FLUKA: present status and future developments

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ABSTRACT

The structure and the capabilities of the FLUKA code are briefly presented and discussed. The hadronic interaction model of FLUKA is briefly described, with particular emphasis on benchmarks. Examples of the code capabilities will be given, highlighting its unique ability to simulate the whole environment of high energy experiments or accelerators. Finally current work to improve the physics of hadron interactions in FLUKA will be outlined, and preliminary results will be presented.

1. Introduction

The importance of shower simulations in many fields of present day physics has grown considerably during the last years, in parallel with the rapid increase in available CPU power. However, there has been no corresponding development concerning the physical models used for such simulations, despite the strong impact that simulation studies have on the analysis of running experiments and on the design of future detectors.

A great importance has been attached instead to the development of sophisticated informatics packages to describe and visualize complex detectors and to provide the generic user with powerful interactive tools for detector modelling and data analysis. Perhaps the best example of such philosophy is the GEANT code [1], developed at CERN and widely used in the high energy physics community; and while the most advanced research trend in this domain emphasizes the manipulation of "objects", the physical content of the objects themselves seems still to deserve very little consideration. The actual "engines" of most simulation codes, namely physical models like the Bertini intranuclear cascade, have undergone practically no development since thirty years.

In this desolate land FLUKA was a lonely but significant exception. Although it was used for many years for tasks usually regarded as secondary by high energy physicists, it was developed with care, giving priority to solid physical bases rather than to graphics and other "bells and whistles". As a result, it was from FLUKA that the majority of the existing high energy transport codes (GEANT, CALOR, HERMES, LAHET) had to "borrow" their hadronic event generator. But there is much more worth borrowing in FLUKA than just its hadron generator, as will be described below.

2. A brief description of the code

The very first ancestor of FLUKA can be traced to a program written in the middle sixties by J. Ranft to simulate hadron cascades in matter. The code was based on an inclusive model for hadron production and on an approximate treatment of electromagnetic showers and of particles with energy below 50 MeV. The shielding of the Fermilab accelerator and of the CERN SPS were largely based on the FLUKA inclusive model.

In 1979 a collaboration CERN–Leipzig University–Helsinki University of Technology was set up to restructure the program. A first release of the new code was called FLUKA82. In the following years the inclusive hadron generator was replaced with two new exclusive models developed at Leipzig (one for the highest energy range and one for intermediate energies). The two models, with various improvements and refinements, are still part of FLUKA today. The version which was released in 1987 contained new cross sections and dealt with a larger number of particles. In particular, electrons and photons were followed in detail by means of a link on-line to the EGS4 code [2].

The "revolution" which has transformed a good shielding program into a multi-purpose tool with possible applications in calorimetry, detector design, cosmic ray simulation, dosimetry and many other fields, started just after the 1987 release and is due essentially to the work done in the Milan section of INFN. As a result of that effort, which was prompted by the new challenging requirements connected with a new generation of proton colliders, FLUKA has developed into a highly efficient and accurate instrument, capable to follow in a single run a whole hadronic cascade from 20 TeV down to thermal neutron energies, or muons from 1000 TeV to rest.

The list of improvements is very long and only a short summary can be given here. Physical models will be described below; on the technical side the stress has been put on three apparently conflicting requirements, namely efficiency, accuracy and flexibility. The part of the code where these three aspects have combined giving the most effective results is the new FLUKA geometry. Derived from the known Combinatorial Geometry package, it has been entirely rewritten. A completely new, fast tracking strategy has been developed, with special attention to charged particle transport, especially in magnetic fields.

Another feature of FLUKA, probably not found in any other Monte Carlo program, is its double capability to be used as a biased code as well as a fully analog code.

