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ON THE PREDICTION OF RADIATION LEVELS IN LHC EXPERIMENTS

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Abstract

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*Presented at the
3rd International Conference on Advanced Technology and Particle Physics
22-26 June, 1992, Como, Italy*

CERN, Geneva, Switzerland
24th August 1992

On the Prediction of Radiation Levels in LHC Experiments

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1. INTRODUCTION

An SSC Task Group on Radiation Levels in Collider Detectors [1] summarized both experimental data and cascade calculations (hadronic and electromagnetic) in order to derive simple analytic relationships for the variation of the maximum dose in a slab structure, the maximum neutron flux and the albedo neutron flux as functions of incident hadron or photon energy. These data are necessary for estimating the doses to be expected in the different components of the detectors proposed for the Large Hadron Collider (LHC) which is planned for construction in the tunnel of the Large Electron-Positron collider (LEP) at CERN and the Superconducting Super Collider (SSC) which is under construction at Waxahachie in Texas (USA).

At the time the Task Group Report was published, there was a dearth of experimental information on the number of neutrons with energies between 0.1 and 10 MeV in the cascades originating from 1 to several hundred GeV hadrons. Most data as then existed exist were obtained for shielding studies and generally only the high-energy cascade-propagating components of the cascade were studied. The theoretical data on which the Task Group Report were based were obtained from Monte-Carlo simulation programs such as HETC [2] where low-energy neutron transport codes used in reactor design had been coupled with high-energy hadron-cascade codes.

*On behalf of the ROSTI and FLUKA collaborations.
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However without experimental measurements of low-energy neutrons from cascades initiated by hadrons of known energy and in simplified geometries, one cannot decide if the predictions of the simulation programs in the complex geometries of collider detectors and in cascades initiated by the secondaries of the hadron-hadron collisions are correct. The ROSTI collaboration was therefore set up in order to measure neutron longitudinal and radial profiles and energy distributions within the volume of various calorimeter-type structures having different absorber materials. The results of experiments using lead and iron as the absorber materials and with incident hadrons of 24 and 200 GeV/c have now been published [3-5] and this paper will summarize the most important conclusions that can be drawn from these data.

In recent years there has also been a significant effort to improve the accuracy of the simulation programs. In the following, the improvements made to one of them, FLUKA, [6] will be summarized and it will be shown how accurately the above experimental data can be reproduced.

Finally an indication will be given of the type of data that can be obtained from these simulation programs and the use of these data in predicting damage in hadron collider detectors.

2. THE ROSTI EXPERIMENTS

In the ROSTI series of experiments, calorimeter-like structures were constructed from 5 cm thick slabs of iron or lead. The size of the plates was $30 \times 30 \text{ cm}^2$ for the iron and $50 \times 50 \text{ cm}^2$ for the lead structure. Gaps of 6 mm were left between the slabs in order to house thin aluminium plates which carried neutron activation detectors and dosimeters. The activation reactions selected

for these studies were the $^{27}\text{Al}(h, x)^{18}\text{F}$ reaction which is sensitive to all hadrons having energies above about 35 MeV, the $^{27}\text{Al}(h, x)^{24}\text{Na}$ reaction which is mainly sensitive to neutrons in the 6–25 MeV region, the $^{32}\text{S}(n, p)^{32}\text{P}$ reaction which is mainly sensitive to neutrons in the 3–25 MeV region and the $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ reaction which is predominantly sensitive to neutrons in the 0.5–50 MeV region. Discs of aluminium, sulphur and indium were placed on the vertical and horizontal axes of the aluminium support plates: the size of the detector increased with radial distance from the beam axis so as to try to equalize as much as possible the activities created. Full experimental details are given in the original references [3–5].

Results from these experiments come in the form of tables of the number of radioactive atoms created per parent atom which can be converted using an effective cross-section into a nominal fluence of neutrons (or hadrons) per incident proton, averaged over the physical size of the activation detector. It is difficult to find a suitable graphical form in which to express these results. Figure 1 is an attempt to display the radial profiles at different depths in the structure, and because both the fluence levels and radial shapes of the profiles change with depth it is necessary to introduce arbitrary normalization factors into the plots. But this does not avoid all confusion in the presentation.

The radial integrals of the fluences were determined from the measured fluences at the different radii. These are plotted as a function of depth in the structure for the 200 GeV/c and 24 GeV/c experiments in iron in Figure 2. Only the data from the ^{27}Al – ^{24}Na and ^{32}S – ^{32}P reactions are given. This plot illustrates one of the difficulties of such experiments *viz.* that it is not possible to expose all detector systems at every depth in the structures.

