DESIGNING ELECTRON ACCELERATOR SHIELDING WITH FLUKA

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ABSTRACT

The radiation field of electron accelerators includes several components: bremsstrahlung photons, fast neutrons, and - at energies higher than a few GeV - high-energy hadrons and muons. The tools available so far to design electron accelerator shielding were mostly empirical techniques based on source terms and attenuation lengths which had been obtained experimentally for a few typical situations, or had been calculated using different specialized Monte Carlo codes to transport separately each radiation component. No code has been generally available that could simulate not only the transport but also the generation of all such components. The most recent version of the FLUKA code, originally used mainly to design shielding for high-energy proton accelerators, can now be used to perform a full simulation of the radiation field of electron accelerators over a very extended range of energies and of possible configurations. The conventional shielding techniques currently used by various laboratories are presently being assessed by comparing their estimates with results of FLUKA calculations.

I. INTRODUCTION

Several techniques are available to designers of accelerator shielding, and a number of reference books[1–5] provide guidelines and useful data referring to the most common layouts. However, there are frequent cases which cannot be easily brought back to some standard configuration. Applying universal formulae or "cookbook recipes" to situations with complex geometries or strong magnetic fields can lead to large uncertainties, and therefore to excessively conservative design. Also, the available information is often empirical and has been tested only over a limited range of particle energies, target sizes, materials and attenuation depths; and the steady technological progress continuously brings about new machine designs, for which no previous shielding experience exists.

For such reasons, Monte Carlo radiation transport programs are used more and more, when available, in accelerator shielding design. Until a few years ago, since the radiological environment of particle accelerators is typically made of many radiation components, each with different transport and shielding characteristics, it was necessary to use several distinct programs to investigate the attenuation of each component separately (electrons and photons, neutrons, high-energy hadrons, muons). Recently, some attempts have been made at merging several of such specialized programs into a single package.[6–8] However, since all these code systems deal with the interface between different radiation components by means of off-line exchanges of large files, they have not yet achieved a full integration of the component programs and are very demanding on the user's time and organizational effort. Another difficulty lies in the fact that most high-energy transport programs are not provided with variance reduction algorithms, and therefore require prohibitive computing times to carry out deep penetration calculations.

One of the few exceptions is represented by the program FLUKA, originally a simple hadronic code, which has been extended in the recent years to deal with the transport of electrons, photons, low-energy neutrons and muons.[9,10] FLUKA is not a collection of specialized programs, but a single, integrated code which can treat in a same run complete hadronic cascades (generation and transport of about 30 different particles) over an energy range spanning more than 14 orders of magnitude. Its rich set of biasing options makes it very suited for shielding applications, and its capability to predict correctly the radiation fields found outside the thick shielding of proton accelerators has been recently confirmed.[11]

However, no existing Monte Carlo code has been able until now – at least to our knowledge – to give a complete and satisfactory description of the stray radiation fields characteristic of electron accelerators. These are multi-component fields just as in the case of proton accelerators, but with the exception of bremsstrahlung, which is of concern only outside relatively thin shields, the main radiation components are generated by physical mechanisms (photonuclear reactions) ignored by most available transport programs. Indeed, although all important particles are transported by many programs, the mutual interaction of the hadron and of the photon field is generally accounted for only in one direction: secondary photons are generated in hadron interactions, but not vice versa.

For this reason, present electron accelerator shielding design must rely on empirical attenuation formulae and on simplified models[2,12] even in cases where a detailed simulation would be more appropriate. Monte Carlo codes have been used sometimes to transport neutrons produced in photonuclear reactions,[13,14] but *ad hoc* assumptions had to be made concerning their space, angle and energy distribution.

A first attempt to introduce photonuclear reactions in FLUKA, restricted to the GeV energy range, was made some time ago in an earlier version of the code.[15] The model used appeared promising,[16] but was implemented only in a non-analog way (out of user control) and was not systematically tested. In addition, until now, it was not fully consistent with the more accurate description of the nucleus contained in the present version. In practice, its usefulness for shielding was limited by the lack of coverage of photon energies below 1 GeV. This deficiency has been eliminated in the most recent version of FLUKA, which can deal with photonuclear reactions over the whole energy range. Simple physical models have been used, but properly integrated within the FLUKA hadronic event generators (Dual Parton Model,[17] cascade-preequilibrium,[18] evaporation). In the following, the models used will be described, and some preliminary comparison with experimental data will be presented.

