APPLICATIONS OF THE FLUKA MONTE CARLO CODE IN HIGH ENERGY AND ACCELERATOR PHYSICS

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Abstract

This document summarizes some of the recent applications of the FLUKA Monte Carlo code in HE physics. In particular we address topics as accelerator physics and high energy cosmic ray physics in underground laboratories.

INTRODUCTION

FLUKA is a Monte Carlo code able to simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide energy range [1]. It is a multi-purpose, multi-particle code that can be applied in many different fields. Presently the code is maintained for various platforms with Unix Interface: Linux, Compaq-Unix, HP-Ux and Sun-Solaris.

The validity of the physical models implemented in FLUKA has been benchmarked against a variety of experimental data over a wide energy range, from accelerator data to cosmic ray showers in the Earth atmosphere. FLUKA is widely used for studies related both to basic research and to applications in radiation protection and dosimetry, including the specific matter of radiation damage in space missions, radiobiology (including radiotherapy) and cosmic ray calculations. After a short description of the main features that make FLUKA valuable for this physics, we summarize a few of the most recent applications in high energy physics.

HIGH ENERGIES IN FLUKA

FLUKA has been initiated in the 70's by J.Ranft with the aim of preparing a calculation tool for physics at colliders. Now FLUKA has evolved into a much more complete and flexible simulation tool, but the original goal has remained one of the priorities for its development. Therefore a continuous effort has been maintained until now to upgrade the code in view of the increasing requirements in terms of energy and precision demanded by the evolution of accelerator physics. In particular, since the end of 80's, it has been driven by the design of LHC at CERN, both from the point of view of the machine engineering and the main detector developments (ATLAS, CMS and ALICE). In the '90s new applications to neutrino and cosmic ray physics ICARUS, CNGS, NASA) further pushed the code upgrade. The high energy developments concerned mostly the e.m. and the hadronic parts, but the whole transport has required a particular care so to avoid typical numerical problems connected to machine accuracy (like for instance cancellations) which typically may occur when dealing with asymptotic regions and when widely separeted scales co-exist in the same problem. Physics models in FLUKA are described in detail elsewhere[1,2]. Here we recall the main features which are relevant for this paper.

Electro Magnetic models

The e.m. part of FLUKA allows a reliable physics in the range 1 keV-10000 TeV, ensuring full coupling in both direction with hadrons (and low energy neutrons), and in particular the database for photonuclear cross sections is now largely improved. In order to optimize the calculation speed, whenever possible analytical sampling is preferred to rejection techniques. Table lookup is privileged with respect to analytical formulae in order to preserve accuracy. Energy is conserved within the computer double precision. LPM effect is considered in bremsstrahlung and is under construction for pair production. At present the photoproduction of muon pairs is being prepared.

Hadronic models

At intermediate energies FLUKA uses the PEANUT (Pre-Equilibrium Approach to NUclear Thermalisation) model, which consists of intranuclear cascade (INC), pre-equilibrium, evaporation and de-excitation. At energies above 5 GeV/n, a model based on the Dual Parton Model

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(DPM) is used, which can be reliably extended for interactions up to 100 TeV. FLUKA is now capable of simulating the interaction and transport of nuclei. Below 5 GeV/n, down to ≈100 MeV/n, FLUKA is coupled to the Relativistic Quantum Molecular Dynamics code RQMD-2.4 [3]. At higher energy the interface to DPMJET-II.53 [4] is now working. DPMJET-II is also based on the Dual Parton Model in connection with the Glauber formalism, and includes the lowest order contributions from perturbative QCD. It allows not only the sampling of nucleus-nucleus collisions, but also of hadron-hadron and hadron-nucleus interactions, in alternative to the original FLUKA model, up to 10^9-10^{11} GeV/n, thus extending the FLUKA energy limits for hadronic simulations in general. A beta-version of an interface to DPMJET-III[5] is now available.

