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THE RADIATION FIELD IN AND AROUND HADRON COLLIDER DETECTORS

Graham R. Stevenson and Alberto Fassò
CERN, 1211 Geneva 23, Switzerland

Alfredo Ferrari and Paola R. Sala
INFN, Via Celoria 16, I-20133 Milan, Italy

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I. INTRODUCTION

In the coming generation of hadron colliders such as the Large Hadron Collider (LHC) which is planned for construction at CERN or the Superconducting Super Collider (SSC) which is under construction at Waxahachie in Texas (USA), the collision rate between protons having an energy of up to a few tens of TeV will approach 10^9 per second. The power dissipated by these collisions is some 3 kW, mainly appearing in the form of energetic secondary pions, about 200 per interaction. The average energy of these secondaries varies from more than 10 GeV at angles to the primary beam of less than 5° to 0.5 GeV at angles of 90° . These secondaries will generate hadronic and electromagnetic cascades, which, in addition to providing information of use in understanding some of the more exotic examples of proton-proton collisions, will cause radiation damage to the inner parts of the detector, especially in the forward regions. A typical collider detector is described in the Letter of Intent of the Solenoidal Detector Collaboration for the SSC [1]. Given the importance of these experiments in terms of the physics yield and the money and resources devoted to them, it is essential to be able to predict correctly both the nature and the magnitude of this radiation exposure. One is not only interested in the type of exposure which will cause organic insulating materials to become brittle and will damage scintillating materials, but also in the large number of low-energy neutrons produced by spallation, evaporation and fission processes in the high-energy hadron interactions in the cascade. These will damage electronic components and silicon-based detector systems.

In the following section it will be demonstrated that existing knowledge from the present generation of hadron colliders, *i.e.* the proton-antiproton machines at CERN and at Fermilab near Chicago, allow reasonable extrapolations of the average behaviour of the angular distributions of secondaries from proton-proton collisions in the 10 TeV range to be made. Computer programs have been developed, such as DTUJET of Ranft and his co-workers [2, 3], which can generate secondary particles according to specific physical models which have been rigorously tested at existing colliders. The energy and angular distributions of the different secondary particles will be illustrated.

These secondaries are then used as input to computer simulations of the cascades in the collider detectors. These computer simulations have been developed at a number of laboratories in the U.S., Russia and CERN. They are used in the prediction of damage and radioactivation in both space and accelerator-produced radiation fields. A short summary of these cascade simulations will be presented.

Experimental evidence will be given to indicate the reliability of these codes in providing information on the type and energy distributions of the secondaries in the cascades. In typical experiments the radial and longitudinal distributions of different cascade components have been measured, (see, for example [4, 5, 6]). Without these experimental checks of the numbers of low-energy neutrons from cascades initiated by hadrons of known energy and in simplified geometries, one cannot decide if the predictions of the cascade programs in the complex geometries of collider detectors and in cascades initiated by the fragments of the proton-proton collisions are correct.

It is especially important to include the correct mixture of heavy inorganic materials which play a dominant role in the development of the electromagnetic cascades and in the production of low-energy neutrons. It is also essential to include the correct mixture of hydrogenous materials since the moderating effects of these materials on the observed neutron spectrum can be quite dramatic.

Finally data will be presented concerning the particle fluences and energy distributions in different parts of a typical collider detector. The shape and distribution of detector elements will be shown to have a major effect on

Figure 1: Pseudorapidity distributions of charged particles at 0.54, 0.9, 1.8, 16 and 40 TeV (from bottom to top of this Figure). The symbols represent experimental data at the lowest three energies [7] and the histograms are predictions made using DTUJET [3].

expected flux levels.

