FLUKA92

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Abstract

The structure and the capabilities of the lastest version of the FLUKA code are briefly presented. This code is a general purpose tool whose range of applications spans from target design and shielding to calorimetry, prediction of radiation levels and activation, dosimetry and detector design. FLUKA is capable of analogically simulating the whole development of a cascade in a single run, including transport of muons, EM cascades and slowing down of neutrons. At the same time the code can perform biased transport simulations. A few examples of code predictions are presented and compared with available experimental data.

1 Introduction

The first radiation studies for the design of proton colliders of the new generation soon showed the limits of application of the 1987 version of FLUKA. The large multiplicities expected at energies above 1 TeV caused the number of particles to be followed in a single cascade to become enormous. To predict radiation damage to some of the materials used in modern electronics, the 50 MeV energy cut-off was too high, especially for neutrons. The extended use of superconducting magnets, which could be quenched by local fluctuations of energy deposition in a volume of a few cubic millimetres, set severe requirements on tracking (especially in magnetic fields), on the treatment of delta rays and more in general of low-energy electrons, and on scoring strategies. And of course, new physical effects had to be taken into account at the higher particle energies, such as the LPM effect for bremsstrahlung and the electromagnetic interactions of hadrons and muons.

The upgrading work originating from this challenge not only brought about an extension of radiation components treated , the energy range and interactions, but also a completely re-structured code. To overcome the combined effect of large multiplicities, high precision tracking, low energy cut-offs and accurate simulation of physical effects on demands for CPU time, a sophisticated statistical set of transport biasing techniques was introduced. In addition some well-established "old" physics was also revised, especially concerning electrons and photons [13].

The present paper is not intended as a detailed description of such developments (see [8, 10, 11, 12, 13, 14]), but as a general presentation of the code and of its most outstanding features.

1.1 "Analog" or "Biased" calculations: Why not both?

Analog codes are those designed to simulate all physical processes as closely as possible to their natural way of occurence. In these codes the statistical weight of each particle is the same and all particles are followed in detail down to predetermined energy or time thresholds. While such codes are essential in simulations aiming at reproducing correctly fluctuations and correlations (the typical example being calorimetry predictions), their use is not practical for a large variety of problems where only average quantities are of interest and the complexity and/or the large attenuations involved would result in enormous CPU times.

Biased particle transport has always been used in low-energy neutron codes to speed up convergence of the results. Such techniques have also been applied extensively in some high-energy programs used mostly for shielding work [30, 29], but are generally ignored by the high-energy physics community. Both approaches have their advantages and their limitations. Statistical variance reduction methods can save computer time, sometimes in a non-negligible way, and may even become mandatory to cope with the endless random walk of thermal neutrons in a non-absorbing medium. On the other hand, a better statistics is attained in some phase space regions at the price of a slower convergence in others; and whereas a biased simulation can predict average values correctly, it cannot reproduce fluctuations and correlations.

In general, the codes used by particle physicists are fully analog [16]. A few programs, because of their possible application to shielding or dosimetry, offer some limited biasing possibilities (e.g. the leading particle option in EGS [15]), but generally each code belongs essentially to only one of the two categories.

FLUKA is indeed fully analog and non-analog at the same time. There is a fairly long list of available biasing techniques which can be activated on request (see the following section), but it is also possible to simulate physical events in full detail. The great flexibility of the code extends further than simply lending itself to be used by both the shielding and the high-energy particle community. Indeed event biasing has been found useful also to study some rare events of interest to particle physicists such as hadron punch-through and muon production by π and K decay over short decay lengths.

2 A brief description of the code

2.1 A short summary of the FLUKA history

The FLUKA code has existed (under different aliases) since at least 1964 [1, 2]: written by J. Ranft it was originally intended as a tool for designing shielding of high–energy proton accelerators. Various versions of the original program were used at CERN until about 1980, mainly for radiation studies connected with the 300 GeV Project [3, 4] and its actual realization, the 450 GeV SPS accelerator [5].

