wilcox, Jr.

‡ The maximum dose in the electromagnetic calorimeter due to incident photons from primary π^0 decay, as reported in Ref. 1 and in numerous conference proceedings, was high by a factor of three because of a trivial conversion error in Appendix 7. Corrected results given here. They are thought to be correct for the metallic part of the calorimeter, but to obtain the dose in the active part of the calorimeter they should probably be corrected upward by the stopping power ratio for the two media. For lead/scintillator the ratio is about 1.6.

This assessment could be wrong, and with some low priority neutron irradiations should be carried out. However, in most experimental test situations we can imagine, damage by boiloff neutrons (with the ≈ 1 MeV spectrum expected in the SSC environment) is completely overwhelmed by damage by incidental gamma rays. Reactor sources also produce a copious thermal neutron flux not present at accelerators. It is our subjective conclusion that experiments in which effects of the several kinds of irradiation are not unraveled are of very limited usefulness.

2. Assumptions

On the basis of SSC design parameters and extrapolation from S$\bar{p}$pS and Tevatron operating experience, the following assumptions were made:

- The machine luminosity at $\sqrt{s} = 40$ TeV is $\mathcal{L} = 10^{33}\,\mathrm{cm^{-2}s^{-1}}$, and the p-p inelastic cross section is $\sigma_{\rm inel} = 100$ mb. This luminosity is effectively achieved for 10^7 s yr^{-1}. The interaction rate is thus 10^8 s^{-1}, or 10^{15} yr^{-1}.
- All radiation comes from p-p collisions at the interaction point. For the SSC, the nominal luminosity contributes (300 hr)$^{-1}$ to the reciprocal current lifetime, so p-p collisions contribute as much radiation as dumping one of the beams into the apparatus every 6 days. Moreover, any process of comparable importance would prevent normal operation of the machine.
- The charged particle distribution is (a) flat in pseudorapidity for $|\eta| < 6$ and (b) has a momentum distribution whose perpendicular component is independent of rapidity, or approximately independent of pseudorapidity:

$$\frac{d^2 N_{\rm ch}}{d\eta\, dp_\perp} = H\, f(p_\perp) \tag{1}$$

(where $p_\perp = p \sin\theta$). Integrals involving $f(p_\perp)$ are simplified by replacing $f(p_\perp)$ by $\delta(p_\perp - \langle p_\perp \rangle)$; in the worst case this approximation introduces an 8% error.

- Gamma rays from π^0 decay are as abundant as charged particles. They have approximately the same η distribution, but half the mean momentum.
- The values $H \approx 7.5$ and $\langle p_\perp \rangle \approx 0.6$ GeV/c for $\sqrt{s} = 40$ TeV are obtained by extrapolating experimental results[4, 5], and are in good agreement with results obtained with standard fragmentation models. These values together with Eq. (1) are thought to describe particle production at the SSC within a factor of two or better.

3. Dose from direct particle production

Since $d\eta/d\Omega = (2\pi \sin^2\theta)^{-1}$, it follows from Eq. (1) that the flux of charged particles from the interaction point passing through a normal area da located a distance $r_\perp$ from the beam line is given by

$$\frac{dN_{\rm ch}}{da} = \frac{1.2 \times 10^8\,\mathrm{s^{-1}}}{r_\perp^2}\ . \tag{2}$$

In a typical organic material, a relativistic charged particle flux of 3×10^9 cm^{-2} produces an ionizing radiation dose of 1 Gy, where 1 Gy $\equiv$ 1 joule kg^{-1} (= 100 rads). The above result may then be rewritten as

$$\dot{D} = \frac{0.4 \text{ MGy yr}^{-1}}{r_\perp^2} \tag{3}$$

for an absorber much thinner than a nuclear interaction length, where $r_\perp$ is in cm.

In the presence of a magnetic field, low-energy particles make multiple passes through a test sample and so contribute to the dose more than once. This increases dose by about a factor of two.

Further dose enhancements might be expected from the secondary radiation ("albedo") of objects subjected to very high incident flux. For example, tracking devices which can "see" small-angle parts of the calorimetry will be subjected to back-scattered ionizing radiation.

