FLUKA: HADRONIC BENCHMARKS AND APPLICATIONS

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ABSTRACT

The FLUKA code, which simulates the development of showers initiated by high-energy particles and which was originally used to design shielding for high-energy proton accelerators, has recently been the subject of important improvements and development work. The production and transport of more than 30 different particle types can now be followed, covering an energy range from thermal energies to several tens of TeV, more than 15 orders of magnitude. Applications of the code cover calorimetry, radiation damage, dosimetry and the design of detectors for particle-physics experiments. In contrast to other codes, FLUKA can follow all the components of a hadronic cascade in a single run using either analog or biased sampling techniques, or both. Selected benchmark comparisons with experimental data are presented to illustrate the performance of the code.

1. Thirty years of FLUKA

The history of what is now called the FLUKA code goes back at least to 1964[1,2]. Written by J. Ranft for the IBM 7090, it was originally non-analog (*i.e.* based on weighted sampling) and intended as a tool for designing the shielding of high-energy proton accelerators. However, the name FLUKA (FLUctuating KAskade) is derived from a fully analog version of the code, written in 1970 and which was one of the first applications of Monte-Carlo cascade simulations to calorimetry[3]. The program, which could only follow the cascade development in a single material, was based on an inclusive hadron-production model and was limited to nucleons and charged pions having energies of more than 50 MeV. The emphasis of the program was on the correct treatment of the highest energy hadrons, considered to be the dominant component of energy transport in the cascade. The spatial distribution of energy deposition by electromagnetic cascades and low-energy hadrons was calculated in an approximate way by sampling from empirical distributions. The predictions of these early simulations agreed with experimental data to within a factor of 2 or 3, an uncertainty considered sufficient for shielding purposes. The intention of the author was that *"The program should be easy to use for standard applications. That requires that the input data are simple, that no user-*

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supplied subroutines are necessary, that standard analysis routines are included, ...and that the results ...are printed and plotted in an easily understandable way"[4]. A description of the early codes and of the physical models used was published in the Proceedings of a Course held in Erice in 1978[4]. The present program, while being much more sophisticated and complex, still uses the same approach as far as the user-interface is concerned. In particular, a fast algorithm is used to calculate detailed energy deposition distributions in a user-defined regular mesh. This simple and powerful analysis tool is absent from most modern Monte-Carlo transport codes but was available in the earliest versions of Ranft's program and has been kept as a feature of FLUKA.

At the end of the 70's, FLUKA was the name of only one of some 14 different specialized Monte-Carlo programs available on the CDC 7600 of CERN[4,5] *e.g.* TRANKA was used for deep penetration problems, FLUKU to calculate particle fluxes emerging from a target, MAGKA to simulate beam losses inside a dipole magnet. Each program was built around a specialized task. In 1979 a collaboration was started between members of CERN, Helsinki University of Technology and Leipzig University in order to combine the existing programs into a single flexible tool which could treat all tasks. The new code, which eventually became known as FLUKA82, was designed to be modular allowing for different geometry packages and event generators.

The following years saw revisions of the hadron interaction models developed at Leipzig University: inclusive particle production formulae were replaced by an exclusive generator (`NUCEVT`) based on the Dual Parton Model (including diffraction)[6,7] and by a quasi-two particle production model (`NUCRIN`) for the intermediate energy range[8]. New nuclear elastic and total cross-section data were introduced, and the number of particle types treated was extended. An on-line link was made to the EGS4 code[9] for the treatment of the electromagnetic cascades originating from π^0 decay. The inclusion of EGS4 allowed the development of hadronic cascades from photonuclear interactions to be simulated by adopting a simple scheme based on the Vector Meson Dominance model[10]. This phase of FLUKA development was completed in 1987[11]. It should be noted that the hadron generator of FLUKA87 version has since been "borrowed" by several other hadron cascade programs[12,13,14,15].

Close to the time when FLUKA87 was released, two members of the Milan section of INFN joined in the collaboration, starting a period of intensive development of FLUKA which is still continuing. It is the purpose of the present paper to give a short summary of the recent developments concerning neutron and high-energy hadron physics. Improvements in the treatment of intermediate-energy hadron interactions and in electron and photon physics are described in two other papers presented at this conference[16,17].