II. THE P-P INTERACTIONS

In assessing the damage to be expected due to radiation inside a collider detector one is interested in the number, type and energy and angular distribution of the secondaries that come from the inelastic p-p interactions. Because most of the secondaries and the most energetic are produced close to the direction of the incoming proton, one does not express the angular distribution in terms of the space-angle, θ between the outgoing secondary and one of the incoming protons, but rather in terms of the pseudorapidity, η , where.

$$\eta = -\ln(\tan \theta/2). \quad (1)$$

Using this representation of the angle, measured angular distributions of hadronic secondaries, mainly pions, are given in Figure 1 for p- $\bar{p}$ interactions at beam energies of 270, 450 and 900 GeV (centre-of-mass, c.m., energies of 540, 900 and 1800 GeV) [7]. The number of neutral pions emitted is about one-half of the number of charged pions, and their angular distribution is essentially the same

In recent years it has become possible to construct theoretical models for the production of secondaries in inelastic p-p collisions. One of these is contained in the program DTUJET [2, 3]. The angular distributions predicted at the energies of the experimental data are also given in Figure 1 and it can be seen that there is good agreement between the model and experimental data. Also shown in this Figure are the distributions to be expected at the energies of the future LHC and SSC colliders. The spectra

Figure 2: Transverse momentum spectrum of charged hadrons as calculated by DTUJET at LHC energies. The symbols correspond to the following pseudo-rapidity intervals. + 0.0-1.0; ◇ 1.0-2.0; □ 2.0-3.0; * 3.0-4.0; × 4.0-5.0; ○ 5.0-6.0.

in general are relatively flat over the pseudorapidity range $-3 < \eta < 3$ and the height of the plateau does not vary strongly with proton energy. The predictions of DTUJET are somewhat sensitive to the structure functions used [8], but extrapolation of existing experimental data to the energies of the future colliders, even if made without the aid of a theoretical model, would involve errors of less than a factor of two.

The transverse momentum distribution for different pseudorapidity intervals obtained using DTUJET at LHC energies is given in Figure 2. It will be seen that the momentum distribution is not strongly dependent on angle. The variation of the mean of these distributions is shown as a function of proton energy in Figure 3, where the predictions of DTUJET again compare well with experimental data [3].

These general characteristics of p-p interactions were summarized in an SSC Task Group Report which was an extensive study of dose and neutron fluence within collider detectors [9] where it was suggested that the multiplicity of 'minimum bias', 'average' events could be well-approximated by a plateau function of pseudorapidity where the number of particles produced per unit of pseudorapidity is a constant, H , with all particles having the same transverse momentum $\langle p_T \rangle$. If

$$\frac{dN_{ch}}{d\eta} = H, \quad (2)$$

then

$$\frac{dN_{ch}}{d\theta} = \frac{H}{\sin \theta}, \quad \text{or} \quad \frac{dN_{ch}}{d\Omega} = \frac{H}{2\pi \sin^2 \theta}, \quad (3)$$

and

$$E \approx p = \frac{\langle p_T \rangle}{\sin \theta}. \quad (4)$$

Figure 3: Variation of the average transverse momentum as calculated by DTUJET over the restricted regions $\eta < 2.5$, $\circ$, and $\eta < 1$, ∇ . The model predictions are compared with experimental data *, $\times$, $\diamond$ and $+$ [3].

The constants for use in these relations are given in Table 1. The values given are based on extrapolations from experimental data, but these are in excellent agreement with predictions based on Monte-Carlo simulation programs of the p-p collisions such as DTUJET.

Table 1: Production constants for the new colliders

Collider	LHC	SSC
Energy	8 + 8 TeV	20 + 20 TeV
H	6.3	7.5
p_T	0.55 GeV/c	0.60 GeV/c
I	10^9 s^{-1}	10^8 s^{-1}

The constant H of equation (2) determined from DTUJET at LHC energies is 6.1 which compares well with the value of 6.3 given in Table 1 taken from the Task Group Report. The mean value of p_T is 0.44 GeV/c which is somewhat lower. The constant H for pi-zero emission is one-half of the value for charged pion emission. Values of the charged pion fluxes at 1 metre from the interaction point at LHC and SSC energies as a function of angle and the mean kinetic energies are given in Table 2. Also given in Table 1 is the maximum design value of the inelastic interaction rate, I , in a collision region of the two accelerators. These data are the input necessary for calculating neutron fluxes and doses in the collider detectors.

