EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

CERN/TIS–RP/97–14/CF

PROCEDURES USED DURING THE VERIFICATION OF SHIELDING AND ACCESS-WAYS AT CERN'S LARGE HADRON COLLIDER (LHC) USING THE FLUKA CODE.

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Abstract

Several examples will be given which illustrate the special features of the Monte-Carlo cascade simulation program FLUKA, used in the verification studies of shielding for the LHC. These include the use of different estimators for dose equivalent, region importance weighting with particle splitting, Russian Roulette and weight windows both at region boundaries and in secondary production at inelastic reactions and decay-length biasing in order to favour secondary particle production.

To be presented at the
American Nuclear Society's 1997 Winter Meeting
Accelerator Applications '97
Albuquerque, New Mexico, U.S.A.
November 16–20, 1997

CERN, Geneva, Switzerland
17th May 1997

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ABSTRACT

Several examples will be given which illustrate the special features of the Monte-Carlo cascade simulation program FLUKA, used in the verification studies of shielding for the LHC. These include a) the use of different estimators for dose equivalent, b) region importance weighting with particle splitting, Russian Roulette and weight windows both at region boundaries and in secondary production at inelastic reactions, and c) decay-length biasing in order to favour secondary particle production.

I. INTRODUCTION

FLUKA is an all-purpose, omni-particle transport code that simulates the propagation of cascades initiated by any high-energy particle with kinetic energy up to 20 TeV.[1–6] All the most important components of the radiation field (hadrons, leptons and photons) are transported in a single pass of the program with the same level of accuracy, and down to very low energies (thermal for neutrons, and 1 keV for all other particles). The fundamental base of the program is the exact modelling of physical processes.[7–10] Interaction cross-sections are continually up-dated [11] and the program is regularly subjected to experimental verification.[12–15]

FLUKA contains many powerful biasing options that allow one to tackle the deep-penetration problems associated with the design of the shielding and access-ways at the Large Hadron Collider of CERN (LHC). This machine is a synchrotron-collider which accelerates and stores two intense beams of particles circulating in opposite directions and collides them head-on at several points where particle physics detectors can study the interactions. The LHC will collide two beams of protons, each containing up to 5×10^{14} particles at energies of up to 7 TeV. The design luminosity is $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is also planned to collide lead ions. The conceptual design of the LHC has been published in a recent design report.[16] A careful cost optimization of performance has led to the main parameters of the LHC given in Table I.

The LHC will be installed in the same underground tunnel which at present houses the Large Electron-Positron (LEP) collider alone. LEP, collides electrons and positrons at energies up to 100 GeV. Since the circumference of the LHC is given by the existing LEP tunnel, the maximum beam energy depends only on the magnetic field which can be reached in the dipole magnets needed to guide the protons around the 27 km of the tunnel. These magnets will use super-conducting coils of NbTi cooled to 1.9 K and will provide a field of 8.4 T. The two opposing proton beams will circulate in ingenious "two-in-one" magnets which provide the necessary twin magnetic channels with opposite sign fields in the same yoke and cryostat. The present optics is based on 23 lattice periods in each of the eight arcs. Each half-period consists of three dipoles with magnetic lengths of 14.2 m and a 3.1 m long quadrupole with a field gradient of $230\ \mathrm{T\,m}^{-1}$. The coil aperture of these magnets is 56 mm and the two beam channels lie side-by-side. In the arcs they are separated horizontally by 194 mm. The beams will only cross in regions where collisions are required.

The layout of the LHC, indicated in Figure 1, is given by the form of the LEP ring which consists of eight arcs with a bending radius close to 3.5 km linked together with 550 m long straight sections to form a regular structure. The two high-luminosity general-purpose detectors ATLAS and CMS will be installed on opposite sides of the collider in new underground areas at P1 and P5. A dedicated heavy-ion detector, ALICE, will be installed in the existing LEP experimental facilities at P2 where the present L3 detector is housed. It is also expected that a specialized B-physics detector, LHC-B, will be installed at P8 where, in order to make the best use of the existing cavern, the normal collision point will be displaced by 11.2 m. With this modification the 18 m long spectrometer of LHC-B will just fit into the cavern presently occupied by the LEP experi-

