Frascati Physics Series Vol. VVVVVV (xxxx), pp. 000-000
XX CONFERENCE – Location, Date-start - Date-end, Year

FLUKA FOR MEDICINE AND BIOLOGY

P.R.Sala
INFN Milan, Italy
for the FLUKA collaboration
(D. Alloni, F. Ballarini, G. Battistoni, M. Campanella, M. Carboni, F. Cerutti, A . Clivio, A. Empl, A. Fassò, A. Ferrari, E. Gadioli, E. Gadioli-Erba, M.V. Garzelli, E. Giroletti, A. Mairani, A. Mostacci, S. Muraro, A. Ottolenghi, V. Parini, M. Pelliccioni, L.S. Pinsky, J. Ranft, S . Roesler, P. R. Sala, D. Scannicchio, G. Smirnov, S. Trovati, R. Villari, V. Vlachoudis, T . Wilson, N. Zapp)

Abstract

The FLUKA Monte Carlo code is briefly described, and examples of applications to medicine and biology are presented

1 A short description of FLUKA

FLUKA [1] is a general purpose tool for calculations of particle transport and interactions with matter. It can handle hadronic and electromagnetic particles from thermal energies (for neutrons) up to cosmic ray energies. 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

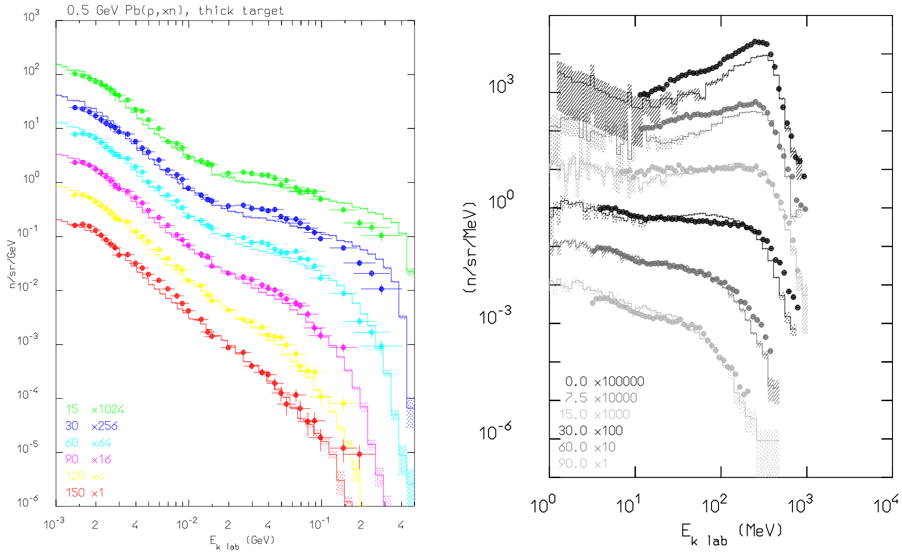

Figure 1: Left: PEANUT results (dashed histogram) and experimental data (symbols) neutron double differential distributions out of stopping length targets for 500 MeV protons on Pb [9]. Right: Modified RQMD results (histograms) and data [10] (dots)for double differential neutron yield by 400 MeV/n Fe ions on a thick Al target.

at each step, results are checked against experimental data at single interaction level. Since detailed descriptions of the FLUKA models and comparison with experimental data are available in the literature [1] and on the FLUKA web page (www.fluka.org), we give here only a short summary.

Hadron-nucleus interaction models depend on projectile energy. The high energy range (> 5 GeV) is treated in the Glauber-Gribov formalism, that couples Glauber multiple scattering to a Dual Parton Model description of hadron-nucleon interactions. Nuclear effects on reaction products are described by a Generalized Intra Nuclear Cascade (GINC) where the formation zone concept plays a fundamental role. At lower energies, the intermediate energy hadronic model of FLUKA , called PEANUT is used. The reaction mechanism is modeled in PEANUT by explicit intranuclear cascade (INC) smoothly joined to statistical (exciton) preequilibrium emission.INC modeling in PEANUT is highly sophisticated (see fig1). Independently from the original projectile energy, the equilibrium steps of the reaction include evaporation in competition with fission and gamma deexcitation. For light nuclei, a Fermi break-up model is implemented.