A complete re-design of the code was started in the early '80s, as a collaboration among CERN, Helsinki University of Technology and Leipzig University. Along with a new modular structure, many changes were introduced in the code physics, the most important being a quark exclusive hadron–production model [6] and a resonance-decay model [7]. FLUKA was also linked on-line with the EGS4 code for the treatment of EM showers originated by π^0 decay. Transport in magnetic fields for hadrons was introduced (but not yet for electrons). This phase of FLUKA development was completed in 1987 when the new version was frozen. At about that time the Milan section of INFN joined in the collaboration, starting a period of strong development. As a result of the work done in the last five years, the accuracy of FLUKA has been improved dramatically and its field of application has been extended well beyond the traditional radiation protection domain. The range of possible applications of FLUKA has been expanded to cover in addition to the original shielding and beam heating studies, also calorimetry, prediction of radiation damage and activation, dosimetry and detector design.

2.2 A Fully Integrated Code

FLUKA is not the only analog code capable of simulating a whole high-energy hadronic cascade from TeV to thermal energies. Several other systems, CALOR, HERMES, LAHET [24, 25, 26] are available, but most of them differ from FLUKA by being essentially built as assemblies of different specialized codes, one for each of the main radiation components (hadronic cascade and muons, electromagnetic shower, low energy neutrons), which communicate with each other off-line via an exchange of files. In such systems, each component code keeps in general its own characteristics and structure. Instead FLUKA handles the complete cascade in a single run, and the treatment of the various components has been integrated as far as possible. Perhaps it is worth noticing that all the three of the quoted code systems use a version of the FLUKA high-energy hadron generator, and all of them – including FLUKA – use a version of the HETC nuclear evaporation model [27, 28]. There is still another code, the well known GEANT package developed at CERN [16], which can be compared with FLUKA, at least to the extent that both are able to simulate in detail and in a single run the hadronic as well as the electromagnetic cascade. However, the GEANT description of the hadronic interactions is done through interfaces to existing hadronic codes, which have a life of their own and are not fully incorporated into its structure (the event generators of the last version 3.15 have as an option that of FLUKA itself, without the preequilibrium-cascade part). In addition, since low-energy neutrons are not treated by GEANT with the same level of accuracy as the other components, that code seems to be restricted to the high-energy research domain and cannot be considered a fully general purpose code.

2.3 Hadron Physics

Hadronic interactions in FLUKA are simulated using different models, depending on the energy of the primary particles. A Dual Parton Model based code [18, 19, 20] is used above 5 GeV/c, while a model based on resonance production and decay [17, 7] is used at lower energies. Many improvements have been made to both generators in the last years: a list of the main ones can be found in [11]. A new model [14] based on a cascade plus preequilibrium plus evaporation sequence in describing hadron inelastic collisions at intermediate energies has been specifically developed and is now used below 300 MeV. This model has proved very successful and has considerably improved the code performances in this energy range: it is presently under further development aiming to extend its range of validity up to at least 1 GeV.

2.4 Electro-Magnetic Cascades

The treatment of EM cascades is perhaps the part of FLUKA which has undergone the most fundamental changes since the 1987 release. The starting point was already a good one, nevertheless most of the EGS4 physics has been drastically improved or completely changed leading to a new code module (EMF, Electro-Magnetic FLUKA) which can now compete with specialized programs like ETRAN [9] in low energy electron and photon problems, and whith the best cosmic ray transport codes at the highest end of the energy spectrum. A detailed description of the changes and of their benchmarking can be found in [10, 13]

2.5 Low Energy Neutrons

The need for transporting neutrons below 50 MeV soon became apparent. A new module of FLUKA, LOWNEU, has been therefore developed. The multigroup approach is similar to that of the MORSE code [21]. Calculations can proceed both in analog or biased fashion, depending on the user choice. Photons are generated according to the appropriate cross sections, but their transport is performed through the EMF part. The energy deposition is usually computed using kerma factors but in the case of hydrogen the recoiling protons are explicitly generated and transported.

A special cross section data set has been developed by the ENEA-Bologna laboratory [22] for the needs of FLUKA. This file contains data for about 50 elements/isotopes at different temperatures (293, 87 and 0°K). Data for hydrogen bound in water or in polyethylene are also available.

2.6 Muons and EM Interactions of Hadrons

Transport of muons and of other massive charged particles, previously rather inaccurate, has been brought to the level of the rest of the code. Bremsstrahlung, pair production and photonuclear interactions are simulated taking into account nuclear form factors and the correct angular distributions of secondaries. Multiple scattering is treated by the same sophisticated algorithm which has been adopted for electrons [10], δ-rays are produced and transported and stopping power is calculated from recent compilations down to an energy of 10 keV.

