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NEUTRONS IN CALORIMETER STRUCTURES

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Abstract

The proposed high-energy, high-luminosity hadron colliders (SSC and LHC) present new, challenging radiation environments for detector components. The universal need for calorimeter coverage in experiments at these colliders means that the full hadronic energy will be deposited in heavy materials close to or interleaved with detectors and electronics. Neutron generation in the hadronic cascades becomes a major damage mechanism. In this paper, previous discussions of neutron fluences to be expected are updated by new data, especially relating to the higher luminosity proposed for the LHC. Recent experimental checks of the conclusions from simulation studies are presented.

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1 Introduction

Two years ago an SSC Task Group was formed to assess the radiation levels to be expected in an SSC detector. The findings of this Task Group were published in an SSC report [1], and several shortened versions have been published since then (see [2] for example). The Task Group Report summarized experimental data and Monte-Carlo cascade simulations from which the following parameters could be derived for an idealized detector geometry: that of a hollow sphere of 2 metres internal radius where forward and backward cones in the high-rapidity region had been removed. The parameters of interest are:

- Dose to thin detectors in the central cavity from charged particles and photon conversions,
- Albedo neutron fluence in the central cavity region,
- Photon albedo,
- The maximum neutron fluence in the calorimeter, and
- The maximum dose in the calorimeter.

The purpose of this paper is to review other evidence which can help in determining especially those parameters concerned with neutron fluence in the central cavity and inside the calorimeter together with summarizing new data which have appeared since the Task Group met.

2 Source Considerations

Evidence was reviewed in the Task Group Report which showed that the the multiplicity of 'minimum bias', 'average' events can be well-approximated by a plateau function of rapidity where the number of particles produced per unit of pseudorapidity η is a constant, H , independent of η and they all have the same transverse momentum, i.e.

$$\frac{d^2 N_{ch}}{d\eta dp_T} \approx H \delta(p_T - \langle p_T \rangle). \quad (1)$$

Thus, integrating over p_T ,

$$\frac{dN_{ch}}{d\eta} = H, \quad \text{and} \quad \frac{d\eta}{d\theta} = \frac{1}{\sin \theta} \quad \text{or} \quad \frac{d\eta}{d\Omega} = \frac{1}{2\pi \sin^2 \theta}. \quad (2)$$

This leads to the very simple relations:

$$\frac{dN_{ch}}{d\theta} = \frac{H}{\sin \theta}, \quad \text{or} \quad \frac{dN_{ch}}{d\Omega} = \frac{H}{2\pi \sin^2 \theta}, \quad \text{and} \quad E \approx p = \frac{\langle p_T \rangle}{\sin \theta}. \quad (3)$$

in Tables 2 and 3. The numbers used by the Task Group are a very close approximation to those found using DTUJET. It was also shown in the report [1] that the error in the calculated neutron production was negligible assuming a unique energy at a given angle instead of integrating over the whole hadron spectrum. However a word of caution is advisable: at low energies one enters into the domain of resonances in neutron production. In addition most particles are pions which when they interact will cause much higher nuclear excitation than protons. Thus the neutron production in objects close to sensitive equipment placed inside the inner cavity may add to the albedo neutrons reflected from the calorimeter. This problem remains to be studied in detail.

Table 2: Mean Energy for p-p collisions

Angle degrees	SSC SR-1033	SSC DTUJET88	LHC SR-1033	LHC DTUJET	Sp $\bar{p}$ S SR-1033	Sp $\bar{p}$ S DTUJET
1 to 5	11.5	11.9	10.5	10.9	8.2	8.3
5 to 10	4.6	3.6	4.2	3.4	3.3	2.8
10 to 20	2.3	1.7	2.1	1.7	1.7	1.5
20 to 40	1.22	0.89	1.12	0.79	0.87	0.80
40 to 70	0.76	0.55	0.70	0.53	0.54	0.48
70 to 90	0.62	0.49	0.57	0.48	0.44	0.41

Table 3: Hadron Fluence for p-p collisions

Angle degrees	SSC SR-1033	SSC DTUJET88	LHC SR-1033	LHC DTUJET	Sp $\bar{p}$ S SR-1033	Sp $\bar{p}$ S DTUJET
1 to 5	526.1	543.5	440.0	440.0	195.0	185.0
5 to 10	73.0	84.0	61.0	67.0	27.0	31.0
10 to 20	18.5	21.0	15.5	17.5	6.9	8.3
20 to 40	5.0	5.5	4.2	4.6	1.85	2.3
40 to 70	1.85	1.95	1.55	1.65	0.69	0.84
70 to 90	1.24	1.26	1.04	1.15	0.46	0.55

3 Neutron spectra in cascades

Estimates of the energy spectrum of neutrons leaking radially from cylinders of different diameters where high-energy protons interact along the axis of the cylinder have been available for some considerable time. O'Brien and McLaughlin solved the relevant Boltzmann

The constants for use in these relations are given in Table 1. The values given are based more on extrapolations from experimental data than from Monte-Carlo simulation programs.