III. IDEALIZED DETECTORS

The SSC Task Group on Radiation Levels in Detectors [9] summarized available experimental data and cascade simulations in order to derive simple relations between the

Table 2: Mean kinetic energy $\langle E_k \rangle$ and charged pion flux densities ϕ at 1 m from the collision point

Angular interval degrees	LHC		SSC	
	$\langle E_k \rangle$ GeV	ϕ $\text{cm}^{-2}\text{s}^{-1}$	$\langle E_k \rangle$ GeV	ϕ $\text{cm}^{-2}\text{s}^{-1}$
0.3–0.8	70	1.3×10^9	76	1.5×10^8
0.8–2.1	26	1.7×10^8	28	2.1×10^7
2.1–5.7	9.4	2.4×10^7	10	2.8×10^6
5.7–15.4	3.4	3.2×10^6	3.7	3.9×10^5
15.4–40.4	1.2	5.0×10^5	1.3	5.9×10^4
40.4–90.0	0.52	1.3×10^5	0.58	1.6×10^4

maximum dose in a slab structure, the maximum neutron flux and the albedo neutron flux as a function of incident hadron energy. It was shown that the maximum laterally integrated dose from a hadron, D_h in $\text{Gy}\cdot\text{cm}^2$, can be represented by:

$$D_h \approx 3.8 \times 10^{-10} E_k^{0.89}, \quad (5)$$

where E_k is the kinetic energy of the hadron in GeV. The actual value of the dose at a given angle is then obtained by multiplying D_h by the hadron fluence at that angle derived from equation (3).

The maximum dose in a photon-induced cascade is given by:

$$D_\gamma \approx 3.2 \times 10^{-9} E_\gamma^{0.89}. \quad (6)$$

The maximum electromagnetic dose in a calorimeter is calculated using the fact that the number of neutral pions emitted is one-half of that given by equation (3), that the mean p_T is the same and that each π^0 gives two photons each carrying one-half of the energy of the π^0 .

The maximum dose is then the sum of the hadronic and electromagnetic components, and can be shown not to depend strongly on material composition.

The maximum area-integrated neutron fluence in a lead calorimeter is given by an equation of the form [9]:

$$\int 2\pi r \phi dr = 31 \times (E_k/1\text{GeV})^{0.67}. \quad (7)$$

In scaling from calculations and experiments with different materials the data of Table 3 taken from [9] can be

used.

Table 3: Neutron Production in Different Calorimeters

	Scale by
U-LAr or Si	1.8
Pb-LAr or Si	1.0
U-Scint	0.6
Fe-LAr or Si	0.4
Pb-Scint	0.3

The maximum dose and neutron fluence in a calorimeter whose geometry has been simplified to that of a spherical lead shell of 2 m internal radius around the collision point is given in Figure 4 for LHC operating conditions with an average collision rate 60% of that given in Table 1 and an operating time of 10^7 seconds per year. It will be seen in a later Section of this paper that care must be taken in using the simple procedures described here in the low pseudorapidity regions when there can be significant albedo from the high pseudorapidity regions of the detector.

The dose rate inside the central cavity of a calorimeter can be determined by multiplying the hadron fluence derived from equation (3) by the conversion factor of 6.4×10^{-10} Gy.cm² [10]. This is a factor of two higher than the conversion factor derived from considering Coulomb energy losses alone of the hadrons. The increase is due to inelastic reactions of the pions. This means that the annual dose to a cylindrical detector of 10 cm internal radius will be 4×10^4 Gy at the LHC.

The neutron fluence inside the central cavity comes from the albedo of the hadron cascade in the calorimeter. For a spherical lead shell calorimeter of internal radius 2 m where the parts of the shell in the region $\eta > 3$ have been removed, it was suggested in [9] that the annual neutron fluence would be approximately 2×10^{13} cm⁻² at the LHC. This neutron fluence is not very dependent on position inside the central cavity. Although sufficient to situate the degree of any radiation damage in the central cavity due to neutron irradiation, the actual value will depend strongly on the actual geometry and materials from which the detectors are made. In certain configurations, fluence values at large angles could be an order of magnitude higher [11].

IV. THE CASCADE SIMULATIONS

Whereas the previous arguments are sufficient in order to roughly estimate the doses and neutron fluences to which detector components will be exposed, the effects of local diffusion and absorption, with channelling of neutrons and the albedo of even several hundred MeV hadrons from the forward regions were not taken into account. In order

Figure 4: The variation with angle of maximum neutron fluence and maximum total dose in a 2 m lead shell under LHC conditions.

to obtain more accurate estimates and to obtain the distribution in type and energy of the radiation field, Monte-Carlo simulations in a geometry more representative of a real detector must be made. In recent years much effort has gone into developing simulation programs in order to follow the showers induced by high-energy hadrons and electrons. In the following only the latest version of the FLUKA code [12] will be described. This code has been widely used at CERN for shielding and radiation damage predictions. Other codes which are available are the HETC code of ORNL [13] and HERMES of KFA Jülich [14] which has been developed from HETC.