2.1 Hadron Physics

Three models are currently used in FLUKA to describe hadronic inelastic interactions in different projectile energy ranges. No detailed description will be given here. We will only mention the recent implementation of a specific model for nucleons below 250 MeV, which combines explicit intranuclear cascade (INC) and exciton based statistical preequilibrium [3]. This model is essential to describe properly the interactions of neutrons at intermediate energies, and represents the best asset of FLUKA for simulations where neutron propagation is important (see ref. [4, 5] for comparisons with experimental data). Inelastic interactions at higher energies are treated in three consecutive steps: primary interactions with the target nucleons, secondary interactions (INC step), evaporation and deexcitation of the residual nucleus. The competition between fission and evaporation is also accounted for. Primary interactions between 250 MeV and 5 GeV/c are described via resonance production and decay, and above 5 GeV/c by multichain fragmentation in the frame of the Dual Parton Model (DPM). Both models are essentially improved and updated versions of those described in ref. [6, 7] The possibility of multiple primary collisions is accounted for in a simplified Glauber cascade framework, and diffractive events are also modelled. The INC description makes use of parametrized multiplicities and energy-angle distributions properly correlated with primary collisions and among each other (see [8, 9]). The evaporation and deexcitation stages will not be described here.

2.2 Electro-Magnetic Cascades

The part of FLUKA which has been most drastically modified in the last years is probably the transport of electrons and photons. The old link with EGS4 has been completely replaced with a new code module with extended performance. As a result of the improvements, which have concerned most of the of the physical models used [10] and the whole charged particle tracking algorithm [11], FLUKA has become probably the only code which can simulate accurately cosmic ray showers up to energies of 1000 TeV as well as energy deposition in thin layers and backscattering of electrons of few keV.

2.3 Low Energy Neutrons

A complete treatment of neutron propagation and slowing-down to thermal energies has replaced the 50 MeV energy cutoff of the previous FLUKA version. A special cross-section set has been expressly prepared for FLUKA from the most recent evaluated data [12]. The file, which includes also kerma factors allowing to calculate the neutron contribution to energy deposition, covers more than 50 different materials of interest in high energy physics and accelerator engineering, including materials at cryogenic temperatures and hydrogen with different kinds of molecular bonds.

2.4 Muons

As for electrons and photons, all the physical models concerning the interaction with matter of heavy charged particles, in particular muons, have been improved and extended at both ends of the energy spectrum. Bremsstrahlung, pair production and photonuclear interactions, described taking into account atomic and nuclear form factors and the correct angular distributions of secondary particles, allow FLUKA to simulate propagation of particles up to 1000 TeV. On the low energy side, the use of recent stopping power compilations has extended transport down to 10 keV. The same refined multiple scattering algorithm is applied, which has been developed for electrons [11], and delta rays production and transport is simulated in detail.

3. Benchmarks

Many papers describing benchmarks of FLUKA physical models have been published in the last years. Only a few examples will be reported in this paper showing the performances of individual models in isolation and of the whole code.

Further comparisons can be found in [8,3–5,10,13,11,14].

3.1 Testing the event generator models

An example of the cascade–preequilibrium model is presented in fig. 1, where calculated double differential cross sections are compared with experimental data [15] on neutron emission from a thin iron target bombarded with 113 MeV protons.

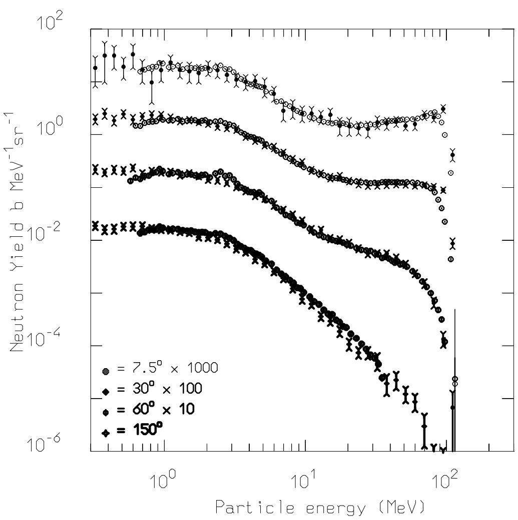

Figure 1: Neutron emission double differential cross section for 113 MeV p on Fe: experimental data (circles) and simulation (symbols with error bars).

