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FLUKA MONTE-CARLO SIMULATION CODE USED FOR RADIATION STUDIES IN ALICE EXPERIMENT

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The main features of the FLUKA Monte-Carlo code, which can deal with transport and interaction of electromagnetic and hadronic particles, are summarized. The physical models embedded in FLUKA are described. The code is applied for the radiation background calculations. Especially, the origin and composition of the intense radiation field to be expected in parts of the ALICE detector for the coming multi-TeV LHC collider are described. It is important to evaluate the risk of radiation damage in detectors and electronic equipment.

Приведено обобщение характерных свойств программы монте-карловского моделирования FLUKA, которая может моделировать транспортировку и взаимодействие электромагнитных и адронных частиц. Описаны физические модели, входящие во FLUKA. Программа использована для вычисления радиационного фона. В частности, описано происхождение и состав интенсивного радиационного поля, ожидаемого в элементах детектора ALICE на коллайдере LHC. Важно заранее оценить риск радиационных повреждений в детекторах и электронном оборудовании.

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INTRODUCTION

FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy, etc.

The highest priority in the design and development of FLUKA has always been the implementation and improvement of sound and modern physical models. Microscopic models are adopted whenever possible, consistency among all the reaction steps and/or reaction types is ensured, conservation laws are enforced at each step, results are checked against experimental data at single interaction level. As a result, final predictions are obtained with a minimal set of free parameters fixed for all energy/target/projectile combinations. Therefore, results in complex cases, as well as properties and scaling laws, arise naturally from the underlying physical models. Predictivity is provided where no experimental data are directly available, and correlations within interactions and among shower components are preserved.

In this paper, physical models and transport algorithms used in FLUKA package as well as main applications of the program are briefly summarized. Then, its application for the radiation calculations for the high-energy heavy ion experiment ALICE at the Large Hadron Collider (LHC) under construction at CERN is described.

1. PHYSICAL MODELS

The FLUKA hadron–nucleus interaction models are based on resonance production and decay below a few GeV, and on the Dual Parton model for higher energies. Two models are used also in hadron–nucleus interactions. At momenta below 3–5 GeV/*c* the package includes a very detailed Generalized Intra-Nuclear Cascade (GINC) with following preequilibrium stage, while at high-energies the Gribov–Glauber multiple collision mechanism is included in a less refined GINC. Both modules are followed by equilibrium processes: evaporation, fission, Fermi break-up, gamma deexcitation. FLUKA can also simulate photonuclear interactions (described by Vector Meson Dominance, Delta Resonance, Quasi-Deuteron and Giant Dipole Resonance). A schematic outline is presented below:

- inelastic cross sections for hadron–hadron interactions are represented by parameterized fits based on available experimental data [1];
- for hadron–nucleus interactions, a mixture of data and parameterized fits is used [2];
- elastic and charge exchange reactions are described by phase-shift analysis, and eikonal approximation;
- inelastic hadron–hadron interactions are simulated by different event generators, depending on energy. For momenta in the range < 5 GeV/*c* and > 20 TeV/*c*: Dual Parton Model [3] is used, while resonance production and decay model [5] are applied below;
- inelastic hadron–nucleus interactions are simulated by different event generators depending on the projectile and its momentum. In the range < 5 GeV/*c* and > 20 TeV/*c* Glauber–Gribov multiple scattering followed by Generalized Intranuclear Cascade (GINC). Below 5 GeV/*c* preequilibrium-cascade model «Peanut» [4] is used;
- all three collision models include evaporation and gamma deexcitation of the residual nucleus [5]. Light residual nuclei are not evaporated but fragmented into a maximum of 6 bodies, according to a Fermi break-up model.

Nuclear interactions generated by ions are treated through interfaces to external event generators. Above 5 GeV per nucleon DPMJET [12] is used and between 0.1 and 5 GeV per nucleon — modified RQMD [13]. Transport of charged hadrons and muons incorporates:

- Bethe–Bloch theory is the base of the energy loss calculations [6, 10];
- delta-ray production and transport including spin effects and ionization fluctuations;
- shell and other low-energy corrections derived from Ziegler [7];
- density effect according to Sternheimer [8].
- special transport algorithm, based on Molière's multiple Coulomb scattering theory [9];
- accurate treatment of boundaries and curved trajectories in magnetic and electric fields;
- path length correction; automatic control of the step;
- nuclear size effects (scattering suppression);
- bremsstrahlung and electron pair production at high energy by heavy charged particles;
- muon photonuclear interactions with or without transport of the produced secondaries.