APPLICATIONS IN ACCELERATOR AND HIGH ENERGY PHYSICS

Within the framework of high-energy physics studies, FLUKA was applied in the past to the prediction of calorimetric performances and the evaluation of background in LHC detectors [6]. More recently FLUKA has been widely used in the design of the CNGS neutrino beam from CERN to Gran Sasso [7]. At present within the projects carried on by the Accelerator and Beams Division of CERN, FLUKA is the main tool to study of the collimation system, beam dumping, activation and in general of many questions which are related to the LHC operation.

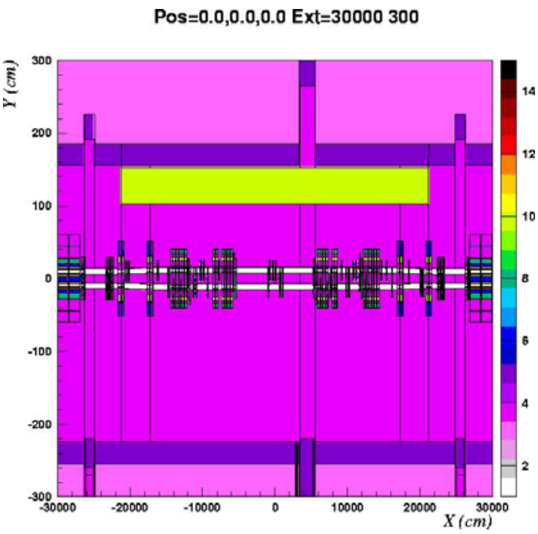

Figure 1: FLUKA geometry of the beam cleaning site in LHC.

All the example reported here share the need for a simulation capable of a reliable simulation in a wide energy range: from TeV to MeV, and below.

In Fig. 1 we show the plot of a section of the geometry description in FLUKA of the beam cleaning position in LHC. For this study the accurate description of the beam lines, including the magnetic systems, is mandatory. Fig. 2 shows a section of the geometry description of one of the hot quadrupoles of LHC, with the color map of the magnetic field (the scale is in Tesla).

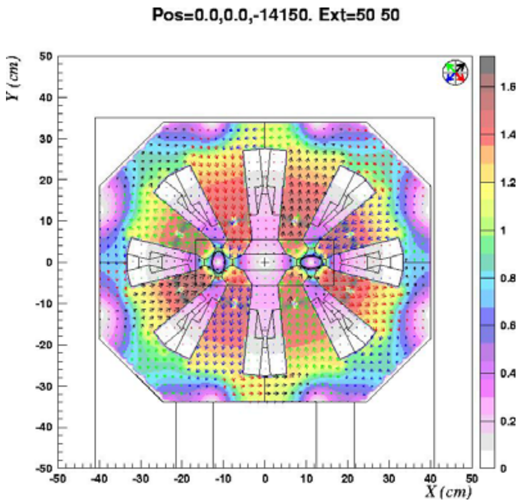

Figure 2: Section of the geometrial description in FLUKA of one warm quadrupole of LHC. The magnetic field color map in Tesla is superimposed.

This activity, at present still under way, has also required the development of new software tools coupled to FLUKA which serve to enlarge the set of general utilities for a wide class of simulation problems. In particular there are now routines to plot the magnetic field maps from the FLUKA input. At the same time FLUKA has been used for the evaluation of damage to the RF system of LHC due to the beam gas interactions.

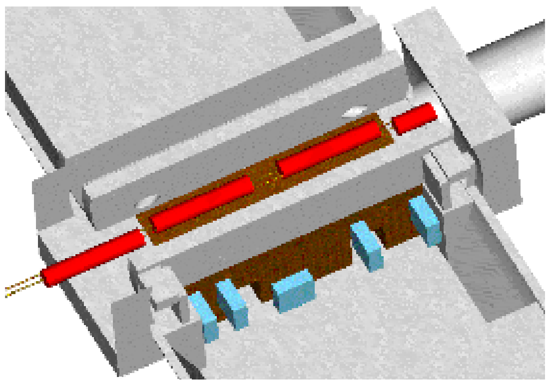

Figure 3: AUTOCAD representation[8] of the FLUKA geometry describing the RF system of LHC. The racks of electronics are represented by the light blue boxes.