2.7 Biasing Options

Many powerful biasing techniques have been implemented into FLUKA and can be used to speed up the calculations. A short summary is given below:

- **Russian Roulette (RR) / Splitting for hadronic interactions:** the average number of secondary particles arising from an inelastic interaction can be tuned by the user on a region–dependent basis. This is especially useful at very high energies in order to reduce the large number of secondary particles to manageable dimensions. The leading particle is always preserved.

- **Importance Biasing at Boundaries:** particle–dependent region importances are used to play RR or splitting at boundary crossings. It can be applied to all transported particles.

- **Weight Windows:** region, energy and particle dependent weight windows are used to control the particle statistical weight at collision sites in order to accelerate convergence of the results. Particle which would otherwise fall outside the weight window are forced to suffer RR or splitting in order to bring their weight inside the window.

- **Leading Particle Biasing (e^-, e^+, γ):** at each electron or photon interaction, only one of the two outgoing particles is retained at random (with a higher probability for the most energetic). This is an EGS4 feature which has been kept in FLUKA, with the refinement of a special treatment of positrons (which even at rest can propagate the shower at some distance by annihilating into photons). Also this option can be activated in user-selected regions. When coupled to a proper weight window, leading particle biasing minimizes the fraction of time spent in simulating π^0-generated electromagnetic showers.

- **Decay Biasing:** the decay length of selected particles can be artificially reduced. This is useful for instance to force the decay into mouns or other decay products in order to improve statistics.

- **Interaction Length Biasing:** as in the previous option, it makes it possible to modify the interaction length of some hadrons in one or all materials. It can be used to force a larger frequency of interactions in a low-density medium.

- **Neutron Non–Analog Absorption:** this biasing technique applies only to low-energy neutrons and is derived from MORSE where it is applied systematically and is not under the control of the user. In FLUKA it has been generalized to give the user full freedom to fix the ratio between scattering and absorption probability in selected regions and within a chosen energy range. While it is mandatory in some problems in order to keep neutron slowing down under control, it is also possible to switch it off completely to get an analog simulation.

- **Neutron Biased Downscattering:** also for low-energy neutrons, it gives the possibility to accelerate or slow down the moderating process in selected regions. It is an option not easily managed by the average user, since it requires a good knowledge of neutron transport.

2.8 Geometry and Transport

FLUKA makes use of the Combinatorial Geometry package initially developed at MAGI [23]. The package has been extensively modified and improved to make it suitable for charged particle tracking and magnetic field tracking. New bodies have been added and the tracking strategy has been completely redesigned, making the code much faster. Magnetic field tracking has been substantially improved and special efforts have been devoted to combine properly multiple Coulomb scattering and the magnetic deflections. The time evolution of the cascade is accurately modelled for all particles and not only for low energy neutrons.

2.9 Scoring

Several quantities of interest can be obtained from the code both at the end of the run or after each event. The options built in the code are powerful enough for most applications, however it is also possible to ask for a complete dump of the run to be further analyzed off-line. Two main classes of scoring options are available:

- **Energy and Star Density:** can be scored by region or in a geometry-independent binning stucture, averaged over the run or event by event, and even total or from electromagnetic shower only. For detector applications, the possibility of calculating coincidences and anticoincidences has been implemented.

- **Flux and Current scoring:** can be performed as a function of energy and angle, via boundary-crossing, collision and track-length estimators.

3 Benchmarks: a few examples

A series of benchmark calculations have been made in order to assess the reliability of the various models of FLUKA. Benchmarks have been performed both to test the individual models in isolation, and the simulation of whole cascades in order to appreciate the global performance of the code (i.e. [11]). In the following only a few examples are illustrated, because of lack of room. Those shown here are from previously unpublished results, and cover the most critical cases while at the same time illustrating different parts of the code. Further comparisons can be found in [8, 10, 12, 13, 14].

3.1 Testing the event generator models

The experimental [31] and simulated spectra of protons emitted by the $^{54}\mathrm{Fe(p,xp)}$ reaction at 62 MeV are presented in Figure 1 as an example of the FLUKA preequilibrium model. The agreement with experiment is excellent even in the high energy part of the spectrum, which is often underestimated in preequilibrium calculations. This has been achieved mostly by preceeding the statistical treatment with a few intranuclear cascade steps. The contribution of nuclear evaporation to the lo–energy part of the spectrum is also shown.