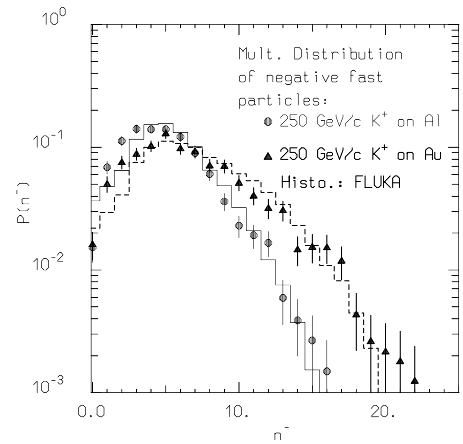

Figure 2: Multiplicity distribution of negative particles for 250 GeV K^- on Al and Au: experimental data (symbols) and simulation (histograms).

In fig. 2 the multiplicity distributions of negative particles following 250 GeV K^- interactions on Al and Au are presented and compared with available experimental data [16].

3.2 EM problem

Several benchmarks can be found in [11,10]. Here two examples referring to bremsstrahlung emission are presented in fig.3 and fig. 4. References for experimental data can be found in ref. [17]

3.3 the TEST36 calorimeter prototype

The TEST36A configuration [18] of the ZEUS lead–scintillator prototype calorimeter has been simulated in detail with FLUKA taking into account scintillator quenching according to the Birks law. The results are compared with the experimental data in Table 1. The comparison refers to the resolutions reported in the original paper with photostatistics and beam momentum resolution unfolded, and to e/π ratios not corrected for the hadronic lateral leakage of the prototype [19]. The overall agreement is satisfactory and compares favourably with that obtained

Figure 3: Bremsstrahlung spectra at $0°$ from 20 MeV (upper curve) and 12 MeV (lower) e^- on W. Points:exp. data; dashed istograms: Fluka with errors

Figure 4: Bremsstrahlung from an Iron target hit by 2 MeV e^-. Spectra at $120°, 60°$ and $0°$ are displayed, scaled by a factor of 100, 10 and 1, respectively

with other codes [20, 21]. Two interesting observations stem from this comparison. The first is that higher order corrections in the FLUKA multiple scattering formalism (see paragraph 3.6 of [11]) account for a ≈ 0.02 increase in the e/π ratio, making evident that these corrections can play a role, although they are neglected in all other general purpose Monte–Carlo codes. The second consideration concerns the non–negligible difference in the e/π ratio predicted by FLUKA and that of GEANT [21]. 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 the D0 ECMH calorimeter prototype

As an example of a liquid Argon based calorimeter, the ECMH module of the D0 detector has been simulated and the computed resolutions, e/π ratio and longitudinal containment have been compared with published experimental data [22,23]. The experimental setup has been modelled as closely as possible to that described in the original references. Responses were simulated for both negative pions and electrons at energies of 10, 25, 50, 75, 100 and 150 GeV. The fitted Monte–Carlo resolutions are:

$$\pi: \ \frac{\sigma(E)}{E} = \frac{41.4 \pm 1\%}{\sqrt(E)} \oplus 1.6 \pm 0.3\% \qquad e^-: \ \frac{\sigma(E)}{E} = \frac{19.7 \pm 0.4\%}{\sqrt(E)} \oplus 0.0 \pm 0.4\% \tag{1}$$

for pions and electrons respectively to be compared with the experimental results [23]:

$$\pi: \ \frac{\sigma(E)}{E} = \frac{41.0 \pm 4\%}{\sqrt(E)} \oplus 3.2 \pm 0.4\% \qquad e^-: \ \frac{\sigma(E)}{E} = \frac{19.0 \pm 2\%}{\sqrt(E)} \oplus 0.8 \pm 0.4\% \tag{2}$$

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. [18]	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. [18]	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. [18]	1.09 ± 0.04	1.08 ± 0.04	1.08 ± 0.04
FLUKA^a	1.03 ± 0.01	1.03 ± 0.01	1.04 ± 0.01
FLUKA	1.05 ± 0.01	1.04 ± 0.01	1.05 ± 0.01

The difference (about 1%) between the experimental value of the constant term for pions and that predicted by FLUKA is consistent with possible instrumental effects, like calibration errors, mechanical and charge collection disuniformities, which of course are not present in the simulation. The same sources of errors are less important for electrons which span just a few cells, and indeed for them the agreement with the simulation is very good.