In Fig. 3 the FLUKA geometry setup to describe one of the RF system as plotted by means of AUTOCAD[8]. Radiation effects to RF electronics will result in the proton beam becoming unstable and being dumped. A part from the several hours needed for recovery, there is a high risk of damage due to the stored energy. The simulation allows to evaluate the impact of cumulative effects, as the total ionizing dose and the

"Displacement Damage" due to non ionizing energy loss. In the first case one has to score the total energy deposition, while in the latter the relevant quantity is the "1 MeV neutron equivalent fluence", i.e. the fluence scaled with the neutron, proton, pion cross-sections for a displacement damage to occur in Silicon. These cross sections are normalized to that of 1MeV neutron.

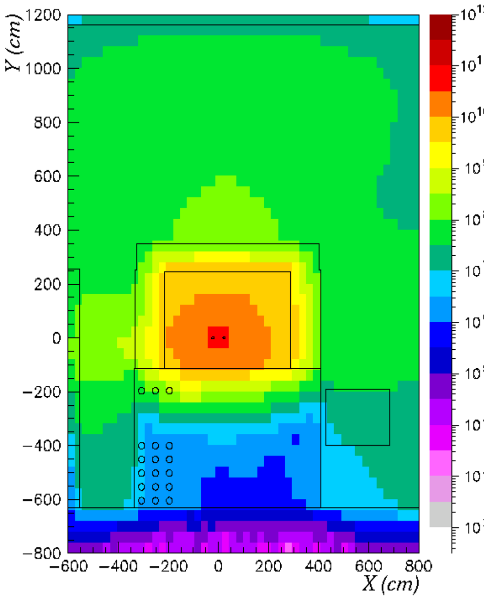

Figure 4: Color map of the FLUKA simulated 1MeV equivalent neutron fluence (cm^{-2} yr^{-1}) in one transverse section of the geometry of one RF station of LHC.

Fig. 4 shows the color map of the calculated 1MeV equivalent neutron fluence (cm^{-2} yr^{-1}) in one transverse section of the geometry of Fig. 3, as obtained directly from the FLUKA output. The results are encouraging as far as the long term LHC operation is concerned. Also the expected rate of "Single Event Upset" (connected to hadron fluence with E>20 MeV) seems to be under control. In the framework of a similar activity, FLUKA has been also used to calculate the level of activation of materials employed in LHC (iron, copper, concrete, etc.). The results have been compared to the experimental results of a dedicated beam test (CERF)[9]. The estimation of the fraction of different radionuclides is one of the hardest job for a Monte Carlo of this type. The results with FLUKA have turned out to be generally successful, thank to the quality of the nuclear fragmentation models. However in some case a refinement was necessary, for instance the introduction of a "multi-fragmentation" model. This is in progress and first results will be presented elsewhere[10]. FLUKA has also the tools to predict the time evolution of the radiation dose rates: see for instance, in the case of copper, some results compared to 2 sets of experimental measurements (having different exp. errors).

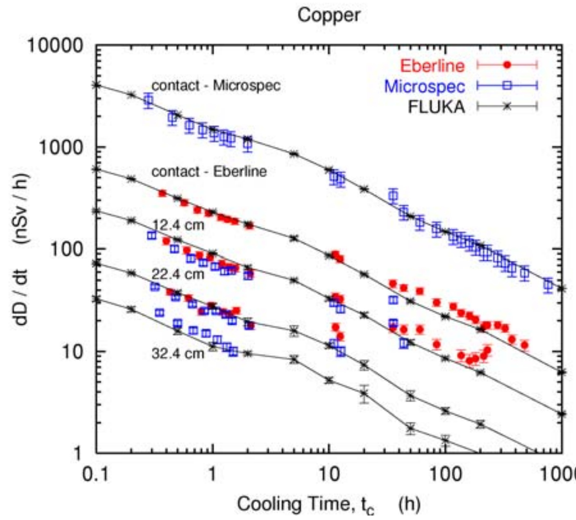

Figure 5: Time evolution of radiation dose rates in copper after exposure in the CERF facility at CERN[9].