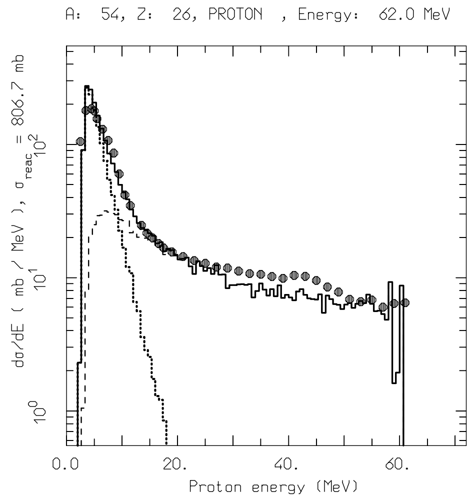

Figure 1: $^{54}Fe(p,xp)$*, at 62 MeV: experimental data (dots) and simulation (full line). The dashed line and the dotted line are the contributions of cascade plus preequilibrium and evaporation, respectively.*

At higher energies new procedures for sampling the number of primary collisions inside the target nucleus and the number and spectra of nucleons emitted during the intranuclear cascade have been implemented. As a result, the code reproduces correctly the experimental energy and angular distributions of cascade nucleons, and the observed multiplicities of particles which cause "fast", "grey" and "black" tracks, together with their mutual correlations – far from straightforward!. Comparisons with experimental data of the average number and multiplicity distributions of charged secondaries for various target and projectile combinations can be found in [12]: the general agreement is fairly good. Here, only examples of their mutual correlations will be presented since these data are by far the most difficult to reproduce. The mutual correlations between particles causing grey and black tracks for 400 GeV/c proton interactions with emulsion nuclei and between fast and "heavy" tracks (black plus grey) for various energies are presented in Figure 2 and 3 (exp. data from [32, 33]).

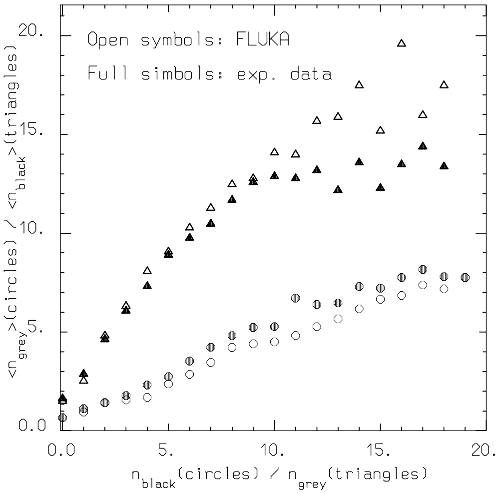

Figure 2: *Simulated and experimental mutual correlations (* $< n_g >$ *vs* n_b *and* $< n_b >$ *vs* n_g*) between black and charged tracks for 400 GeV/c p on emulsion.*

3.2 An example of a pure EM problem:

Problems involving thin layers and interfaces are always very challenging, as they are sensitive to all details of the simulation. In figure 4 a very satisfactory comparison between experimental [34] and calculated values of energy deposition in a multilayer geometry

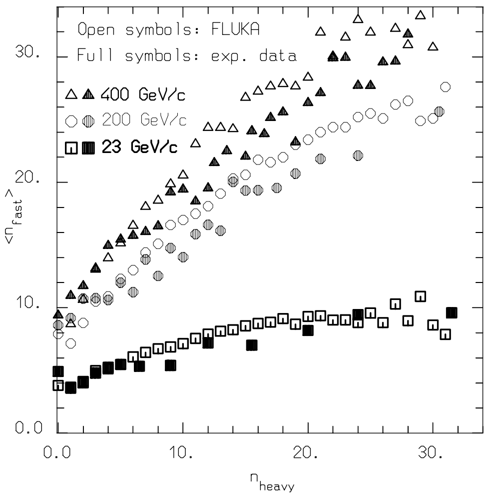

Figure 3: *Simulated and experimental mutual correlations between fast and heavy tracks for p on emulsion*

is presented. It should be stressed that no user-input constraint has been forced on to step–length nor any limitation set to energy loss. The target consisted of adjacent layers of Al (170μ), Au (20μ), and again Al, and was hit perpendicularly by a broad parallel 1 MeV electron beam.