Table 1: Nominal LHC design parameters

	Protons	Pb-Ions
Centre of mass total energy (TeV)	14	1148
Magnetic field in bending magnets (T)	8.4	8.4
Initial luminosity per collision region ($cm^{-2}s^{-1}$)	10^{34}	2×10^{27}
Number of bunches per beam	2835	608
Bunch spacing (m – ns)	7.5 – 25	37.4 – 124.8
Number of particles per bunch	10^{11}	9.4×10^{7}
Number of collision regions assumed	2	1
Beta parameter at interaction point (m)	0.5	0.5
r.m.s. beam radius at collision point (μm)	16	15
r.m.s. collision region length (mm)	54	53
r.m.s. energy spread σ_E/E	1.1×10^{-4}	1.1×10^{-4}
Beam crossing angle (μrad)	200	100
Luminosity lifetime (h)	10.0	6.7
Stored energy per beam (MJ)	334	4.8
Synchrotron radiation per beam (kW)	3.6	–

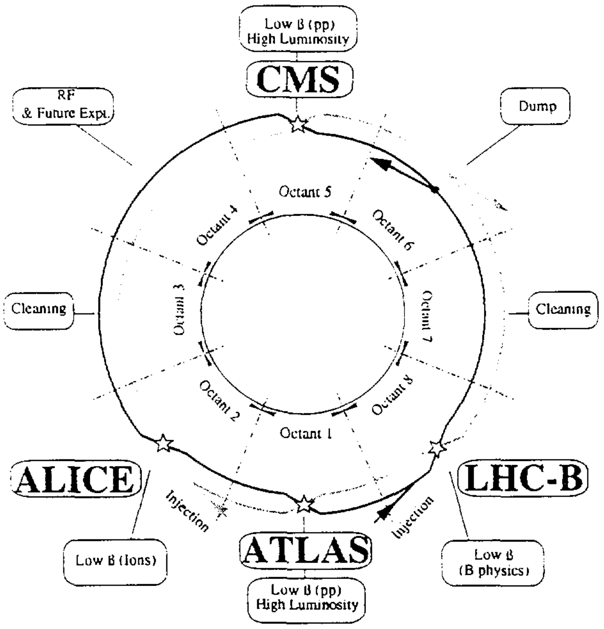

Figure 1: A schematic layout showing the assignment of the eight long straight sections of the LHC to experiments and utilities

ment DELPHI.

The remaining straight sections will be used for LHC machine utilities, one at P6 to provide safe external abort systems for the beams at the end of each run, another at P4 for the accelerating system of Radio Frequency cavities and the remaining two at P3 and P7 for the beam cleaning systems, where systems of collimators will ensure that all particles which fall outside the dynamic aperture of the machine in any of the six dimensions of phase space, will be safely removed and absorbed in suitable shielding. If these halo particles were to be allowed to circulate until they struck the vacuum pipe near superconducting magnets they would deposit their energy in the coils and cold masses of the magnets causing superconducting to normal transitions, or "quenches". The efficiency to be achieved in these cleaning sections is of order 99.9%, as the LHC halo is expected to contain about 3×10^{9} protons per second while as few as 10^{6} may cause a quench. Two beam halo cleaning insertions are foreseen, both using a FODO lattice of classical magnets with a dog-leg at either end where the beam separation is increased from 194 to 224 mm. These insertions will be equipped with two stage collimator systems consisting of three scattering blocks at each stage, designed to remove the betatron halo in P7 and off-momentum particles in P3. The dog-legs are required to prevent off-momentum particles from inelastic interactions in the collimator blocks being lost in the adjacent superconducting machine elements.

The RF accelerating system, consisting of eight 400.8 MHz superconducting cavities per beam, will be installed in a special insertion at P4. The separation between the beams will be widened to 420 mm so as to allow the installation of separate superconducting cavities for each beam. The cavities are placed at the ends of the straight section in such a way as to leave the central region clear for an additional collision region and experiment if necessary. Since the beams do not cross at P4 a scheme with additional bending magnets to bring the beams together into one vacuum chamber and back out again will be required if collisions are needed for an additional experiment.

At the start of a coast the beams will have total stored energies of up to 334 MJ. It is essential to be able to extract the beams at any time from the ring and absorb the protons in external beam dumps. The beam abort system is to be installed at P6 where it will require the full straight section to reliably and cleanly extract each beam with a system of horizontally deflecting fast kicker magnets and a vertically deflecting double Lambertson septum magnet in the centre of the straight section. A 3 μs gap left in the bunch train of each beam will be sufficient for the rise time of the kickers and with the proper synchronisation will ensure that no particles strike the septum. The dump blocks will be placed in special caverns alongside the arc tunnel some 750 m downstream of the septum magnet. To limit the local energy deposition in the carbon core of the dump blocks to reasonable values, the 86 μs long bunch train will be swept in an approximately circular trajectory over the front face of the absorber block by a pair of orthogonally deflecting kicker magnets.