The longitudinal shower development and the e/π ratio are also well reproduced by the simulation, as shown in fig 5 and 6, respectively. The simulated e/π ratios have been corrected with the factors reported in ref. [22] in the same way as the experimental data. The e/π ratios obtained at two energies including the spin–relativistic corrections in the multiple scattering formalism [11] are also reported in fig. 6: they result in a slight improvement as well as for the T36 case.

4. Future Developments

FLUKA is now a very complete radiation transport code, and its pace of development is expected to slow down somewhat in the near future. Nonetheless, some of the models used can be further improved, and it could be interesting to add a few interactions which are still missing or incompletely described. A short summary of the work in progress will be given below.

4.1 PEANUT

A substantially improved cascade plus preequilibrium algorithm will be implemented soon in FLUKA. The new version is intended to eventually handle nucleon, pion and α particle interactions with nuclei between reaction threshold (or 20 MeV for neutrons) and about 1 GeV. Curved path transport of primary and secondary particles inside the nucleus and a detailed treatment of pion-nucleus interactions up to about 300 MeV have already been included in the PEANUT code

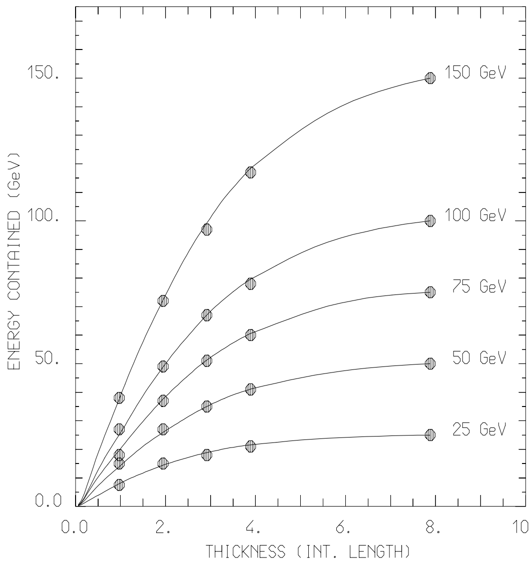

Figure 5: Longitudinal hadronic shower containment. Line: FLUKA calculations, dots: experimental data

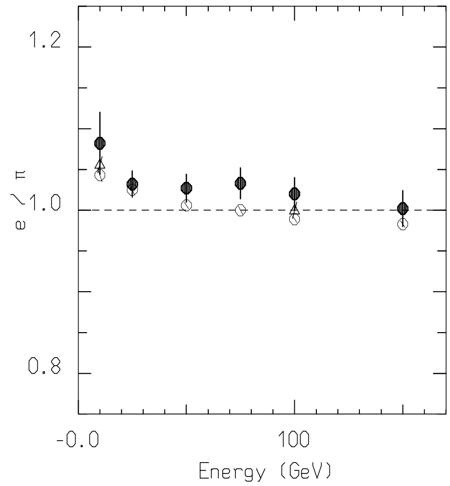

Figure 6: e/π ratio as a function of energy Open symbols: FLUKA calculations, triangles for spin-relativistic correction, full symbols: experimental data

(for PreEquilibrium Approach to NUclear Thermalization), a stand-alone version including a detailed modelling of pion scattering, charge exchange, and absorption on two and three nucleons. All these processes are completely integrated into the cascade simulation, so that multiple pion interactions and the subsequent particle emission/deexcitation are automatically taken into account. Examples of the results obtained for pion absorption and single charge exchange are shown in fig 7 and 8. Experimental data are from [24–26]. The inclusion of single pion production is currently in progress and will raise the range of applicability of PEANUT up to about 1 GeV.

4.2 DTUNUC

The dual parton model provides a unique picture not only for hadron–hadron interactions, but also for the description of particle production in hadron–nucleus and nucleus–nucleus collisions at high energies. DTUNUC [27], our Monte Carlo realization of the model which will soon supplement the high energy event generator in FLUKA, includes the cascading of secondaries within the target as well as in the projectile. The cascade is suppressed by the formation time mechanism [27]. At lab energies below 5 GeV the conventional intranuclear cascade is used.The application of DTUNUC to hadron–nucleus and nucleus–nucleus collisions beyond RHIC energies, i.e. $\sqrt{s}\simeq$200 GeV and $E_{lab}\simeq$5 to 10 TeV, resp., is not recommended, because minijet production [30] is not included.