II. PHYSICAL MODELS

Photon reactions with nuclei show features (cross-sections, particles emitted) which are strongly changing with energy, in correspondence with very different interaction mechanisms at the nuclear level. The classification widely reported in the shielding literature[2,4,12]: Giant resonance, Quasi-deuteron region, High-energy range, is based rather on the different attenuation and dosimetric properties of the secondary particles generated than on nuclear physics considerations. For modelling purposes, therefore, it has been necessary to make a further distinction between a Delta resonance energy region, and a high-energy range with different interaction characteristics. The boundaries between the four energy domains are not sharp and depend somewhat on atomic number; on the other hand at some energies an overlap of two different modes of interactions seems to be likely, although very poorly documented in the experimental and in the theoretical literature. These transition regions could only be treated empirically, by making some reasonable assumption of continuity about the interaction cross section.

For each of the four models described below, it has been necessary to establish two algorithms providing:

- the value of the total interaction cross section as a function of photon energy and target nucleus
- the initial energy and momentum transfer between the photon and one or more particles inside the nucleus

Once the photon energy has been transferred, further interactions of the particles set in motion with the nucleons of the target nucleus are described by the normal intranuclear cascade, pre-equilibrium and evaporation FLUKA models.

A. Giant Dipole Resonance

At the lowest end of the energy range, namely below about 30 MeV and above the threshold for removing one neutron (typically 7–8 MeV), photonuclear reactions take place mainly via the Giant Dipole Resonance (GDR). The actual mechanism is a collective interaction of all nucleons which is difficult to simulate in a Monte Carlo; however, the energy of the absorbed photon is dissipated in a way very similar to that of a typical compound nucleus. Therefore it was decided, at least in a first stage, to treat this kind of interaction as evaporation, with a preequilibrium component at the higher end of the energy range.

The total cross section can be parameterized as a function of nucleus and energy only with limited accuracy, especially for the lightest nuclei. On the other hand, data are not available for all isotopes. Therefore the following scheme was adopted:

- if experimental data are available, values are tabulated from an empirical smooth fit and the cross section is obtained by table lookup
- otherwise a Lorentz fit is used if parameters are available
- in all other cases the three parameters of the Lorentz curve (energy of the maximum, peak value, width) are obtained by an analytical fit to existing data

By this scheme, it is possible to gradually improve the cross section tables as new information becomes available, while being able to run the code, albeit with reduced accuracy, even with materials for which no data has yet been entered. For the time being, cross sections have been tabulated only for the lightest nuclei, for which a Lorentz fit is not possible. Most data, including the Lorentz parameters for medium and heavy nuclei, have been taken from the Atlas of Dietrich and Berman[19] which provides cross section for neutron emission rather than total cross section: for heavy nuclei the two cross sections are approximately equal, but the difference is not negligible at low atomic number. In the near future, it is planned to introduce the relevant experimental data on channels without neutrons in the final state whenever available, to get the total photonuclear cross section. An empirical Z-dependent correction factor will be computed by running the code and scoring the fraction of GDR events where no neutron is emitted for those elements where such data are not available.

The nuclear dynamics after GDR absorption is described in the PEANUT preequilibrium code[18] by the exciton model followed by evaporation; the initial configuration is assumed to be 2p-2h . This last assumption is somehow arbitrary, but the smallness of the excitation energy makes the evaporation stage dominant, and the pre-equilibrium one less sensitive to the initial configuration. Results relative to thick targets bombarded by electrons are shown in figs 1 and 2 together with experimental data from ref.[20] Differences up to about 20% show up at the highest energies for lead targets. The asymmetry of the angular distribution of neutrons emitted with relatively high energy (above 3-4 MeV), as measured in ref.[21] could be an explanation of such a discrepancy, since the experimental yields have been calculated measuring the number of photoneutrons at 90 degrees and assuming an isotropic angular distribution. The uranium case is less sensitive to this problem since neutrons originating from fission, which are a significant fraction of the total, are truly isotropic.

B. Quasi-deuteron

In the energy range between approximately 30 MeV and 200 MeV, the Levinger quasi-deuteron absorption mechanism[22] has been implemented in the frame of PEANUT.[18] A similar linking of the two models had already been proved successful by Blann et al.[23] and Wu and Chang,[24] but the only previous Monte Carlo attempts to describe quasi-deuteron interactions seem to have been in connection with intranuclear cascade models.[25,26] Here the intranuclear cascade, used at incident energies larger than 50 MeV, is followed by a statistical (exciton) preequilibrium model and by evaporation. The intranuclear cascade is initiated by a neutron and a proton, whose angular distribution (and hence the energy partition) is equal to the experimental one in the γ-deuteron reaction. At γ energies lower than 50 MeV, the interaction is treated directly in the exciton model, starting with a 2p-2h configuration.