II. LHC SHIELDING CRITERIA

In the present LEP installation, 9 m diameter shafts some 60–100 m deep give access for personnel to cooling and ventilation equipment and to klystron galleries which are separated from the LEP machine by about 2 m of concrete. The experimental areas are accessible during collider operation since the iron yokes of the experimental magnets themselves provide sufficient shielding.

At the LHC, very simple calculations are sufficient to show that a 2 m wall is insuffcient shielding for any proton collider operation at 7 TeV and that access cannot be allowed to the experiments during operation. Thus the main objective of the LHC shielding studies has been to provide accessible areas for the electronics associated with the LHC experiments and safe areas alongside the main ring for special equipment that needs to be accessed during operation.

Since the losses that will occur around a high-energy proton storage ring with superconducting magnets must be kept to a minimal level under standard operating conditions for the storage ring to work at all, shielding requirements are not based on estimates of normal beam losses. It is more usual to base them on the potential exposure in the case of an unexpected loss of the circulating beam (or beams) at a single point or on the loss of an injected beam. The damage caused to the accelerator by such losses could be dramatic, and every effort will be made to ensure that they will not occur. However, although the probability of such events is extremely small, they cannot be excluded from consideration.

One of the design constraints chosen for the LHC is that the loss of one circulating beam at 7 TeV and at full intensity should not give rise to an Ambient Dose Equivalent of more than 50 mSv at the outer surface of the shield leading to a Controlled Radiation Area. This should not then involve any declaration of a radiological incident or accident to a controlling authority and would not jeopardize the future work with radiation of any persons involved.

Another criterion is that the dose rate from a continuous loss under the worst credible circumstances should never exceed 100 mSv h^{-1}. In addition the design dose rate averaged over 24 hours for normal, expected situations is 10 μSv h^{-1}.

III. DOSE EQUIVALENT DETERMINATION

Whereas physical quantities such as particle current, fluence and energy deposition can be estimated reliably in Monte-Carlo simulations of hadron-induced cascades, the estimation of dose equivalent suffers from many difficulties, some of which are administrative artifacts. Some dose equivalent quantities such as Effective Dose Equivalent and Effective Dose, which rely on the determination of dose or dose equivalent in different organs of the body, differ for persons of different size and depend on the orientation of the human body with respect to the incident radiation field. Ambient Dose Equivalent was defined by ICRU [17] and ICRP [18] as being the nearest equivalent to a physically measurable quantity, and can be directly related to the incident fluence by conversion factors determined from Monte-Carlo simulations of radiation transport in a 30 cm diameter sphere made of tissue-equivalent material.

The problems of determining dose equivalent in FLUKA simulations is illustrated in [19] where 7 TeV protons were made to hit the centre of an iron cylinder of 20 cm radius (density 7.88 g/cm^3) which lay along the axis of a cylindrical tunnel (radius 2 m) with concrete walls. Neutrons were followed down to thermal energies. Electron and photon cuts were set inside the tunnel walls to 10 and 1 MeV respectively. This means that a significant portion of the electromagnetic cascade was not transported, but since the smallest scoring dimension was 20 cm, this had no net effect, except close to the wall surface. Hadrons were followed down to 1 MeV and ranged out thereafter. Particle track-length, total and electromagnetic energy deposition and star densities of hadrons above 50 MeV were scored inside the walls in r × z bins of 20 × 50 cm^2.

The energy density scoring of FLUKA provides the deposited energy due to all processes directly as GeV/cm^3 per unit primary particle weight. From this it is easy to calculate the dose in units of Gy. Since, however, the radiation field in the concrete is very complex, it is not trivial to determine the appropriate quality factor Q with which to multiply dose in order to determine dose equivalent. For neutrons Q varies between 5 and 20, while it is unity for the electromagnetic energy deposition. A reasonable "ball-park" average for a typical field inside concrete is 5.