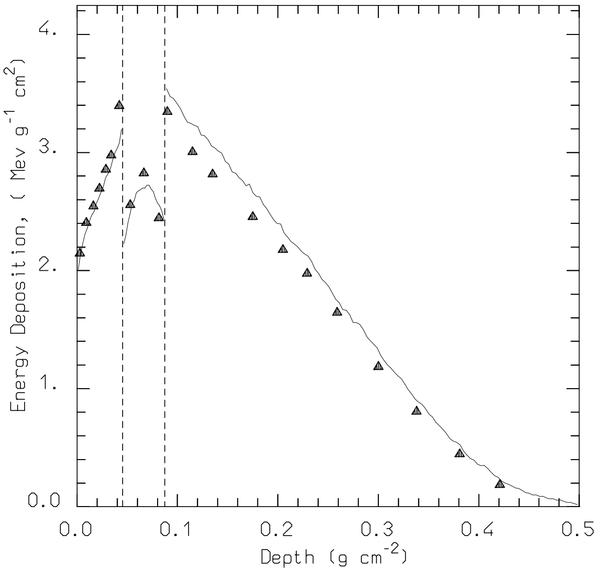

Figure 4: *Comparison of calculated and experimental energy deposition in an Al/Au/Al target hit by 1 MeV electrons*

3.3 An "Analog" FLUKA example: the TEST36 calorimeter prototype

As an example of the performances of FLUKA when used for calorimetry calculations, the results obtained when simulating the TEST36A configuration [35] of the ZEUS lead–scintillator prototype calorimeter are presented in Table 1. The calorimeter configuration, which is described in detail in the experimental paper [35], has been accurately modelled in the FLUKA geometry. The energy deposition in the scintillator plates has been recorded for each event and quenched according to Birks law with the constant generally adopted for SCSN38. The experimental resolutions quoted in Table 1 are those of the original paper with photostatistics and beam momentum resolution unfolded as appropriate for comparisons with Monte–Carlo calculations. The simulated resolutions have been obtained computing a restricted rms deviation over a $\pm 2\sigma$ interval after applying the experimental cuts (i.e. interaction in the first calorimeter section, the "EM compart", required) to the simulated data. These restricted rms deviations are completely equivalent to the resolutions obtained with a Gaussian fit on the same interval, and they are more stable against variations of the adopted binning. The overall agreement between the experimental and the computed resolutions is satisfactory both for e^- and π^- and compares favourably with those obtained with other codes [37, 38]. Further comments are required on the e/π ratio: the value reported in the original paper, 1.05 ± 0.4, has been obtained correcting the experimental data for the insufficient hadronic lateral containment of the prototype, estimated to be $\approx 4\%$. The values reported in Table 1 are the uncorrected ones [36]. The agreement is again satisfactory and better than reported in [37, 38]. Two interesting observations stem from this comparison. The first is that the use of higher order corrections in the multiple scattering formalism in FLUKA (see paragraph 3.6 of [10]) accounts for a ≈ 0.02 increase in the e/π ratio, making evident that these corrections, neglected

Table 1: *Resolution (%) and* e/π *ratios for the TEST36 lead–scintillator prototype;* $FLUKA^a$ *figures have been calculated without the inclusion of spin-relativistic corrections in the multiple scattering algorithm*

	Energy (GeV)		
	10	30	75
res. π^- :			
Exp.[35]	13.8 ± 0.4	7.92 ± 0.2	4.95 ± 0.2
FLUKA^a	12.8 ± 0.5	8.50 ± 0.4	5.50 ± 0.3
FLUKA	13.2 ± 0.5	7.83 ± 0.3	5.18 ± 0.3
res. e^- :			
Exp.[35]	7.15 ± 0.1	4.13 ± 0.1	2.61 ± 0.1
FLUKA^a	6.87 ± 0.4	4.01 ± 0.2	2.74 ± 0.2
FLUKA	7.15 ± 0.2	4.25 ± 0.3	2.71 ± 0.2
e/π :			
Exp.[35]	1.09 ± 0.4	1.08 ± 0.4	1.08 ± 0.4
FLUKA^a	1.03 ± 0.1	1.03 ± 0.1	1.04 ± 0.1
FLUKA	1.05 ± 0.1	1.04 ± 0.1	1.05 ± 0.1

in all other general purpose Monte–Carlo codes can play a role. The second consideration concerns the non–negligible difference in the e/π ratio predicted by FLUKA and that of GEANT. Since GEANT is using the FLUKA generator for the hadronic part, the better result of FLUKA must be due to a difference in transport or, more likely, to a more accurate treatment of EM cascades.