Table 1: Production constants for Three Colliders

Collider	SSC	LHC	Sp $\bar{p}$ S
Energy	20 + 20 TeV	8 + 8 TeV	0.315 + 0.315 TeV
H	7.5	6.3	2.8
p_T	0.60 GeV/c	0.55 GeV/c	0.42 GeV/c

The hadron energy spectrum averaged over the angular interval 5 to 10° as calculated by the DTUJET program [3] is shown in Figure 1 for SSC, LHC and Sp $\bar{p}$ S energies. Most hadrons can be considered as pions. It will be seen that the shape of the energy spectrum has very little dependence on primary proton energy: only the number of particles changes. This is also true at larger angles.

Figure 1: Hadron energy spectrum as calculated by DTUJET-88. The average over the angular interval 5 to 10° is given for the SSC (o), LHC (*) and Sp $\bar{p}$ S (+). The energy bins correspond to one-tenth of a decade on a logarithmic scale.

A comparison of the mean energies and the total hadron fluence as determined from the DTUJET spectra and from the assumptions used in the Task Group Report are given

equation using the method of Spherical Harmonics [4] and Figure 2 shows the result of such calculations for an iron cylinder (data taken from [5]). More recently neutron spectra have been calculated using Monte-Carlo simulation programs. Figure 3 taken from the work of Tesch and Zazula is an example of these [6]. It will be seen that there is very little difference between the two spectra, calculated some 20 years apart, especially in the energy region above 100 keV. This should lead to some confidence in using such generalized spectra in the cascade for damage prediction.

The maximum neutron fluence in a uranium/scintillator calorimeter assembly is shown as a function of incident hadron energy in Figure 4 (taken from [1]). Most data points in this Figure come from Monte-Carlo simulations, but there are two data from experiments by Wigmans et al [7]. Another point derived from experimental data is that at 200 GeV/c from work of Russ et al [8].

Since the Task Group Report was published new data are available from an experiment similar to the latter in all respects except that the incident proton momentum was 24 GeV/c [9]. In these experiments the measured radial profiles of neutrons were identical at depths in the cascade equal to and greater than the depth of cascade maximum. This means that the numerical adjustments for leakage and material dependence used in [1] are identical for the two cases. In scaling from calculations and experiments with different materials the data of Table 4 taken from [1] was used. (The lead:iron ratio appears to be confirmed after a recent experiment using 200 GeV/c protons on a lead structure in which the present authors were involved). The new data point at 23 GeV falls close to the "best fit" line of Figure 4. Thus there is no reason to change the relation recommended by the Task Group for estimating the maximum neutron fluence:

$$\int \phi da = 18 \times (E_k/1\text{GeV})^{0.67}, \quad (4)$$

where E_k is the incident hadron energy. (The area-integrated fluence for one incident hadron is numerically equal to the neutron fluence for an incident hadron fluence of one per cm²).

These last two experiments were designed in part as benchmarks for Monte-Carlo simulation programs. Zazula has already simulated the low-energy neutron fluence distribution in the iron structure to better than a factor of two everywhere [10]. However Russ et al point out that very naïve simulations can also predict neutron fluences to better than a factor of two in such simple geometries.

Figure 2: Neutron energy spectra from the analytic calculations of O'Brien [5]. The particles leak radially from a small iron cylinder bombarded by high-energy protons.

Figure 3: Neutron energy spectra from the Monte-Carlo calculations of Tesch and Zazula [6]. The particles leak radially from a small iron cylinder bombarded by high-energy protons.

Figure 4: Radially integrated neutron fluence at cascade maximum. The data correspond to a uranium/scintillator calorimeter. Open circles (o) are from Monte-Carlo simulations. Vertical crosses (+) are experimental data from Wigmans [7]. Stars (*) are experimental data from Russ et al [8] at 200 GeV/c and Fassò et al [9] at 2.1 GeV/c. The solid line is the equation $\int \phi da = 18 \times (E_k/1\text{GeV})^{0.67}$, while the dashed lines are a factor of two higher and lower.

Table 4: Neutron Production in Different Calorimeters

	Scale by
U-LAr or Si	3.0
Pb-LAr or Si	1.7
U-Scint	1.0
Fe-LAr or Si	0.7
Pb-Scint	0.5

Coupling the mono-energetic source model discussed in the previous section with the above formula for neutron production in cascades, and changing the basic conditions to the reference values of the LHC (i.e. a luminosity of 10^{31} cm^{-2} , an annual operating time of 10^7 seconds, an inelastic cross-section for p-p interactions of 60 mbarns and a reference calorimeter of a hollow lead sphere having an internal radius of 2 metres with the forward and backward cones at $\eta > 6$ removed), the annual neutron fluence as a function of rapidity will be as shown in Figure 5.