The model starts from the impulse approximation for the interacting nuclei – i.e. with a frozen discrete spatial distribution of nucleons sampled from standard density distributions. The primary interaction of the incident high–energy projectile proceeds via n elementary collisions between n_p and n_t nucleons from the projectile (for incident hadrons n_p =1) and the target nuclei, resp. Actual numbers n, n_p

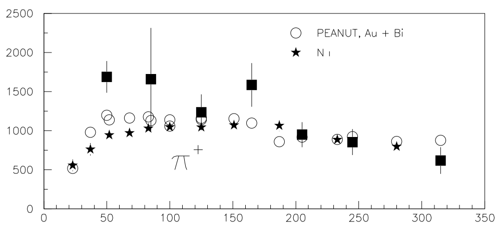

Figure 7: Absorption cross section on Au and Bi as a function of pion energy

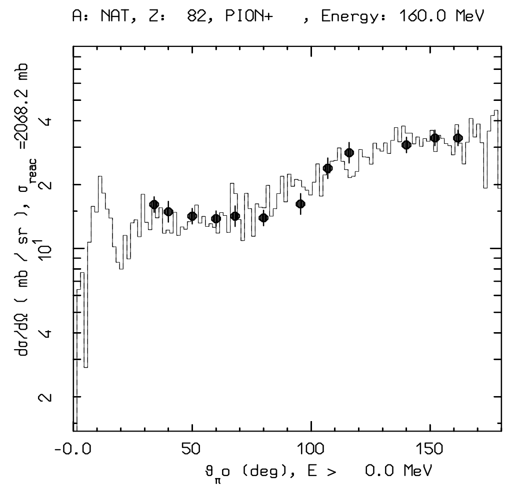

Figure 8: Angular distribution of outgoing π^0s after bombardment of natural Lead with 160 MeV π^+. histogram: PEANUT, dots: experimental data

and n_t are sampled on the basis of Glauber's multiple scattering formalism using the Monte Carlo algorithm of ref. [28]. Note that individual hadrons may undergo several interactions. Particle production in each elementary collision is described by the fragmentation of two color–neutral parton–parton chains. Below 9 GeV inelastic secondary interactions are described by the Monte Carlo code HADRIN [6].

First results obtained with DTUNUC and comparison to data on hadron production in hadron–nucleus collisions have been published [27,31,32] . The model has been succesfully compared to data for hadron–nucleus collisions as well for the produced particles as for the particles resulting from the cascade. In Fig.9 we compare the charged particle rapidity distributions in p–Ar and p–Xe collisions with data [33]. Good agreement is also obtained for nucleus–nucleus collisions, especially for the production of strange particles [32].

The model reproduces the gross features of grey particle production and of the correlations between grey and shower particles. In Fig.10 we compare the model with data on grey particle multiplicity distributions in collisions of protons with various nuclei at 200 GeV [34] .

4.3 Other effects

Among the most important effects still not treated by FLUKA are heavy and light ion transport and interactions, nuclear fragmentation and low-energy photonuclear reactions. The introduction of the DTUNUC generator is a first step towards a complete treatment of heavy ions, but more work will be needed to provide stopping powers and nuclear electromagnetic interactions. Different models of fragmentation are being investigated, but no choice has yet been made. Photonuclear reactions

Figure 9: Charged particle rapidity distribution por p–Ar and p–Xe interactions. DTUNUC calculation compared to data

Figure 10: Comparison of the grey particle distribution from DTUNUC with data from the WA80 Collaboration .

will be implemented soon in the framework of the PEANUT model.

5. Conclusions

The high priority given to the development of accurate physical models and the large amount of work done in only a few years have not left much time for documentation and "cosmetics". For this reason, use of the code has been restricted to a few users individually trained and in daily strict contact with the authors. Although the performances and the number of potential applications of FLUKA could interest a much wider user population, of course such a scheme cannot be extended for practical reasons. Therefore, it will take still some time before the code is made generally available.

6. Acknowledgments

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