A second method of determining dose equivalent relies on the fact that, to a good accuracy, the dose equivalent inside a concrete shield is related to the hadronic star density. A conversion factor of 4.5×10^4 pSv cm^3/star was suggested in reference [20], which takes into account also the electromagnetic component due to produced π^0s.

The most reliable method is to use energy-dependent conversion factors such as those of references [21] and [22] to derive the dose equivalent from particle fluences. These energy dependent factors exist separately for neutrons, pions and protons and in the present comparison have been applied to the two-way fluence crossing the scoring surface (*i.e.* including the particles coming back from deeper parts of the shield in addition to those moving away from the source). Normally the electromagnetic energy deposition would have to be added to the dose equivalent deduced in this way from the hadron fluences. FLUKA has the capability to score track-lengths in either cylindrical or Cartesian bin-meshes which are independent of the geometry of the problem. In this scoring the track-length can be weighted by the energy-dependent conversion factors so that dose equivalent is scored directly.

These estimates of dose equivalent are plotted as a function of depth in the concrete wall of the tunnel in Figure 2. These are the maximum values of dose equivalent at a given radial depth. In order to enhance the difference between the estimates, the data have been multiplied by the square of the distance from the tunnel axis before plotting. It will be seen that the dose-equivalent obtained from two-way fluence scoring gives the highest estimate. That obtained from star-densities is about 20% lower, but this could be due to the fact that in the original determination of the conversion factor, the dose equivalent was related to the outward-going (one-way) fluence only. The dose equivalent determined from star densities is significantly lower in the inner layers of the shield where the incident neutron energy spectrum is softer due to the presence of the iron cylinder. That obtained from the energy deposition gives the lowest estimate by about a factor of two, suggesting that a Q value nearer 10 would be more appropriate.

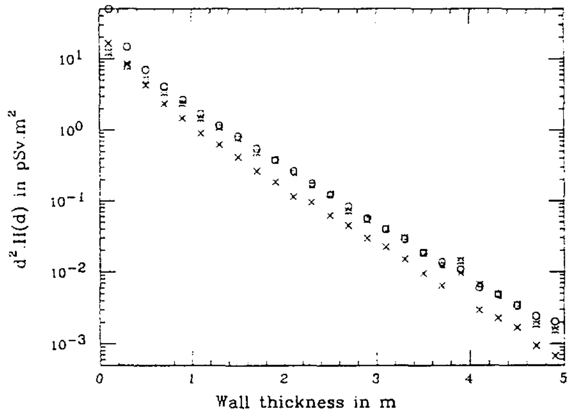

Figure 2: Variation of dose equivalent per proton of 7 TeV as a function of tunnel wall thickness for the FLUKA simulations. ∗ – from star densities; ∘ – from fluences; × – from energy densities.

Similar differences were found in shielding studies for the walls of the CMS experimental cavern [23], but in a study of the shielding around the ATLAS experiment, a Q value of 5 was found to provide very good agreement between the dose equivalent estimates.[24] The difference between the various studies is thought to have its origins in the presence or not of muons in the radiation field. Muons were discarded in the cylindrical shield studies and they are not capable of leaving the heavily shielded central region of the CMS detector in significant quantities. However the ATLAS experiment is based on an air-cored magnet (with a lower field than that of CMS): thus muons can penetrate into the shield and raise the energy deposition without a proportional rise in dose equivalent, thus lowering the apparent Q value.

IV. REGION IMPORTANCE WEIGHTING, PARTICLE SPLITTING, RUSSIAN ROULETTE AND WEIGHT WINDOWS

A certain feeling for the shielding situation at LHC can be obtained from the fact that without any shielding around the collimators which are placed between the interaction point and the low-β quadrupoles to prevent an excessive heat load on their cryogenic cooling system, the dose rate in the experimental caverns would be close to 1 Sv/h when the machine is operating at its peak luminosity. This dose rate has to be lowered by five orders of magnitude in order to meet the design limit for occupied areas. To a first approximation and assuming that cascade multiplicities are low (true only at low energies), this means that there must be approximately 10^5 source particles for one to penetrate the shield

The exponential increase of the required source number with shield thickness can be counteracted by proper biasing. Two different strategies are available in FLUKA to achieve this. The conceptually simpler one consists of region importance weighting, where each region is assigned a single weight. If the particle moves from a region with lower weight to one with a higher weight, it is split in proportion to the importance ratio and at the same time the weight carried by each of the resulting particles is reduced. For particles going in the opposite direction, they are killed (their history is terminated) with a probability in proportion to the importance ratio (Russian Roulette) and weights of surviving particles are increased. In deep penetration problems region importance biasing can be used to maintain an approximately constant particle population in all parts of the shield. The weights carried by the particles then on average carry information on the number of attenuation lengths traversed.