Since the radial positions of the detectors were identical for the two iron irradiations at 200 and 24 GeV/c, it is possible to calculate fluence ratios directly from the experimental data at cascade maximum and for the albedo fluence without the need for radial interpolation. These ratios are given in Table 1 for the different detector systems. In this analysis one must exclude some of

Figure 1. Radial variation of the neutron fluence as measured by the $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ reaction at different depths in the 200 GeV/c Lead irradiation

Figure 2. Variation with depth of the radially integrated fluence as measured by the ^{27}Al – ^{24}Na and ^{32}S – ^{32}P reactions in the 200 GeV/c and 24 GeV/c experiments in iron

the RPL dosimeter results where there is a recognized measurement error in certain dose regions, and also exclude the beam-axis ratios which are affected by the presence of the incident protons. It will be seen that the ratios at cascade maximum and for the albedo fluence are essentially independent of detector system and have mean ratios of 5.4 ± 0.1 and 2.8 ± 0.4 respectively. These can be compared with values derived from the analytic formulae of the SSC Task Group Report [1] which are 4.1 for the ratio at cascade maximum and 2.9 for the albedo fluence ratio. The experimentally determined ratio at cascade maximum is somewhat higher than the Task Group ratio suggesting an $E^{0.8}$ power law rather than the $E^{0.67}$ law assumed in the Group report (E being the kinetic energy of the incident primary hadron), but the albedo ratio is in good agreement with the Task Group value.

Table 1
200 GeV/c:24 GeV/c fluence ratios at cascade maximum and for albedo neutrons

Detector System	Cascade Maximum	Albedo
$^{27}\text{Al}-^{18}\text{F}$	5.3 ± 0.2	3.8 ± 1.3
$^{27}\text{Al}-^{24}\text{Na}$	5.44 ± 0.04	2.7 ± 0.5
$^{32}\text{S}-^{32}\text{P}$	5.6 ± 0.2	-
$^{115}\text{In}-^{115m}\text{In}$	5.0 ± 0.1	2.8 ± 0.2
RPL	5.4 ± 0.3	-
SSC Task Group [1]	4.1	2.9

The dependence of fluence on structure material is illustrated in Figure 3 where the radial integrals of the fluences from two of the detector systems are plotted as a function of depth in the structure for the lead and iron experiments at 200 GeV/c. Whereas the two systems give very similar flux values for the two iron experiments at different energies, the fluence as measured by

Figure 3. Variation with depth of the radially integrated fluence as measured by the $^{27}\text{Al}-^{24}\text{Na}$ and $^{32}\text{S}-^{32}\text{P}$ reactions in the 200 GeV/c lead and iron experiments

the $^{32}\text{S}-^{32}\text{P}$ reaction is significantly higher than the fluence measured by the $^{27}\text{Al}-^{24}\text{Na}$ reaction in the lead experiment.

The difference in neutron spectrum between lead and iron in the 3-5 MeV energy region is further illustrated in Table 2 where the mean values of the ratios of the radial fluence measurements are given at cascade maximum and for the albedo fluences. These data are complicated by the fact that it was not possible to design the experiments so that the radial positions of the detectors were identical in the lead and iron structures, and so it was necessary to interpolate between some of the radial positions to obtain these ratios. It will be seen in this Table that the ratio of fluences in the different materials at cascade maximum depends strongly on the detector system. The high-energy hadron fluence as measured by the $^{27}\text{Al}-^{18}\text{F}$ reaction is the same in both the iron and lead structures. The ratios of the responses of the $^{27}\text{Al}-^{24}\text{Na}$ and $^{115}\text{In}-^{115m}\text{In}$ detectors are approximately equal and significantly greater than unity but are less than the ratio of the number of neutrons in lead and iron nuclei. However the lead:iron ratio for the $^{32}\text{S}-^{32}\text{P}$ reaction is almost twice as large as the ratios for the other two detectors. It should be noted that the mean energy of evaporation neutrons from an iron nucleus

is somewhat higher than that for a lead nucleus and that spallation processes in lead will lead to a wider range of neutron energies than in iron. Both these effects will tend to increase in a relative way the number of neutrons in the 3-5 MeV region in the lead experiment. However it is not possible to be more precise and to quantify the spectral differences since, due to the limited number of detector systems used, it is not possible to unfold the shape of the neutron energy spectrum with any degree of certainty.

Table 2
Lead:Iron neutron fluence ratios at cascade maximum and for albedo neutrons

Detector System	Cascade Maximum	Albedo
$^{27}\text{Al}-^{18}\text{F}$	1.10 ± 0.05	1.6 ± 0.2
$^{27}\text{Al}-^{24}\text{Na}$	2.3 ± 0.1	3.6 ± 0.4
$^{32}\text{S}-^{32}\text{P}$	4.7 ± 0.3	-
$^{115}\text{In}-^{115m}\text{In}$	2.8 ± 0.5	3.7 ± 0.7
SSC Task Group [1]	2.5	2.5

It was been found that in experiments associated with the ROSTI series where when indium was exposed with silicon detectors to a variety of isotopic and cascade-induced sources of neutrons the fluence as measured by the indium activation technique was proportional to the damage induced in the silicon detectors [7]. It is therefore interesting to give the radially integrated fluences for this reaction as measured in the three experiments. These are listed in Table 3. Another complication in the analysis of the experimental data is evident from this Table *viz.* that the radial depth covered by the lead and iron experiments is not the same.