FLUKA has undergone substantial improvements since its previous 1986 release [15]. Improvements to the inelastic event generator include a) modifications to the sampling procedures for the number of nucleon-nucleon collisions inside a nucleus and the number of secondaries emitted during the intranuclear cascade and evaporation phases of the interaction, b) an improved treatment of the nuclear well potential and of the Fermi motion of nucleons inside the nucleus and the use of accurate atomic mass tables to account for nuclear binding energy, c) a more exact determination of the nuclear excitation energy, and d) a more consistent treatment of collisions with hydrogen nuclei. Other major upgrades have been the incorporation of a nuclear evaporation model, accounting for the emission of neutrons, protons, heavy fragments and gamma rays from excited nuclei, and the introduction of a new cascade pre-equilibrium model which represents a substantial improvement over existing models for proton and neutron induced reactions in the energy range 20 to 250 MeV.

There have been major improvements to the transport module for photons and electrons which was originally derived from the EGS4 code [16]. There are completely new treatments of multiple Coulomb scattering, the angular distribution from pair production, the photoelectric

effect and bremsstrahlung with an inclusion of the Landau-Pomeranchuk-Migdal effect [17, 18].

Changes to the transport module of FLUKA are mainly concerned with lowering the energy thresholds for particle transport. In particular, it is now possible to follow neutron collisions and transport down to optionally defined region-dependent energy cut-offs which can be as low as thermal energies. This part of the FLUKA code is very similar to the transport part of the MORSE code [19] but so many modifications were required that completely new subroutines were written. New cross-section data sets were made available in a collaboration with the Italian ENEA-Bologna laboratory which is specialized in nuclear data processing [20]. These contain data for some 40 elements which are commonly used in accelerator and detector technologies. They contain 72 neutron energy groups and, whenever available, gamma production data have been included. Reduced Doppler broadening has been taken into account for a few materials where data sets are available at liquid argon (87°K) and liquid helium ($\approx 4^\circ\text{K}$) temperatures. Finally, neutron dose can be determined from kerma files.

V. BENCHMARK EXPERIMENTS

As part of a series of experiments at different primary energies and with different absorber materials, measurements were made of the radial and longitudinal distribution of high-energy hadron fluence, low-energy neutron fluence and dose in iron and lead calorimeter-like structures irradiated by 200 GeV/c and 24 GeV/c hadrons [4, 5, 6]. The objectives of this series of experiments were twofold. Firstly they provide experimental data that can be used directly to predict the damage to be expected in collider detectors. Secondly these measurements provide benchmarks for hadron cascade simulation programs such as FLUKA.

One of the activation detectors used in these experiments to determine the neutron fluence above a threshold of about 0.5 MeV uses the $^{115}\text{In}(n,n')^{115m}\text{In}$ reaction. The conditions of the experiments were simulated as accurately as possible using the FLUKA program. The actual production of the ^{115m}In isotope per proton incident on the calorimeter structure and per mole of parent atom was determined in the simulations using known cross-sections and compared with the measurements. This production can be converted in neutron fluence using average "effective" cross-sections, but the fluences can never be guaranteed to have systematic errors due to this conversion of less than 50%. This is why comparisons must be made on the basis of production rather than fluence. An example of these comparisons is given in Figure 5 taken from [21] where the radial profiles are given at different depths in a lead calorimeter placed in a beam of 200 GeV/c protons.

Figure 5: Variation of the production of ^{115m}In from ^{115}In as a function of radial distance off-axis in an iron calorimeter structure irradiated by 200 GeV/c protons. The data at the different depths have been multiplied by the given factors before plotting in order to clarify the Figure.

Figure 6: The variation of the radially integrated production of ^{115m}In from ^{115}In as a function of depth in iron and lead structures irradiated by 200 GeV/c and 24 GeV/c protons.