A generalization of this procedure is the application of weight windows, where the weight carried by any given particle type can be limited to a specified range in order to limit large statstical fluctuations in quantities scored.. Particles with a weight higher than the upper window limit are split, while those below the lower limit undergo Russian Roulette. Within FLUKA, weight windows can depend on the region, the particle type and its energy. Thus they can be used to perform exactly the same as region importance biasing, but in addition they can control weight fluctuations which might arise from other biasing strategies.

A second type of biasing, but one which can introduce very large weight fluctuations, is the use of Russian Roulette and particle splitting at interactions; this can be the equivalent leading-particle biasing. This technique can be used to control cascade multiplicities when the incident particle energy in different parts of the geometry varies significantly. As an example of this related to the LHC, the multiplicity of the high-energy secondaries interacting in the low-β collimator can be strongly suppressed, which allows one to sample more elementary beam-beam collisions within a fixed CPU time.

Several aspects have to be kept in mind when biasing:

1. A biased simulation can conserve energy and quantum numbers only on average.
2. The error for a biased simulation has to be estimated from a number of independent batches.
3. Biasing is always dangerous, because it introduces something in the simulation which has no counterpart in reality, but from the mathematical point of view it is rigourously correct and when correctly done it will converge to the correct results.
4. Overbiasing is especially dangerous, since it can lead to apparently good convergence but towards a wrong value.
5. If biasing is incorrectly applied then convergence may take place on a geological time-scale.

With a homogeneous shielding wall and a purely hadronic problem biasing is relatively straightforward. Simple region importance biasing is all that is needed. It is simply a matter of defining the proper weight increments. For concrete, dose equivalent in an accelerator shield is reduced by a factor of $1/e$ in about 50 cm. This suggests that an increment in the importance of 1.5 every 20 cm would just compensate for the attenuation. But it is the particle histories that are split, not the dose. So going to this limit introduces the danger of overdoing the biasing, which would create apparently very good statistics within the shield from only a very few events incident on that part of the shield, and this is more harmful than useful. It has been found by practical experimentation that the proper weight increment for LHC shielding studies is close to 1.3 every 20 cm in concrete. It should be emphasized that the actual choice of biasing factor, provided it is less than 1.5, will not affect the results, only the cpu time needed to obtain them. With the 1.3 biasing factor it is not a problem to calculate attenuation through more than 5 m of concrete in a reasonable cpu time with good statistical accuracy.

Penetration through labyrinths has been found to be facilitated by increasing region importances by factors of three at depths determined by the so-called universal attenuation curves [25], where the attenuation is a function of the length of a tunnel divided by the square root of its cross-sectional area. In addition, one applies a reduction of importance by a factor of three in the corresponding sections of the concrete walls of the labyrinth for the first 30 cm of depth in the concrete, with another reduction factor of three thereafter. Figure 3 shows a comparison between the universal attenuation curves and FLUKA simulations for two different designs of an access way leading from the low-β region of LHC Point 5 to the counting room of the CMS experiment. The access way has a cross-section of $2 \times 2\,\mathrm{m}^2$. The source was provided by 100 GeV protons interacting in an idealized iron target of 10 cm radius distributed uniformly along the beam axis. This represents well the losses in the string of super-conducting magnets close to the high-luminosity interaction region. In both designs the access ways consist of three legs with two right angled bends. In the first design the three legs starting from the source wall of the LHC tunnel have lengths of 4 m, 8 m and 5 m,respectively. In the second design the counting cavern has been moved away from the LHC tunnel by 4 m, but at the same time an enlargement of 1.5 m has been added to the tunnel. The three legs have now lengths of 3.5 m, 10 m and 8 m, respectively. It should be noted that the data in both curves of Figure 3 have been normalized to unity at the entrance of the access ways. Another point worth remarking is the accuracy of the attenuation estimates using the universal curves, which are based on AMC calculations some 25 years old.