3.4 An example of "Biased" FLUKA: the recent CERN dosimetry experiment

In the last two years, two dosimetric intercomparisons have been organized by the CERN RP Group. A secondary hadron beam of 205 GeV/c momentum consisting mainly of protons was sent on to a target in the H6 beam line, in the framework of an European project to create a standard High Energy test facility. Doses and fluxes were recorded with several kinds of monitors at different places around the shielding. A description of the 1991 experiment and of its results can be found in [42]. When repeating the experiment in October '92 with a slightly different configuration, care has been taken to check each detail to allow its faithful reproduction in a Monte–Carlo simulation. The results of this last experiment are not yet available, however the Milan group has already performed the analysis of the data taken with its own instrumentation and a preliminary comparison with FLUKA predictions is presented in the following.

An isometric view of the target and shielding configuration can be seen in figure 5. The target was a 80x80x160 cm^3 iron block surrounded by a 160 cm thick concrete shielding on the side and by a composite concrete-iron-concrete shielding on the roof. The 205 GeV/c hadron beam (composed roughly of 2/3 protons and 1/3 positive pions) was hitting the centre of the target in a direction nearly parallel to the shielding blocks. An ionization chamber placed in the beam path and three other counters were used to monitor the beam intensity. An independent check of the integrated beam intensity was provided through the reaction $^{27}\mathrm{Al(h,x)}^{24}\mathrm{Na}$ using an Aluminium foil. The neutron induced ambient dose equivalent $H^*(10)$ was measured at the five different positions indicated in figure 5 by means of a LINUS rem counter[39, 40, 41] (an Andersson–Braun Neutron Rem Counter suitably modified to detect also high energy neutrons). Positions A, B and C were located on the forward concrete block, on the central iron block and on the backward concrete block of the shielding roof respectively. Positions H and S were located on the side, at a depth of 60 and 435 cm respectively from the target front face. FLUKA has been used to simulate the full geometry, discarding the EM component which was of no interest. Extensive use has been made of variance reduction techniques to favour particle streaming towards the detector locations. Importance biasing and energy dependent weight windows were applied so as to minimize the CPU time wasted in tracking particles with low probability of giving a detectable contributions. The overall speed–up factor was estimated to be as large as 50. The responses of the LINUS counter to monoenergetic neutron beams had been previously simulated, again with FLUKA. These factors were finally folded with the fluxes scored at the five locations to get the estimated number of counts per incident beam hadron reported in Table 2. The experimental counts of the BF_3 counter placed at the centre of the LINUS detector are also reported. The agreement between the two sets of data is fairly good, and proves the reliability of FLUKA in transporting hadrons in a complex geometry with large attenuation factors over $\approx$ 14 orders of magnitude in energy (it should be stressed that the BF_3 counter practically detects only thermal neutrons). Two sets of dose rates are also reported in the Table: one was calculated by folding the computed fluxes with proper conversion factors [43], the other was obtained experimentally using a calibration of LINUS [41] made with conventional low energy neutron sources. The good agreement is a proof that this counter can indeed be used to monitor the whole neutron energy spectrum.

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Figure 5: *Sketch of the CERN dosimetry experiment setup*

4 Present FLUKA Applications

Even though the trasformation of the original code was prompted by a need to improve its predictive power in the traditional field of accelerator construction, the interest of using it in many other fields soon became apparent.

The new capability to deal with the low-energy component of the cascade has extended the field of interest to include damage to electronics and other sensitive detector parts. Thus in recent times FLUKA has been used successfully to simulate calorimeter performances, but still its mostly widespread application in calorimetry has been in connection with radiation damage to the detector themselves. It is interesting to note that all three LHC experimental proto-collaborations, ATLAS, CMS and L3P [44, 45, 46], have used FLUKA to predict doses and neutron fluxes in their respective detectors.