The first radiation studies for the design of the new generation of proton colliders soon demonstrated the physical and technical limits of FLUKA87. With increasing energy new physical processes must be taken into account (e.g. LPM effect on bremsstrahlung, electromagnetic interactions of hadrons and muons with nuclei). Technical limits appeared due to the increasing number of particle histories

Table 1: *FLUKA structure*

- ⋆ ≈ 60000 lines of `FORTRAN` (`COMMON`s and `PARAMETERS`s excluded)
- ⋆ 135 `INCLUDE` files
- ⋆ ≈ 300 **routines**
- ⋆ Fully **double precision**, including:
  - all constants (parameterized)
  - random number generator
- ⋆ **Dynamical dimensioning** of:
  - geometry
  - scoring arrays
  - cross-sections
  - biasing parameters
- ⋆ **Keyword**-based input (≈ 60 keywords)
- ⋆ **No user-written code** needed for input or analysis
- ⋆ 700 kb physical data to be read from **external files**
- ⋆ 5 to 8 Mb **storage** required

to be followed in a single cascade. At TeV energies multiplicities are so large that analog sampling techniques become impractical. The 50 MeV energy cut-off is too high to predict the fluence of particles which limit the useful life of electronic components: these can be damaged by neutrons with energies of less than 1 MeV. Superconducting magnets can be quenched by high levels of dose in volumes of the order of few cubic millimetres; this sets additional severe requirements on tracking (especially in magnetic fields), on the treatment of δ-rays and of low-energy electrons in general and on scoring techniques.

To meet these needs, the lower energy limit for the transport of charged particles has been lowered from 50 MeV to 10 keV and to thermal energies for neutrons (an early attempt to implement low-energy neutron transport in FLUKA had already been done by Zazula[18]). At the other end of the energy spectrum, although the present hadron event generator can be used with confidence only below about 20 TeV, muon transport can be simulated successfully up to 1000 TeV (in total, an energy span of 15 to 17 orders of magnitude!). The number of types of particles which can be followed has been increased from the original 4 (charged pions and nucleons) to cover all "stable" baryons and mesons as well as all particles formed in electromagnetic showers. The accuracy of the simulation has been greatly improved at several levels (physical models, tracking, scoring); biasing options have been implemented; new applications have been found or are planned. Finally, the code has been completely re-structured (see Table 1).

2. A fully integrated code

The FLUKA92 code can now simulate all aspects of a hadronic cascade from TeV to thermal energies. However several well-known packages can do the same, for instance CALOR[12], HERMES[13], LAHET[14], but these are *code systems* rather than integrated codes *i.e.* they are simple assemblies of different specialized codes where each of the main radiation components is treated separately. All the three of the above systems use the FLUKA87 high-energy hadron generator (although transporting only a limited set of the particles produced) and one of the many HETC versions at lower energy; EGS4[9] is used for electromagnetic showers, and MORSE[19] (or MCNP[20]) is used to follow low-energy neutrons. In these assemblies, each component code keeps its own characteristics and structure and is run independently of the others. Similar remarks apply to GEANT[21], another code which can be used to transport several radiation components (with the exception of low-energy neutrons), even though its structure is very different from that of the code systems discussed above. Although it deals with electromagnetic showers without interfaces to other programs, it still has recourse to external codes (FLUKA among others) for its hadronic event generator.

FLUKA is different: it handles the complete cascade in a single run, and the treatment of the various components is completely integrated. Even the parts which have been inspired by other programs (*e.g.* the evaporation model), have been rewritten in order to fit into the general FLUKA structure. It should be emphasized that this is not only a question of style: interfaces often cause a loss of information in correlated events.

The only multi-component code which can perhaps be compared with FLUKA for its internal consistency is MARS[22]. However MARS differs from FLUKA in other aspects, mainly by being based on an inclusive treatment of particle production and on a systematic use of statistical weighting methods (these are optional in FLUKA). MARS is an accurate and fast code, but has not been designed to provide information on correlations.

3. A multi-purpose code

FLUKA's unified approach ensures a rather uniform level of accuracy in dealing with each radiation component to within the limits set by available cross-section data, rather than allowing the overall quality of hadron cascade simulations to be spoiled by one or more weak parts of the code. This means that FLUKA can be used to solve purely electron-photon, muon or low-energy neutron problems. Its performance is now comparable to that of the best programs specialized in any particular radiation component. This is exemplified by the unique asset of its neutron cross-section data base (obtained from the most recent evaluations and including more than 50 different elements and single isotopes at different temperatures) and by its capability to deal with low-energy electron problems which is illustrated in a separate paper[17].