The situation becomes more complicated if there is both penetration through the main shield wall coupled with the presence of a labyrinth. The problem is then in balancing the streaming through the labyrinth walls and the streaming through the tunnel itself. Once again, with infinite cpu time available everything is guaranteed to come out correctly, but if the run is limited then biasing can introduce large errors and still apparently indicate a good statistical accuracy. This can happen especially in the case where one important channel for radiation has been essentially blocked by a wrong biasing strategy. A simple example is that of a relatively thin wall with an opening in it. One would expect to apply strong region importance biasing through the opening, but only a very weak biasing through the wall. Thus it might happen that in the simulation there is not a single particle history that comes through the wall and on the other side only the contribution through the opening is seen, and this in reality could be a relatively minor contribution. Thus very strong negative region importance biasing can act like a black hole in the geometry. Often they are only recognized in the final results by a total disappearance of particle histories. If this goes unnoticed then the results can be very wrong.

In the shielding studies for the LHC, full contour maps of the particle flux or dose have proved to be very useful tools to ensure that biasing is properly done. With these one can ensure that particles get through every possible channel. The mathematics of the biasing in the program then takes care that the results are either correct or that a problem is indicated by large errors in the final result (caused by few particles carrying a very high weight passing through a channel which has been suppressed too strongly).

V. DECAY-LENGTH AND INTERACTION-LENGTH BIASING

In the simulation of cascades with FLUKA, the interaction length of selected particles can be artificially reduced for regions chosen by the user. Whereas this has not had many applications directly in resolving shielding situations at the LHC, the capability of forcing a large number of interactions in a thin target or a low-density medium has been applied to studies involving interactions of the beams with the residual gas in the vacuum chambers.

More useful from the shielding point of view has been the possibility in the program of artificially reducing the decay-length of selected particles, thus improving the statistics of daughter production via decay from these particles. This technique was used in a study of the production and transport of high-energy muons at small angles to the beam direction. The muons originated from pion and kaon secondaries of the p-p interactions in the high-luminosity experiments [26]. In order to speed up the calculation, all par-

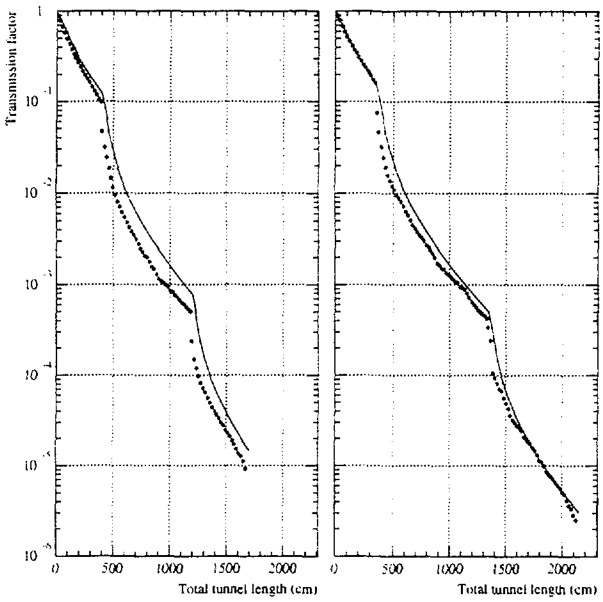

Figure 3: Variation of dose equivalent as a function of depth in a labyrinth leading from the low-β region of the LHC. The points are from FLUKA simulations, the data are from the Universal Curves – see text.

ticles were discarded except those contributing to the muon fluence, *i.e.* all except pions, kaons and muons. Then the decay length of pions and kaons only was reduced to 10 m (instead of in the case of pions 55 m per GeV/c of momentum) in order to force their decay in the "transparent" inner-detector region. As the muons then entered other regions of the detector, it was possible to exempt them from a heavily attenuating region-importance biasing which effectively removed pions and kaons surviving decay in the inner detector region. Without these techniques it would not have been possible to obtain a statistically sound estimate of the muon dose rate in a reasonable cpu time.

VI. CONCLUSIONS

The large changes and improvements to the FLUKA program which have taken place since 1989 came to fruition at the right moment for the program to be used successfully in the shielding calculations for the LHC. Without the biasing options described above it would not have been possible to study the many different problems in the same amount of detail.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the help and many fruitful discussions with the other principal authors, A. Fassò, J. Ranft, and P. R. Sala, of the current FLUKA program. They also wish to acknowledge the many contributions made to the previous versions by P. Aarnio, H-J. Möhring and J. M. Zazula.

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