4. Dose and fluence in a calorimeter

In a medium in which cascades can develop, the ionizing dose or neutron flux is at least roughly proportional to the particle energy striking unit area at a distance r from the interaction point. The charged particle flux is proportional to $(r^2 \sin^2\theta)^{-1}$, and the energy carried by the particles is proportional to $\langle E \rangle \approx p = p_\perp / \sin\theta$. The dose or fluence at cascade maximum is hence proportional to $1/(r^2 \sin^3\theta)$. Symbolically, this logic flow is as follows:

$$\left.\begin{array}{l}\left.\begin{array}{l}\left.\begin{array}{l}\dfrac{dN_{\rm ch}}{d\eta} = \text{Const} \\[2ex] \dfrac{d\eta}{d\Omega} = \dfrac{1}{2\pi \sin^2\theta}\end{array}\right\} \dfrac{dN_{\rm ch}}{d\Omega} = \dfrac{\text{Const}}{\sin^2\theta} \\[2ex] \qquad\qquad\qquad E \approx p = \dfrac{p_\perp}{\sin\theta}\end{array}\right\} \dfrac{dE}{d\Omega} = \dfrac{\text{Const}}{\sin^3\theta} \\[2ex] \qquad\qquad\qquad\qquad\qquad\qquad \dfrac{d\Omega}{da} \propto \dfrac{1}{r^2}\end{array}\right\} \begin{array}{l}\text{Neutron fluence} \\ \text{or ionizing dose}\end{array} = \frac{K}{r^2 \sin^3\theta} \tag{4}$$

This result is incomplete for a number of reasons. In the first place, the constant K must come from Monte Carlo simulations, hopefully supplemented by experimental measurements. Secondly, since showers lengthen with energy the maximum amplitude is not quite proportional to the incident energy density, so that the power of $\sin\theta$ is a little less than three. This is true for both electromagnetic and hadronic cascades. Finally, hadronic activity increases less rapidly than linearly with energy because π^0 production progressively "bleeds off" more and more energy to the electromagnetic channel as the incident energy increases, further reducing the power of $\sin\theta$ for processes such as neutron production. Even in this case, the combined effect is to reduce the exponent to about

2.7, so the above equation still provides guidance. The inverse r^2 dependence remains rigorously true, providing a serious constraint on detector design.

We rewrite the result as

$$\text{Ionizing dose rate} \equiv \dot{D} = \sigma_{\text{inel}} \int \mathcal{L}dt \, \frac{H \langle p_\perp \rangle^\alpha}{r^2} \frac{\text{Constant}}{\sin^{2+\alpha}\theta} = \frac{A}{r^2} \cosh^{2+\alpha}\eta \tag{5}$$

where the dependence on some machine-dependent parameters is made explicit. The second form is obtained with the aid of the identity $\cosh\eta = \sin\theta$.