Special treatment of low-energy neutrons transport is one of the most important features of FLUKA. For neutrons with energy lower than 20 MeV, FLUKA uses its own neutron cross-section library (P5 Legendre angular expansion, 72 neutron energy groups), containing more than 140 different materials, selected for their interest in physics, dosimetry and accelerator engineering and derived from the most recently evaluated data. The ingredients of the transport code are:

- standard multigroup transport with photon and fission neutron generation;
- detailed kinematics of elastic scattering on hydrogen nuclei;
- transport of proton recoils and protons from $N(n,p)$ reaction;
- capture photons generated according to the multigroup treatment, but transported with the more accurate E_{MF} package which performs continuous transport in energy and allows for secondary electron generation.

For nuclei other than hydrogen, kerma factors are used to calculate energy deposition (including low-energy fission).

2. MAIN FLUKA APPLICATIONS

While early FLUKA was essentially a specialised program to calculate shielding of high-energy proton accelerators, the present version can be regarded as a general purpose tool for an extended range of applications. In addition to traditional target design and shielding, applications are now spanning from calorimetry to prediction of activation, radiation damage, isotope transmutation, dosimetry and detector studies.

The present version of FLUKA has been successfully used in such diverse domains as background studies for underground detectors, cosmic ray physics, shielding of synchrotron radiation hutches, calculation of dose received by aircraft crews, evaluation of organ dose in a phantom due to external radiation, detector design for radiation protection as well as for high-energy physics, electron and proton radiotherapy, nuclear transmutation, neutrino physics, shielding of free-electron lasers, calculation of tritium production at electron accelerators, energy amplifiers, maze design for medical accelerators, etc.

Prediction of radiation damage has always been a traditional field of application of FLUKA, restricted, however, in earlier versions to the damage to accelerator components due to hadrons. The new capability to deal with the low-energy neutron component of the cascade has extended the field of interest to include electronics and other sensitive detector parts.

3. ALICE EXPERIMENT AT LHC

ALICE is a general-purpose experiment, whose detectors measure and identify hadrons, electrons, photons, and muons produced in proton–proton, proton–nucleus and nucleus–nucleus interactions at the CERN LHC. ALICE is optimized for heavy-ion reactions and thus is of very different design than the other three LHC experiments (ATLAS, CMS, LHCb). It has to be able to track and identify particles from very low ($\sim$ 100 MeV/c) up to fairly high ($\sim$ 100 GeV/c) transverse momentum, to reconstruct short-lived particles such as hyperons, D and B mesons, and to perform these tasks in an environment of extreme particle density.

ALICE will study Pb–Pb collisions at a centre-of-mass energy of 5.5 TeV per nucleon pair. The physics programme also includes running with lighter ions, in order to study the energy-density dependence, as well as data taking during regular proton–proton operation at the LHC and dedicated proton–nucleus runs, in order to provide reference data for the heavy-ion programme and to address specific pp and pA physics topics accessible to ALICE [14].

4. CALCULATIONS AND RESULTS

The ALICE detector has been designed to cope with significantly high particle densities. These event related particle densities determine the detector occupancy and influence track reconstruction and particle identification. They are also related to the expected radiation load which is needed to evaluate the risk of radiation damage in detectors and electronic equipment determining the failure rate and long-term deterioration of the detectors. Together with the running scenario (collision systems, luminosities and running time) they fix the order of magnitude of the expected radiation. For the assessment of radiation effects one has to consider both, the integrated fluence or dose and the instantaneous flux or dose rate. Which one of the two is appropriate depends on the detector type and the expected radiation effects. For instance, occupancies in detectors depend only on the instantaneous particle rate (only integrated over the short time during which the detector is sensitive ($< 0.1-100\ \mu$s), whereas radiation damage often is a cumulative effect integrated over years.

We took data with proton and light- or heavy-ion beams for different time periods and different luminosities. The radiation load on the various parts of the detectors must therefore be calculated for a combination of beam conditions. There are three major sources of radiation in ALICE:

- particles produced at the interaction point (IP) in planned collisions;
- beam losses due to mis-injection, since ALICE is located near the injection point;
- beam–gas interactions in pp operation.

The beam gas interaction rate itself depends on the estimated residual pressure in the beam pipe and we have to base our estimate on conservative predictions. The radiation load from losses at injection depend on the types of accidental scenarios, that have to be taken into account, and their rate.

A full description of the radiation field has to take into account the reinteraction of primary particles in the absorbers and structural elements of the experiment initiating hadronic and electromagnetic showers, therefore a substantial effort has been devoted to finding the best parameters and approximations to describe the ALICE experimental set-up in FLUKA, so that it remains feasible to implement, maintainable and keeping the computing time low without loosing on the precision of the results. FLUKA can handle even very complex geometries, using an improved version of the well-known Combinatorial Geometry (CG) [11]. The FLUKA CG has been designed to track correctly also charged particles in the presence of magnetic or electric fields. Two concepts are fundamental in CG: bodies and regions. Regions are defined as combinations of bodies obtained by boolean operations: Union, Subtraction and Intersection. Each region is not necessarily simply connected (it can be made of two or more noncontiguous parts), but must be of homogeneous material composition. About 3000 regions are needed to describe the full ALICE experimental area. It includes the cavern, tunnels, vertical shafts, rooms, shielding, the surrounding hall, magnets of LHC optics near IP2, ALICE detectors with services and racks with electronics. Each detector has been described with the accuracy considered as sufficient.