Table 2: *Experimental and computed LINUS counter counts per incident hadron in the CERN dosimetry experiment. Corresponding $H^*(10)$ dose rates are reported in parentheses (see text for details) . Quoted errors are statistical only. Systematics errors can be estimated of the order of 10% on experimental values(due to beam intensity normalization) and around 5% on calculated values (due to the uncertainty on the BF_3active volume)*

LINUS	Counts h^{-1} (H*(10)pSv h^{-1})	
Pos.	Exp.	FLUKA
A	$3.96 \pm 0.05 \cdot 10^{-6}$ $(4.25 \cdot 10^{-3})$	$4.37 \pm 0.44 \cdot 10^{-6}$ $(4.62 \cdot 10^{-3})$
B	$6.44 \pm 0.02 \cdot 10^{-5}$ $(6.91 \cdot 10^{-2})$	$6.05 \pm 0.18 \cdot 10^{-5}$ $(6.19 \cdot 10^{-2})$
C	$2.56 \pm 0.03 \cdot 10^{-6}$ $(2.75 \cdot 10^{-3})$	$2.08 \pm 0.21 \cdot 10^{-6}$ $(2.16 \cdot 10^{-3})$
H	$4.88 \pm 0.10 \cdot 10^{-7}$ $(5.27 \cdot 10^{-4})$	$4.49 \pm 0.30 \cdot 10^{-7}$ $(5.16 \cdot 10^{-4})$
S	$3.47 \pm 0.13 \cdot 10^{-7}$ $(3.73 \cdot 10^{-4})$	$3.88 \pm 0.30 \cdot 10^{-7}$ $(4.36 \cdot 10^{-4})$

After the recent upgrading of muon physics in FLUKA the code is now starting to be applied also for cosmic ray experiments. Detailed simulations of muon transport in rock up to 1000 TeV are in progress for the MACRO experiment at Gran Sasso.

At the other end of the energy scale, FLUKA is currently being used to simulate the background in underground neutrino detectors due to low-energy neutrons and photons [47]. In this context, FLUKA has been chosen for its ability to follow low-energy neutral particles through 40 to 50 absorption lengths. It was stated that an analog code like GEANT would have needed 10^{10} IBM CPU hours to obtain the same result that FLUKA obtained in a mere 40 hours!

A few present or foreseen applications are connected with the electron intermediate-energy range which is particularly interesting for a new generation of storage rings, dedicated to the Φ-factories. For one of these machines (DAΦNE), under construction at the National Laboratory of Frascati (LNF), Italy, shielding studies with FLUKA have been recently carried out [50]. Shielding problems of the 7 GeV Advanced Photon Source in Argonne [51] are also being investigated.

Current or planned applications range from detector design in high and low-energy physics to cosmic ray penetration in aircraft and underground detectors, to basic in-phantom dosimetry. FLUKA was also used, but in its 1987 version, to predict the energy cost of producing muons in studies of muon-catalyzed fusion [48, 49]. This kind of calculation should be much more accurate with the present version, since the treatment of stopping particles has been considerably improved.

A last interesting application is in the domain of nuclear waste transmutation by proton accelerators. For this purpose, the performance of the code is still poor due to the lack of a good nuclear fragmentation model. However, studies are currently underway in several directions to overcome such limitation.

5 Future Developments

The picture could not be complete without a list of what we would like to get from FLUKA that at the present time it **cannot** give (but we hope to fill this gap soon!). High energy fission has not yet been implemented (a drawback for some energy deposition studies, although not a serious one for neutron production calculations). A nuclear fragmentation model is mandatory if accurate predictions for waste transmutation are required. Photonuclear reactions, very important for electron accelerator shielding, are simulated only at high–energies for the time being. Prompt muons from charm decay are not available; these may constitute a non–negligible radiation component at the new high energy colliders.

On a short timescale, it is planned to include the DTUNUC code [52] into FLUKA. This will allow a further improvement of the description of high–energy interaction, together with the possibility of treating nucleus–nucleus collisions. A new neutron cross–section library with a much finer group structure is in preparation and will be ready in May 1993. Finally the preequilibrium model will be extended in the next weeks to cover nucleon and pion interactions up to 1 GeV.

6 Conclusions

The FLUKA code has been going through a period of very fast development which has deeply changed its nature, transforming it into a very powerful and flexible tool. Improvements to the code itself, as described above, are still needed, but probably will be implemented at a slower pace. An effort is now needed to "clean" the code from some leftovers of its glorious 30-years history, and to put together some decent documentation. But this is the same for most other Monte–Carlo codes.

Acknowledgments

The authors are greatly indebted to G. C. Panini who prepared the cross section data library and to P. A. Aarnio who contributed a lot to the development of previous FLUKA versions. A. Ferrari wishes to thank the colleagues of the LINUS collaboration for the permission to show the data before their publication and acknowledges the suggestions and the helpful discussions of dr. G. Battistoni, about high energy processes and MC simulations in general.

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