Ion-Ion interaction are of great interest for new therapeutic beams. FLUKA implements DPMJET [2] as event generator to simulate nucleus-nucleus interactions at $E > 5$ GeV/n. An interface to a modifies version of the RQMD-2.4 [3] was developed to enable FLUKA to treat ion interactions from ≈ 100 MeV/n up to 5 GeV/n [4]. An example is shown in fig.1. For both generators, de-excitation and evaporation of the excited residual nuclei is performed by calling the FLUKA evaporation module. Work is in progress to implement a Boltzmann Master Equation model for A-A interactions at very low energy [5] and to replace the RQMD interface with a new QMD model [4, 6] developed for FLUKA

Transport and interactions of electromagnetic particles are fully coupled to the hadronic sector, allowing for instance to follow in the same event secondary hadrons from photon nuclear interactions and γ rays from nuclear deexcitation. All electromagnetic processes are simulated with high accuracy, accounting for atomic bonds, polarization, electron-positron differences, actual angular distributions etc.

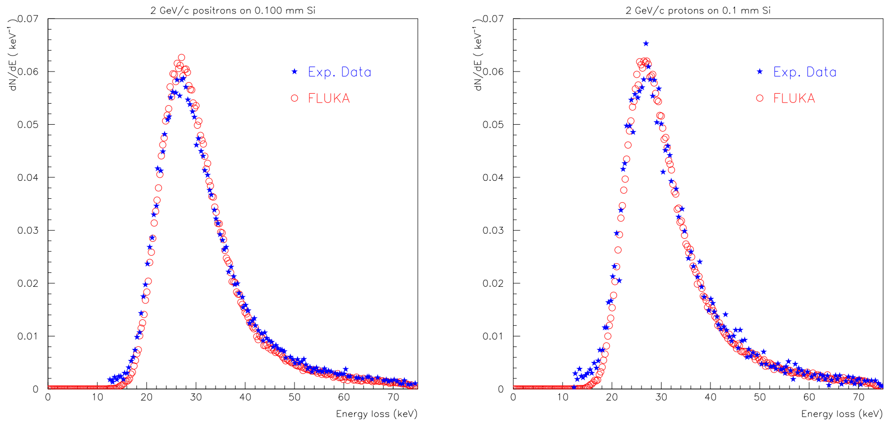

Figure 2: Experimental [11] and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100μm of Si

An original treatment of multiple Coulomb scattering [7] and of ionization

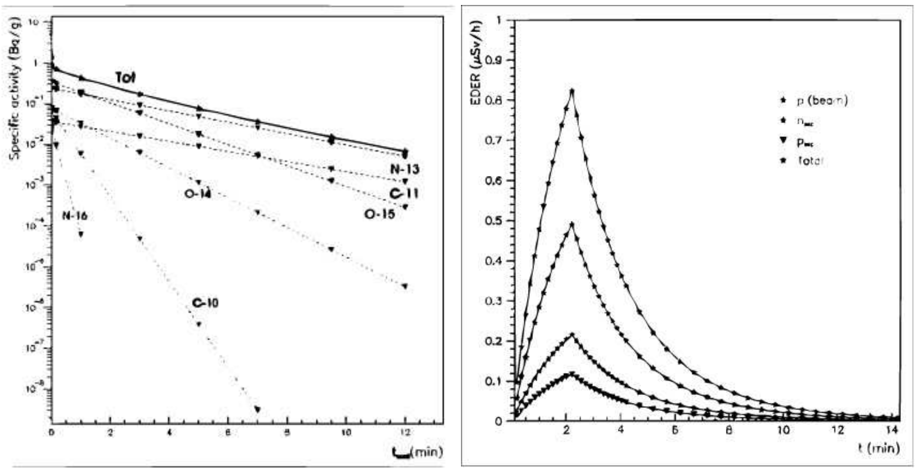

Figure 3: Left: specific activity vs. time after 3 min. irradiation, 400 MeV/n C ion beam. Right: dose rate vs. time during and after irradiation, 250 MeV proton beam.

fluctuations [8] allows the code to handle accurately some challenging problems such as electron backscattering and energy deposition in thin layers (fig.2) even in the few keV energy range. The FLUKA geometrical modeler is based on the Combinatorial Geometry. Recently, the possibility to embed “voxel” regions in the CG has been added.This algorithm was originally developed to allow to use inside FLUKA the human phantoms developed at GSF out of real person whole body CT scans. It was general enough to be coupled with generic CT scans, and applications to automatically assign CT numbers to “organs” have been developed

2 Applications

2.1 Air activation at CNAO

Recent developments in the evaporation model further improved FLUKA performances in predicting residual nuclei production. Activation of air in the future treatment rooms of the CNAO facility is being calculated with FLUKA , both for ion and proton beams. Preliminary examples [12] are reported in fig.3