We move now to high energy physics in underground laboratories. FLUKA has already been used in this context to evaluate the effect of residual high energy muons[11]. This remains a fundamental issue for a large class of experiments, like for instance Borexino[12] at Gran Sasso, a high purity liquid scintillator detector devoted to solar neutrino physics. In this case an activity with FLUKA has started[13] with the aim of learning how to reduce the cosmogenic background due to atmospheric muons (at the Gran Sasso depth their average residual energy is ~ 300 GeV). A particular aim is to reduce by a factor larger than 10 the background coming from the *in situ* production of ^{11}C by muons. The eventual goal is to be able to tag ^{11}C event by event. This goes through the identification of the neutron capture (tagged by a 2.2 MeV γ) following the reaction $\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$. For this purpose the identification efficiency of neutrons predicted by FLUKA has been successfully compared to the measurements performed in the "Counting Test Facility" of Borexino. Now the Monte Carlo can be used to define a veto volume around the muon track and the neutron production point, which is estimated by evaluating the distribution of path length of neutrons.

As a last example we mention the work with FLUKA undergoing in the framework of the ICARUS experiment at Gran Sasso[14] (a high resolution, large mass, liquid Argon TPC experiment). Here FLUKA is used both as event generator for physics items (proton decay, neutrino interaction, etc.) and detector simulation as well. Among the different topics that can be convered in the physics programme of ICARUS, there is also the measurement of the muon multiplicity distribution undeground. A part from being a tool for checking detector operation, the physics of underground muons at Gran Sasso can be used to contribute to high energy cosmic ray physics since these muons carry information about primary energy and composition[15]. In this context a Monte Carlo is essential to analyse data, and FLUKA is being used to go through all the essential steps: primary cosmic ray interaction in the atmosphere (using the interface to DPMJET interface up to 10000 TeV/nucleon), shower development, muon production and transport in the mountain rock and detection. In Fig. 6 we show the FLUKA geometry of Gran Sasso mountain built using the new “voxel” option.

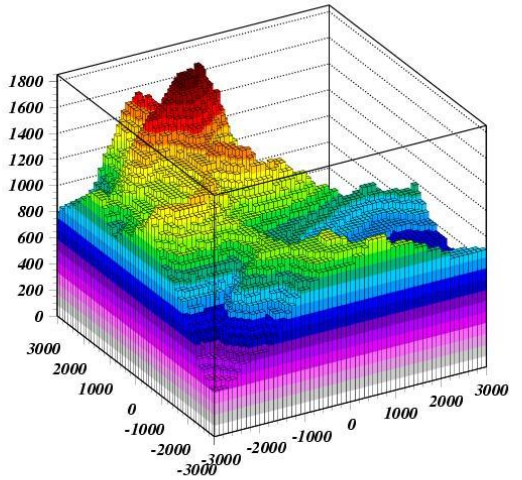

Figure 6: FLUKA geometry in the voxel style representing the Gran Sasso Mountain.

In Fig. 7 a high multiplicity event coming from a shower initiated by a Fe nucleus of 1000 TeV/nucleon as detected by ICARUS is represented by using the same visualization software used for real experimental data.

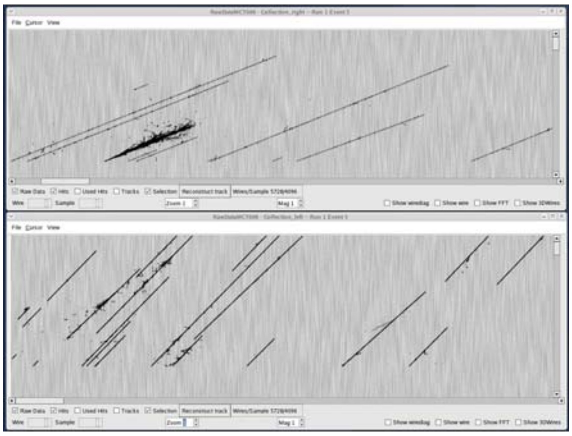

Figure 7: a FLUKA simulated multi-muon event underground as seen by the ICARUS reconstruction program.

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