Although the ROSTI series of experiments provide a significant amount of information on the development of neutron fluences within hadron-

Table 3
Radially integrated neutron fluences as measured by the $^{115}\text{In}-^{115m}\text{In}$ reaction in the three experiments

Integral	to 150 mm			to 400 mm
Momentum in GeV/c	24	200	200	200
Material	Iron	Iron	Lead	Lead
Albedo	7.2	20.0	87.0	250.0
Maximum	30.0	230.0	690.0	1600.0

induced cascades, because of their innate limitations of the physical space occupied by the detectors and the extensive time and effort required to complete such experiments, it is not possible to obtain from them all the information one might require to assess the possible damage to detector systems in collider detectors. They do however provide an invaluable body of data to test the accuracy of hadron-cascade simulations. This initial direct measurement of fluences and the provision of bench-marking data for simulation codes are the two most valuable aspects of the results from the ROSTI collaboration.

3. THE FLUKA PROGRAM

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 [8] 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 [2], HERMES of KFA Jülich [9] which has been developed from HETC and the MARS code [10].

As part of a Research and Development program at CERN to investigate the characteristics of Lead/Liquid Argon Calorimeters, the 1986 release of FLUKA [6] has been significantly extended and updated. Improvements to the inelas-

tic 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 [11]. 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 [12, 13].

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 [14] 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 [15]. 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

Figure 4. Variation of the production of ^{32}P from ^{32}S as a function of radial distance off-axis in a lead calorimeter structure irradiated by 200 GeV/c protons. Histogram - FLUKA, data points - ROSTI.

available at liquid argon (87°K) and liquid helium ($\approx 4^\circ\text{K}$) temperatures. Finally, neutron dose can be determined from kerma files.

As part of the validation program of the FLUKA code, the conditions of the ROSTI experiments have been simulated as closely as possible. For example, the fluences of particles crossing through a given annulus at a boundary corresponding to one of the detector plates have been weighted according to the circular shape of the detector actually used at that radius in the experiment. In the FLUKA simulations the actual production of the radioactive isotope measured in the experiment is predicted in the form of atoms per mole of parent atom using published cross-sections. This is more correct than making the comparison in terms of the effective fluence quoted in the ROSTI experiments and the fluence of hadrons in given energy bands scored in the FLUKA simulations. An example of these comparisons is given in Figure 4 where the radial profiles are given at different depths in the lead structure irradiated by 200 GeV/c protons. It will be seen that the agreement between the FLUKA predictions and the experimental data is better than 25%.

The longitudinal variation of the transversely

Figure 5. 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. Histogram - FLUKA, data points - ROSTI.

integrated production is given in Figure 5 for ^{115m}In production from ^{115}In and in Figure 6 for ^{24}Na production from ^{27}Al . The worst disagreement occurs with lead as the absorber material where the difference between predictions and measurements reaches 40%.

4. SIMULATION PROGRAMS

Much more detail concerning the composition of cascades can be obtained from simulation programs rather than from experiments which inevitably cannot resolve hadron types or provide high-resolution energy spectra. Examples of such energy spectra are given in Figures 7 and 8 for the conditions of the ROSTI experiments.

Considering first the spectra at cascade maximum, the similarity of the spectra in iron at the two different proton energies is evident, apart from a relative excess of high-energy charged hadrons at an incident momentum of 24 GeV/c. However the softening of the neutron spectrum at energies of around 1 MeV is significant for the lead absorber. In relation to the high-energy charged hadrons, the fluence at 1 MeV is almost an order of magnitude higher for the lead absorber than for the iron.

Figure 6. Variation of the radially integrated production of ^{24}Na from ^{27}Al as a function of depth in iron and lead structures irradiated by 200 GeV/c and 24 GeV/c protons. Histogram - FLUKA, data points - ROSTI.

The albedo spectra at the two energies in iron are also very similar, but again the proportion of lower energy neutrons in the lead spectrum is again significantly higher than in the iron spectra.

With the detail given by numerical data relevant to particle spectra, it is possible to justify such qualitative statements. Furthermore, once the damage to a component of a collider detector is known as a function of energy and particle type, it is possible to predict its damage in the radiation environment generated by the proton-proton interactions.

ACKNOWLEDGEMENTS

The author wishes to express his thanks to all members of the ROSTI and FLUKA collaborations for their permission to use freely the data obtained. A special word of thanks is due to J. M. Zazula for his help in preparing some of the FLUKA simulation runs which were used in this paper.

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Figure 7. FLUKA calculations of hadron energy spectra at cascade maximum in iron irradiated by a) 24 and b) 200 GeV/c protons and c) lead irradiated by 200 GeV/c protons

Figure 8. FLUKA calculations of hadron energy spectra at cascade maximum in iron irradiated by a) 24 and b) 200 GeV/c protons and c) lead irradiated by 200 GeV/c protons

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