Analog codes are designed to simulate all physical processes as closely as possible to their natural frequency of occurence. In these codes the statistical weight of each particle is the same. While analog codes are essential in simulations which aim to reproduce correctly fluctuations and correlations (*e.g.* in 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 excessive CPU times. Biased particle transport has always been used in low-energy neutron codes to speed up the convergence of the results. Such techniques have also been applied extensively in some high-energy programs used mostly for shielding work[22,23], but are generally ignored by the high-energy physics community. Both approaches have their advantages and their limitations. Statistical variance reduction methods can significantly save computer time, 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 statistical result is obtained 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[21]. 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[9] or pseudo-collisions in HETC[24]), but generally each code belongs essentially to only one of the two categories. Only FLUKA is fully analog and non-analog at the same time. There are many available biasing techniques which can be activated on request (see Table 2), 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 in short decay lengths.

4. Main improvements in FLUKA physics

Although hadronic interactions at momenta larger than 5 GeV/c are still based in part on the same models as FLUKA87[6,7,8], many improvements have been made. Certain approximations have been removed from the treatment of primary interactions, and an intranuclear cascade-preequilibrium model, also presented at this Conference[16] is now applied to interactions below 300 MeV. New total, elastic and inelastic cross-sections have been obtained from recently published data down to 20 MeV. Multiplicity distributions have been updated. The treatment of the cascade following the primary interaction has been strongly modified in order to conserve correlations and to produce correct energy and angular distributions. Previously, only Fermi momentum was considered among many possible nuclear effects. This and other effects are now taken into account by an accurate description of the Fermi well and by using recent values of nuclear masses and other detailed nuclear data. Interactions of $\overline{\Sigma_s}, \Xi_s, \overline{\Xi_s}, \Omega, \overline{\Omega}$ have been added, and interactions of stopping particles, previously not simulated in detail, are now treated via the resonance-decay model ($\overline{p}, \overline{n}$) or via the preequilibrium model (π^-). Particle evaporation is simulated after the preequilibrium stage by means of a modified version of the EVAP-5 code[13]:

Table 2: *Biasing options available*

- ⋆ **Russian Roulette (RR)/Splitting for hadron interactions:**
  user-tuned average multiplicity by region: useful at very high energy to decrease the large number of secondaries (the leading particle is always preserved)
- ⋆ **Importance Biasing at Boundaries:**
  particle-dependent region importances can be set to play RR/splitting at boundary crossing
- ⋆ **Weight Windows:**
  region, energy and particle-dependent control of particle statistical weight at collision points
- ⋆ **Leading Particle Biasing (e^-, e^+, γ):**
  only one particle out of two is followed after an electron or photon interaction
- ⋆ **Decay Biasing:**
  the decay length of selected particles can be artificially reduced, improving statistics of daughter production
- ⋆ **Interaction Length Biasing:**
  the interaction length of selected hadrons can be artificially reduced, forcing more interactions in a thin target or in a low-density medium
- ⋆ **Neutron Non Analog Absorption:**
  the neutron scattering to absorption ratio can be controlled by the user on a region and energy-dependent basis (physical ratios may also be requested for an analog simulation)
- ⋆ **Neutron Biased Downscattering:**
  accelerates or slows down moderation in selected regions (requires a good knowledge of neutron transport)

relativistic kinematics has been implemented, very light nuclei are fragmented in an approximate way and the Cameron formula has been updated by using a more modern mass scale. Gamma deexcitation of the residual nucleus is simulated using statistical considerations for E1, E2 and M1 transitions, taking into account the yrast line and pairing energies. Great care has been taken everywhere to conserve energy and momentum *exactly* to within the precision set by the computer (an internal check is set at 10^{-10}).

Low-energy neutron transport below 20 MeV is based on a multigroup approach similar to that of MORSE[19], because the use of a down-scatter matrix algorithm is fast and does not put an excessive overload on the total computer time needed to simulate a complete hadronic cascade. Capture gammas are generated according to the appropriate group probabilities, but are transported using the normal continuous energy-dependent cross-sections as any other photon in FLUKA. Energy deposited by low-energy neutrons is computed using kerma factors or, in the case of hydrogen, by explicitly generating and transporting the recoiling protons. A special cross-section library has been developed for FLUKA by an ENEA laboratory in Bologna[25]. It is based on a P5 Legendre expansion and contains 72 neutron groups (generally collapsed to 37 for routine calculations) and 22 gamma groups. It is in a modified ANISN format which allows for kerma factors and partial cross-sections. The file contains data for most elements/isotopes commonly found around accelerators and high-energy physics detectors, at different temperatures (293, 87 and 0°K).