2.2 Biological dose in therapy and space dosimetry

Dose or LET as calculated by any condensed history Monte Carlo are is not sufficient to fully characterize the radiation effects in biological targets, especially if one takes into account that the DNA linear dimensions are of the order of the nm. A better estimator is the "biological dose", represented by the average number of "Complex Lesions" (CLs) per cell in a given organ or tissue, where Complex Lesions are clustered breaks of the DNA double helix. Their yields per Gy and per cell, which depend on the radiation quality, can be calculated by means of "event-by-event" track structure simulations at the nm level [13] and subsequently integrated on-line into FLUKA. This approach was applied [14] with excellent results to the "real" therapeutic proton beam of the OPTIS facility at PSI.

Astronauts' exposure to the various components of the space radiation field is of great concern for long-term missions, especially for those in deep space such as a possible travel to Mars. Calculations of biological dose in a voxel human phantom have been performed for Galactic Cosmic Rays as well as for Solar Particle Events, in several shielding conditions. While SPE doses decrease dramatically even with a relatively thin shielding, calculated GCR doses are almost independent on shielding thickness [15].

2.3 In-beam positron-emission-tomography

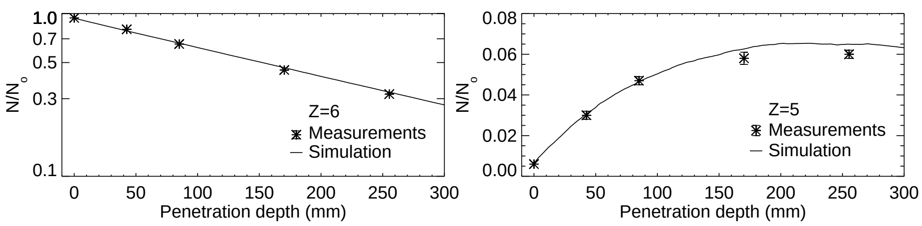

Figure 4: 676 AMeV ^{12}C beam on a water phantom. Left: Carbon ion intensity as a function of depth. Right: Build-up of boron ions as a function of depth. Experimental data from [18, 19].

Fragmentation of therapeutic ion beams is often regarded as an undesirable drawback which deteriorates the selective energy deposition. due to the more frequent electromagnetic energy losses. However, the production of a minor amount of positron emitting fragments offers the possibility to monitor in-situ and non-invasively the precision of the treatment by means of positron-emission-tomography (PET) [16]. An example of comparison [17] of FLUKA predictions to experimental data for fragmentation of therapeutic ion beams in tissue-like material is shown in fig. 4. Further validation is in progress.

References

1. A. Ferrari et al., CERN-2005-010, INFN/TC_05/11 (2005); A. Fassò et al., Proc. of CHEP2003, eConf C0303241 (2003), arXiv:hep-ph/0306267
2. J. Ranft, Phys. Rev. **D51** (1995) 64.
3. H. Sorge, H. Stöcker, and W. Greiner, Nucl. Phys. **A498**, (1989) 567c.
4. V. Andersen et al.,Adv. Space Res. **34** (2004) 1302
5. F. Cerutti et al., proceedings of NPDC19, Pavia, 2005
6. M.V. Garzelli et al. et al., proceedings of NPDC19, Pavia, 2005
7. A. Ferrari et al., Nucl. Instr. Meth. **B71** (1992) 412
8. A. Fassò et al.,KEK Proceedings **97–5** (1997) 32
9. S. Meigo et al., JAERI-Conf **95-008** (1995) 213
10. T. Kurosawa et al., Phys. Rev. **C 62** (2000) 11
11. J.Bak et al. Nucl. Phys. **B288** (1987) 681.
12. Anna Ferrari and M. Pelliccioni, private communication
13. A. Ottolenghi et al., Radiat. Environ. Biophys. **34** (1995) 239
14. M. Biaggi et al., NIM **B 159** (1999) 89
15. F. Ballarini et al., proceedings of NPDC19, Pavia, 5-9 September 2005
16. W. Enghardt et al., Phys. Med. Biol. **37**, (1992) 2127.
17. H. Aiginger et al., Adv. Space Res. **35** (2005) 214
18. I. Schall, D. Schardt, H. Geissel et al, Nucl. Instr. Meth. B **117**, 221 (1996)
19. I. Schall, Ph.D. Thesis, Technische Hochschule Darmstadt, 1994