Figure 5: Maximum annual neutron fluences in a spherical lead shell. The sphere has an inner diameter of 2 metres. Luminosity etc are for the reference LHC working conditions (see text).

The effect of hydrogenous material inside the calorimeter-absorber structure on the fluence of low-energy neutrons has long been the subject of debate. In a recent systematic study using computer simulations of cascades induced by 3 GeV/c and 20 GeV/c negative pions in 7.5 mm iron and 5 mm uranium calorimeter structures, Foruno et al showed that the low-energy neutron fluence could be reduced by as much as an order of magnitude by the insertion of polyethylene layers of approximately 1 cm thickness [11]. Their paper also shows the change in neutron spectrum and the change in the predicted damage in silicon as a function of thickness. However the practicability of introducing a hydrogenous material only for reducing the effect of neutrons where it is not required for calorimetric purposes remains open to question.

4 Albedo Neutrons

The Task Group Report [1] also summarized estimates of the number of neutrons leaving the front face of a uranium/scintillator calorimeter assembly as a function of incident hadron energy. This is given in Figure 6. The new data point from the 23 GeV experiment [9] is also indicated and it will be seen that it fits in with the other data.

Figure 6: The number of albedo neutrons from a uranium/scintillator calorimeter. Open circles (o) are from Monte-Carlo simulations. Vertical crosses (+) are experimental data from Wigmans [7]. Stars (*) are experimental data from Russ et al [8] at 200 GeV/c and Fassò et al [9] at 24 GeV/c. The solid line is the equation $f Ida = 2.5 \times (E_k/1\text{GeV})^{0.50}$, while the dashed lines are a factor of two higher and lower.

Again there is no reason to change the relation recommended by the Task Group for estimating the number of albedo neutrons:

$$\int Ida = 2.5 \times (E_k/1\text{GeV})^{0.50}, \quad (5)$$

where E_k is the incident hadron energy. This corresponds to the current for an incident hadron fluence of 1 cm^{-2} .

These estimates of the number of neutrons leaving the 'front' face of a calorimeter can be used to estimate the fluence of neutrons inside the inner cavity. For a spherical cavity and assuming isotropic emission of the neutrons from the front face, the average fluence of neutrons for a cavity radius of 2 metres will be $2 \times 10^{13} \text{ cm}^{-2}$ for the standard LHC operating conditions. Wilcox has shown that if there is no absorbing material in the inner cavity then the fluence at any point will be higher or lower than this average value by less than a factor of three [12]. If the inner layer were to be lined with 10 cm of polyethylene, then the low-energy neutron fluence in the central cavity would be reduced significantly [13].

In a recent experiment involving the present authors, a measurement was made of the reduction of the albedo neutron fluence by a 10 cm slab of polyethylene placed in front of a lead calorimeter structure irradiated by 200 GeV/c protons. Initial results indicate a reduction factor of four in the neutron energy range covered by indium activation detectors

(> 0.8 MeV). This is consistent with the Monte-Carlo results of Gabriel and Lillie given the different neutron energy ranges considered and the neglect in the Monte-Carlo calculations of neutrons generated by high-energy interactions in the polythene.

The introduction of a neutron absorber will have other effects besides modifying the low-energy part of the albedo spectrum. Due to path-length effects, albedo neutrons from points in the detector far away from the point of interest will be attenuated with respect to those originating nearby. The SSC Task Group Report only considered an 'average' fluence of albedo neutrons in the cavity derived from the total number of neutrons leaving the inner surface of the calorimeter. However the same data (see Figure 6) can be used to calculate the fluence of albedo neutrons close to the calorimeter surface as a function of rapidity where only that part of the calorimeter close to the point of interest contributes to the albedo fluence. (The area-integrated albedo fluence will be twice the actual number of neutrons (current) leaving the front surface). This is shown in Figure 7 for LHC conditions along with a horizontal line representing the 'average' value of the fluence in a cavity without an absorber. It will be seen that, as expected, the fluence at low rapidities is somewhat lower, but at the higher rapidities the fluence may be significantly higher in small localized regions.

Figure 7: Annual albedo neutron fluences in a spherical lead shell. The sphere has an inner diameter of 2 metres. Luminosity etc are for the reference LHC working conditions (see text).

The fluence of albedo neutrons will also depend to some extent on the shape of the calorimeter. Present estimations have been made using a spherical geometry where the hadrons from the p-p collisions are incident normally on the calorimeter face. Most albedo neutrons will be emitted isotropically from the region of cascade maximum. Thus for a cylindrical geometry, and especially at high rapidities, the cascade maximum will be closer to the surface of calorimeter, so increasing the neutron escape probability. This effect needs to be quantified in future calculations.

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