The most important changes in the treatment of multiple Coulomb scattering (for all charged particles) and of electro-magnetic showers are described in a separate paper[17]. Bremsstrahlung, pair production, δ-rays and photonuclear interactions by massive charged particles have been implemented explicitly (or optionally as continuous energy losses) taking into account nuclear form factors and the correct angular distribution of secondary particles. Stopping power is calculated from Ziegler's parametrizations[26] down to a user-defined cut-off (minimum 10 keV); below the cut-off charged particles are "ranged out" without further interaction.

The time evolution of the cascade is accurately modelled for all particles.

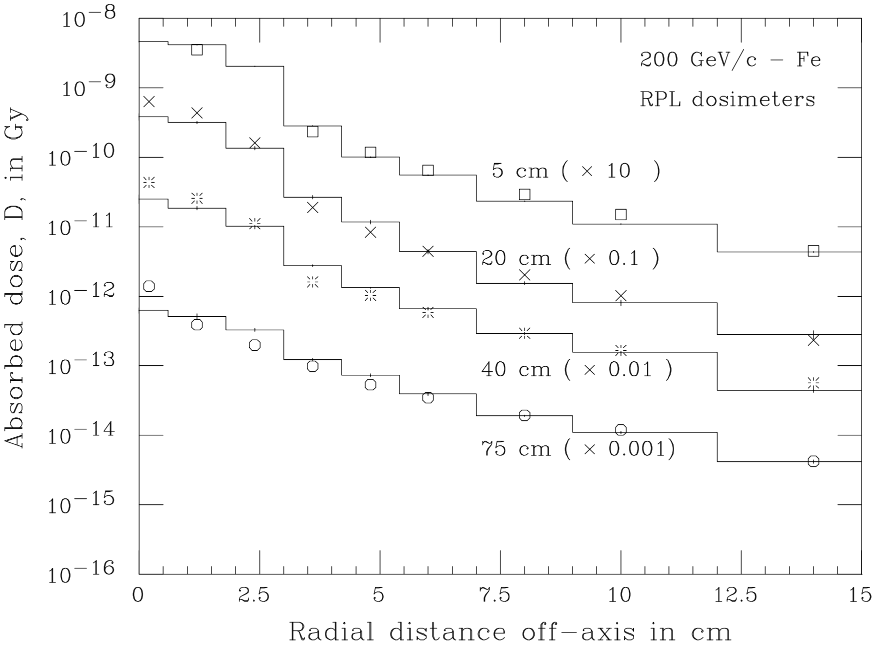

Figure 1: 200 GeV/c hadrons on Iron: longitudinal and radial dose distributions (symbols: RPL measurements, histogram: FLUKA)

5. Other improvements

The Combinatorial Geometry package developed at MAGI[27] for neutron and photon Monte-Carlo transport calculations has been modified in order to allow for the accurate tracking of charged particles. Special efforts have been devoted to the treatment of trajectories in the vicinity of boundaries, taking into account multiple Coulomb scattering, magnetic fields and a combination of both. New bodies have been added and the tracking strategy has been completely redesigned, achieving a considerable gain in speed.

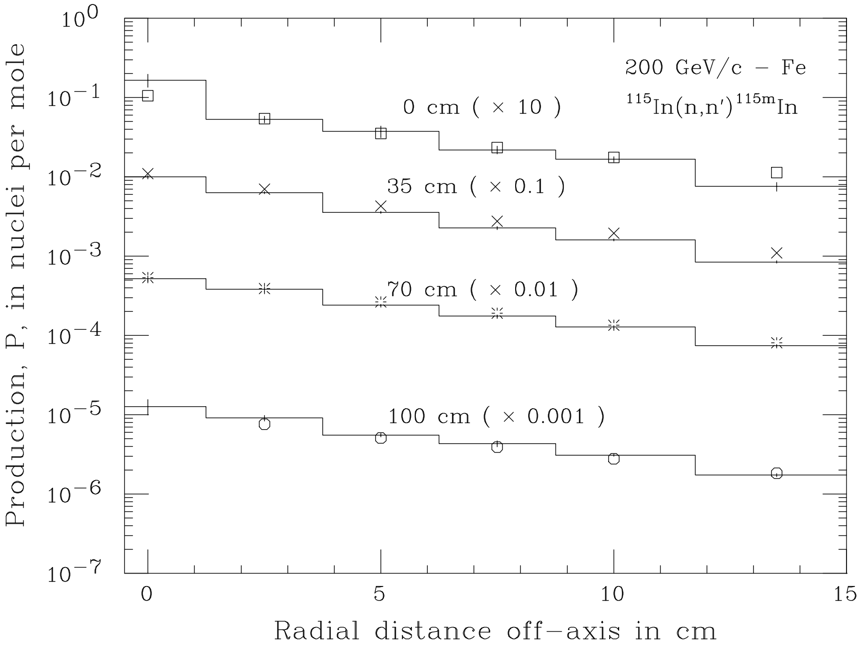

Figure 2: 200 GeV/c hadrons on Iron: longitudinal and radial neutron fluence distributions (symbols: ^{115m}In activation, histogram: FLUKA)