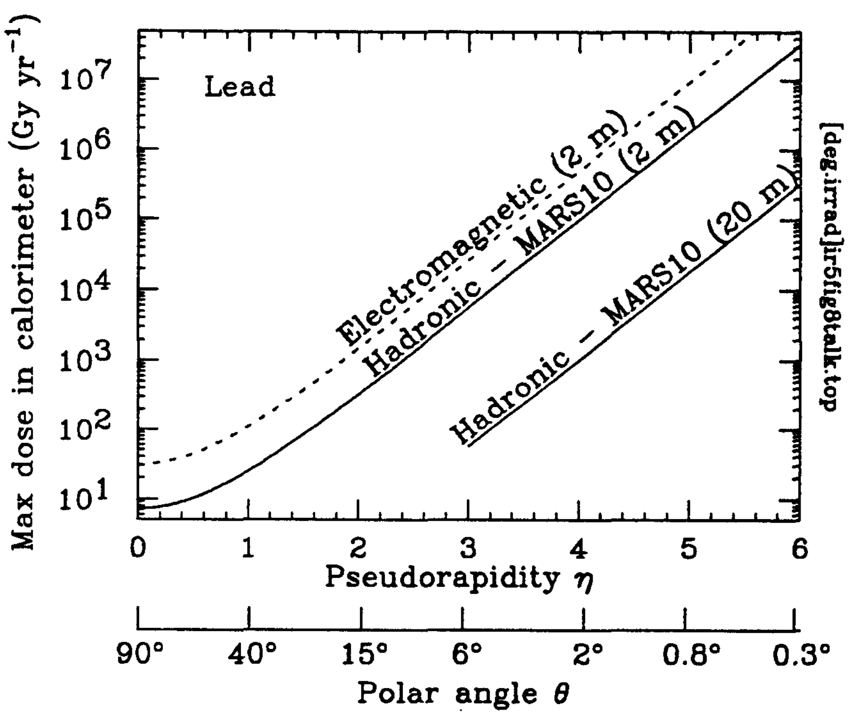

FIG. 1. The maximum hadronic dose as a function of pseudorapidity for a lead sphere, assuming that the maximum dose occurs at the indicated radius. The maximum electromagnetic dose in 1:1 uranium:scintillator is shown by the dashed line. Since the radiation length, nuclear interaction length, and density are nearly identical for the two materials, dose (but not neutron flux) results may be compared directly. The electromagnetic dose has been corrected downward by a factor of three, as described in an earlier footnote. Doses are for the high-Z absorber in the calorimeter, and should probably be corrected upward by a stopping power ratio (1.4 for silicon and 1.6 for scintillator) to obtain the dose in the sensitive material.

Values of A and α are given in Table 1 for the maximum dose rate produced by hadrons and photons from the interaction point. The corresponding functions (Eq. 5) are shown in Fig. 1. The electromagnetic maximum dose under standard conditions ($\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}, 1 yr $\equiv 10^7$ s) and high-luminosity conditions ($\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}, 10 yr $\equiv 10^8$ s) is shown in Figs. 2 and 3.

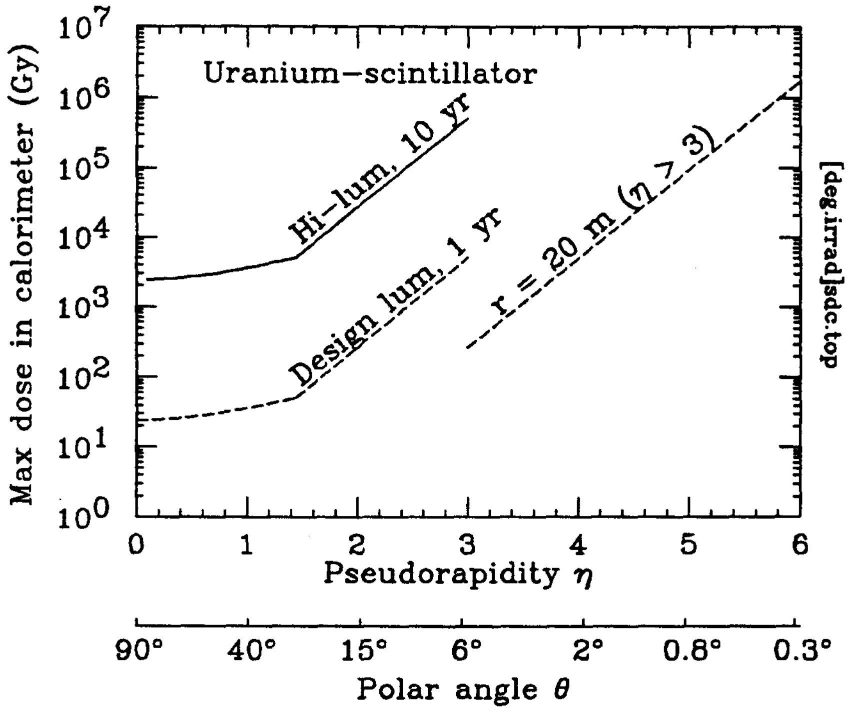

FIG. 2. The maximum dose from incident photons shown in Fig. 1, scaled to the dimensions of the SDC calorimeter (2.2 m to shower maximum in the radial direction, 4.7 m in the z direction). The dotted lines are for standard luminosity for one year, and the solid line is for $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for 10 years.The doses have been corrected downward by a factor of three from those given in Ref. 1, as described in an earlier footnote.