The outer parts of the ALICE detector and the experimental cavern have small impact on the radiation field in the experiment. Instead of omitting them in the simulations the cascade development in them have been disfavored using the region-importance biasing available in FLUKA. By reducing the amount of CPU time per particle this allows one to collect better statistics in the central region, while preserving possible effects due to external elements.

Besides the quantities of central importance for radiation calculation as there are particle fluences and the dose, more specific quantities, mainly to study the damage effects in semiconductor devices, were calculated too. The description of such a damage was realized in the NIEL model, where it is assumed that the damage effects are proportional to the fluence of the particle generating the damage and are expressed in terms of displacement damage functions. To quantify the expected radiation damage an equivalent 1 MeV neutron fluence producing the same bulk damage in a specific semiconductor was used. Besides the study of NIEL effects in relevant semiconductor components the effects of Single Event Upset (SEU) were studied in sensitive devices (FPGs close enough to the beam pipe) too. In such situations the high-energy hadrons interacting with the material of electronics can produce locally very strong ionization. This strong local charging can revert individual trigger or switch or even cause permanent damage of the device.

The results of simulations show that the particle production at the IP is the dominant source of radiation load. There is, however, a non-negligible contribution from beam-gas interactions. Their absolute size is proportional to the residual gas-pressure. Hence, we have to carefully follow the developments of updated predictions. We can expect integrated doses of 0.1–1000 Gy in the ALICE mid-rapidity detectors and 1 Gy in the Muon Spectrometer. The highest expected hadron fluence from collisions at the IP is also produced by primary hadrons and amounts to $10^{13}\,\mathrm{cm}^{-2}$ in the central detectors near beam pipe. The hadron fluence behind large absorbers is dominated by neutrons; it is usually 2–3 orders of magnitude larger than the charged particle fluence. The highest hadron fluence expected in i forward Muon Spectrometer is 10^{12} cm^{-2}. The doses in the racks with electronics are low enough even if we compare them to CERN's reference dose limit for persons exposed in the exercise of their proffesion or even to the natural background. This is very short overview of global result of radiation level calculations in all subdetectors and electronics asssuming the whole 10 years of ALICE operation [15]. Besides that, at least another two important issues have been solved by FLUKA calculations in ALICE:

- optimization of radiation level in the muon and trigger chambers leading to proposal of a shielding — front and small angle absorbers — in the ALICE muon arm;
- induced activity calculations to define waste zoning in ALICE.

REFERENCES

1. *Particle Data Group.* Review of Particle Physics // Phys. Lett. B. 2004. V. 592. P. 1–1109.
2. *Prael R. E. et al.* // Proc. of the 4th Workshop on Simulating Accelerator Radiation Environments (SARE4) Knoxville (Tenn.), Sept. 14–16, 1998. P. 171–181.
3. *Capella A. et al.* // Phys. Rep. 1994. V. 236. P. 225–330.
4. *Ferrari A., Sala P. R.* // Proc. of MC93 Intern. Conf. on Monte Carlo Simulation in High-Energy and Nuclear Physics, Tallahassee (Florida), Feb. 22–26, 1993.
5. *Ferrari A. et al.* // Z. Phys. C. 1996. Bd. 71. S. 75–86.
6. *Bethe H. A.* // Ann. Phys. 1930. V. 5. P. 325–400; Selected Works of H. A. Bethe. Singapore, 1996. P. 77–154.

7. *Ziegler J. F., Andersen H. H.* N. Y.: Pergamon Press, 1977. V. 1–4.

8. *Sternheimer R. M., Berger M. J., Seltzer S. M.* // At. Data Nucl. Data Tab. 1984. V. 30. P. 261–271.

9. *Molière G. Z.* // Z. Naturforsch. 1948. Bd. 3a. S. 78–97.

10. *Bloch F.* // Ann. Phys. 1933. V. 16. P. 285–320.

11. *Emmett M. B.* The MORSE Monte Carlo Radiation Transport System Oak Ridge National Laboratory report ORNL-4972. 1975; Revision: ORNL-4972/R2. 1984.

12. *Roesler S., Engel R., Ranft J.* // Proc. of Monte Carlo 2000 Conf., Lisbon, Oct. 23–26, 2000 / Eds. A. Kling et al. Berlin, 2001. P. 1033–1038.

13. *Aichelin J.* // Phys. Rep. 1991. V. 202. P. 233 and references therein.

14. *ALICE Collab.* ALICE Physics Performance Report. V. I. CERN/LHCC/2003-049.

15. *Morsch A., Pastirčák B.* Radiation in ALICE Detectors and Electronics Racks. ALICE-INT-2004-017.