It will be seen that the agreement between the FLUKA predictions and the experimental data is better than 20%. The longitudinal variation of the transversely integrated production is given in Figure 6. The worst disagreement occurs with lead as the absorber material where the difference between predictions and measurements reaches 40%.

Measurements of the radial distribution of dose at different depths using radiophotoluminescent detectors were also simulated. Examples of FLUKA comparisons with selected data are given in Figures 7 and 8. It will be seen that the agreement is not as good as with the data from activation detectors.

VI. MORE EXACT SIMULATIONS

Figure 7: Variation of dose as a function of radial distance off-axis in an iron calorimeter structure irradiated by 24 GeV/c protons. The data at the different depths have been multiplied by the given factors before plotting in order to clarify the Figure.

Figure 8: The variation of the radially integrated dose as a function of depth in iron and lead structures irradiated by 200 GeV/c and 24 GeV/c protons.

Figure 9: The geometry of the calorimeters for the EAGLE detector. The arrow indicates the region between the electromagnetic and hadron calorimeters of the barrel part of the detector where the spectra reported in this paper have been calculated.

In the current studies for the LHC, the calorimeters of the EAGLE detector have been simulated, see Figure 9, and calculations made of the spectra and dose in different parts of the detector. As an example of these calculations, details of which are reported elsewhere [12], Figures 10 and 11 give the neutron spectra and charged hadron spectra at the point indicated by the arrow in Figure 9. The neutron spectrum has a strong peak near to an energy of 100 keV. This is typical of detectors where no hydrogenous material is present. The charged pion and proton spectra are very similar to the neutron spectrum above an energy of 150 MeV. Below this energy, slowing-down by Coulomb interactions causes the charged particle spectra to fall below the neutron spectrum. It will be seen in Figure 11 that the charged kaon contribution is negligible.

Using simulation programs such as FLUKA it is possible to obtain the energy spectra of all components of the radiation field, including electrons and photons. However a significant allocation of computer time is required. One simulation requires about 30 minutes of cpu time on an IBM 3090/E computer (equivalent to several hours of IBM 370/168-3 cpu time).

VII. GEOMETRICAL AND OTHER EFFECTS

The material composition and the geometrical design will greatly influence the radiation levels in different parts of the detector. For example lining the inner surface of the electromagnetic calorimeter with 10 cm of polyethylene will reduce the fluence of neutrons with energies above 100 keV in the central cavity by almost an order of magnitude [9].

Figure 10: The neutron spectrum at the reference position between the electromagnetic and hadron calorimeters of the barrel part of the detector.

Figure 11: The charged hadron spectra and the high-energy part of the neutron spectrum at the reference position between the electromagnetic and hadron calorimeters of the barrel part of the detector. + neutrons; * protons; o charged pions and x charged kaons.

Figure 12: The neutron fluence under LHC operating conditions close to the inner surface of spherical lead calorimeter for different opening angles of the cone. Solid histogram refers to a cone angle of pseudorapidity 5, $\theta = 0.8^\circ$, the dotted histogram to a cone-angle of pseudorapidity 3, $\theta = 6^\circ$ and the dashed histogram to a cone-angle of pseudorapidity 1, $\theta = 40^\circ$.

The opening cone angle through the end-cap of the detector is also of great importance. It was shown in some very early studies [22] that the energy fluence incident on the 0–1 pseudorapidity interval (*i.e.* in the angular interval between 40 and 90°) is an order of magnitude higher than the energy fluence emitted from the p-p collisions into this angular interval when the cone-angle through the forward part of the detector is reduced to nearly zero degrees. In some recent calculations using a spherical lead shell to simulate the detector [11], the neutron fluence close to the inner surface of the shell was also shown to depend strongly on the cone opening angle, as can be seen in Figure 12.

VIII. CONCLUSIONS

Simple calculations based on analytic representations of secondary production from p-p collisions and empirical formulae for the variation of neutron fluence and dose in hadron cascades with energy already indicate that the annual doses to various parts of a collider detector are such that without careful selection of components radiation damage is inevitable. More information on the composition of the radiation field inside the detector can be obtained using Monte-Carlo simulations of the secondary particle production and of the hadron cascades. Comparisons of cascade simulations using programs such as FLUKA in simplified geometries and with a single energy and type of incident hadron are however essential in order to have confidence in the predictions of these same programs in the complex geometries of collider detectors.

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