Several quantities of interest can be scored after each event or averaged over several primary histories at the end of the run. Powerful built-in options avoid the need of any user-written analysis in most cases, but easy “hooks” exist that allow the linking of standard analysis packages such as HBOOK or PAW or of user-supplied routines. It is also possible to ask for a complete dump of any event-related information for off-line analysis. The built-in options include collision and track-length estimators providing fluences as a function of energy of any particle by region, while boundary crossing estimators can be used to score fluences or currents, double-differential in energy and angle, at the surface between two adjacent regions. Energy deposition can be determined on a regional basis or in regular grids which are independent of the problem geometry[17]. This feature can also be used to score the spatial distribution of collision densities.

6. Benchmarks

A series of experiments have been carried out at CERN in the last few years in which calorimeter-like structures were irradiated with high-energy hadron beams[28]. Doses and neutron fluences were measured as a function of depth and radial distance from the beam axis by means of passive detectors. One of the aims of this series of

Table 3: *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.[32]	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.[32]	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	6.85 ± 0.3	4.25 ± 0.3	2.71 ± 0.2
e/π :			
Exp.[32]	$1.09 \pm .04$	$1.08 \pm .04$	$1.08 \pm .04$
FLUKA[a]	$1.03 \pm .01$	$1.03 \pm .01$	$1.04 \pm .01$
FLUKA	$1.05 \pm .01$	$1.04 \pm .01$	$1.05 \pm .01$

experiments was to provide data which would test the performance of high-energy hadron transport codes. The experiments represent excellent benchmarks, since the simulation must follow a cascade over an energy range spanning more than 5 orders of magnitude, and in order to get a good agreement with the measured threshold detector data not only the spatial development of the cascade but also the particle energy spectra must be correctly reproduced. The comparisons shown in Fig. 1 and 2 come from recent detailed FLUKA simulations[29] and have been chosen to illustrate two examples of predictions for neutron fluence above 1 MeV and dose (two quantities of particular interest for radiation damage to electronic components).

FLUKA, when used in analog mode, can successfully predict quantities of interest in calorimetry such as resolution and e/π ratio. An example is given in Table 3. It refers to the TEST36A configuration of the ZEUS lead-scintillator prototype calorimeter[30]. The simulation presented is compared with the original uncorrected data (details are reported elsewhere[31]). The data show two particularly strong points of the FLUKA simulations: the non-negligible advantage due to the inclusion of higher-order corrections in the multiple scattering algorithm[17], and the sensitivity of the e/π parameter to a balanced Monte-Carlo treatment of hadronic and electromagnetic cascades.

7. New applications

The new, more stringent requirements in the fields of accelerator shielding and radiation damage which triggered the development of FLUKA have provided a new powerful and flexible tool which can be applied in many other domains. For example for all three proposed LHC experiments, ATLAS, CMS and L3P, FLUKA has been used to predict doses and neutron fluxes in their detectors[32,33,34]. This would not have been possible without the new capability to handle the low-energy component of the cascade.

Transport of low-energy neutrons and gammas, and the new powerful biasing capabilities of FLUKA are currently exploited to simulate the background in a neutrino detector[35]. Neutral particles are followed through 40 to 50 absorption lengths, an impossible task for any analog code. The upgraded treatment of muon interactions at very high energies is attracting some interest in the field of cosmic ray research. Muon transport in the atmosphere and in rock at energies as high as 1000 TeV is presently being studied for the MACRO experiment at Gran Sasso.

The shielding of electron accelerators is a recent application of FLUKA: this is currently being investigated at Frascati in the frame of the DAΦNE Φ-factory project, and at Argonne's Advanced Photon Source. Other applications currently being considered are the estimation of dose to air-crews from cosmic rays, the dosimetry in phantoms of different types of radiation, detector design and nuclear waste transmutation. The latter idea has again started a new line of code development, because it needs a good fragmentation model and this is still missing from FLUKA. If the studies in progress are successful, radiation protection will also profit from the new capability to predict yields of radioactive nuclides: thus completing a circle of beneficial mutual interactions between different areas of applied physics.

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