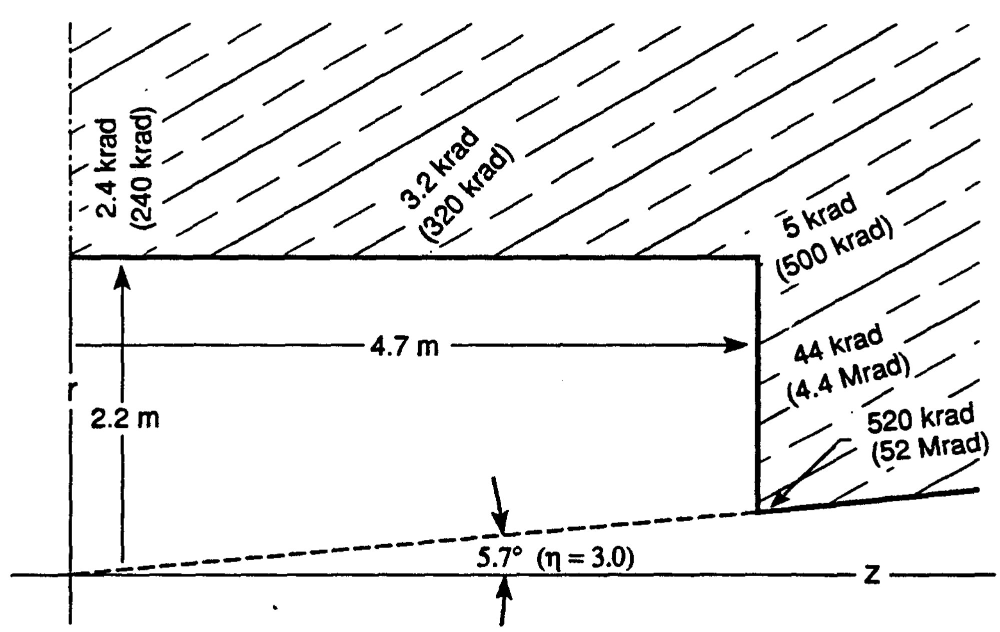

FIG. 3. Ionizing dose at electromagnetic shower maximum in the SDC detector at SSC design luminosity for one year and (in parenthesis) at $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for 10 years. The doses have been corrected downward by a factor of three from those given in Ref. 1, as described in an earlier footnote, and are for the high-Z absorber, not the sensitive material.

Table 1

Coefficients $A/(100 \text{ cm})^2$ and α for the evaluation of radiation levels at cascade maximum in SSC calorimetry under nominal operating conditions. At a distance r and angle θ from the interaction point the annual fluence or dose is $A/(r^2 \sin^{2+\alpha}\theta)$.

Quantity	$A/(100 \text{ cm})^2$	Units	$\langle p_\perp \rangle$	α
Dose rate from photons	124*	Gy yr^{-1}	0.3 GeV/c	0.93
Dose rate from hadrons	29	Gy yr^{-1}	0.6 GeV/c	0.89

*Corrected value.

On the average, a certain fraction of an electromagnetic shower at a given energy is contained in a distance $n_{EM}X_0$, where X_0 is a radiation length in the material. Similarly, a hadronic shower is contained in a distance $n_{\text{had}}\lambda_I$, where λ_I is the nuclear interaction length. Very roughly, $n_{EM} \approx 20$ and $n_{\text{had}} \approx 6$ for 99% containment at 1 GeV. About half as much energy is carried by π^0's as by other hadrons. We thus expect the maximum dose due to photons from π^0 decay to be about $\frac{1}{2}(n_{\text{had}}\lambda_I)/(n_{EM}X_0)$. The radiation length in lead is 6.37 g cm^{-2}, and the nuclear interaction length is 194 g cm^{-2}. The ratio is about 5, while the ratio obtained from Table 1 is 9.1. The agreement is regarded as satisfactory, given the uncertainty in n_{had} and n_{EM}.

6. Scaling to other machines

Using the scaling discussed in connection with Eq. (5) above, examples of scaling to other accelerators are given in Table 2. It should be noted that the assumption that all radiation comes from the interaction point does not apply to the present generation of accelerators.

Table 2

A rough comparison of beam-collision induced radiation levels in calorimetry at the Tevatron, УНК, high-luminosity LHC, and SSC.

	Tevatron	УНК-3	LHC	SSC
$\sqrt{s}$ (TeV)	1.8	6	16	40
$\mathcal{L}_{\text{nom}}$ ($\text{cm}^{-2}\text{s}^{-1}$)	2×10^{30}	4×10^{32}	$4 \times 10^{34\dagger}$	1×10^{33}
σ_{inel}	59 mb	80 mb	86 mb	100 mb
H	4.1	4.5	6.3	7.5
$\langle p_\perp \rangle$ (GeV/c)	0.46	0.52	0.55	0.60
Scale factor‡	5×10^{-4}	0.2	27	1

† High-luminosity option.

‡ Proportional to $\mathcal{L}_{\text{nom}}\, \sigma_{\text{inel}}\, H\, \langle p_\perp \rangle^{0.7}$

7. References

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