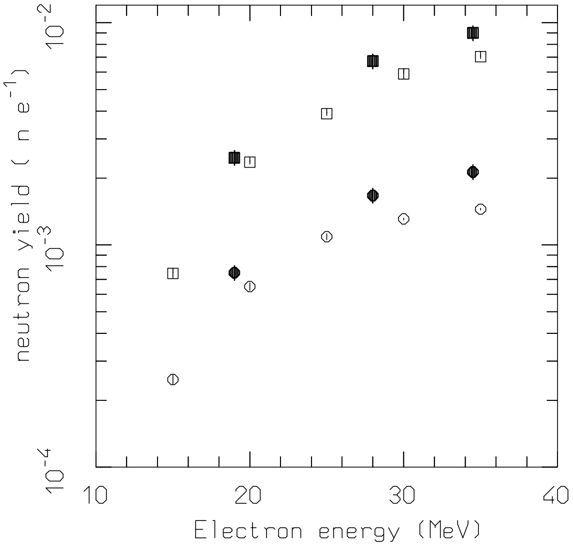

Figure 1: Yield of neutrons per incident electron as a function of initial electron energy for natural lead targets of 1.01 (lower points) and 5.93 (upper) radiation lengths. Open symbols: FLUKA, closed symbols: experimental data.

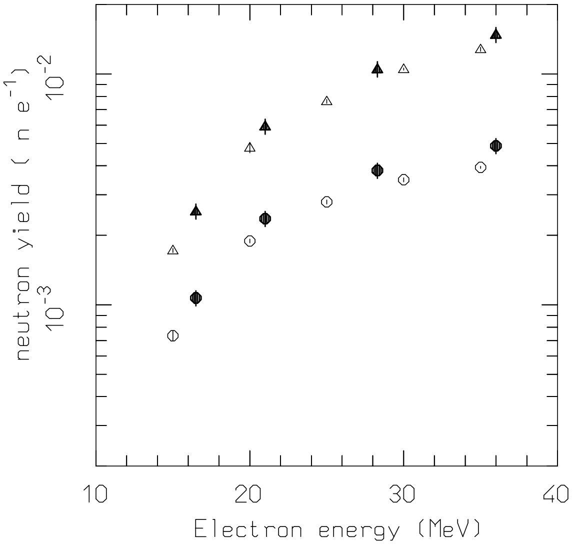

Figure 2: As in the previous figure for natural uranium targets of 1.14 (lower points) and 3.46 (upper points) radiation lengths. Open symbols: FLUKA, closed symbols: experimental data.

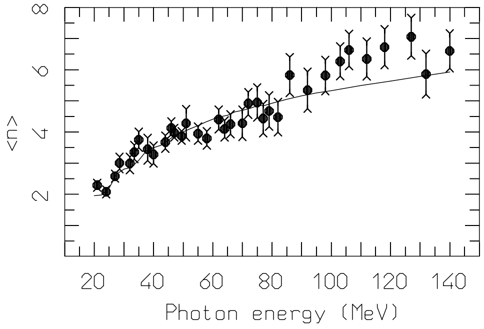

Figure 3: Neutron average multiplicity versus incident photon energy for a natural lead target. Points : experimental data, solid line: FLUKA results

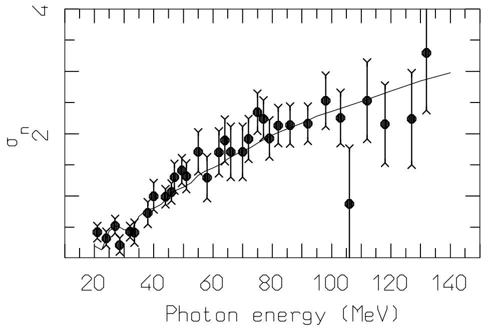

Figure 4: Width of the neutron multiplicity distribution for a lead target as a function of photon energy. Symbols: experimental data, line: FLUKA results

The cross section has been expressed as

$$\sigma_{QD}(E_\gamma) = L\frac{NZ}{A}\sigma_D(E_\gamma)f(E_\gamma) \tag{1}$$

where L is the Levinger constant, given as a function of A in,[27] $\sigma_D(E_\gamma)$ is the cross section for deuteron photodisintegration, equal to $C(E_\gamma - E_{th})^{3/2}/E_\gamma^3$ with $C = 62.4$ mb,[28] and $f(E_\gamma)$ is a Pauli-blocking function as calculated by Chadwick et al.[29]

Results for neutron inclusive production on lead are shown in figs. 3 , 4, 5 and compared with experimental data from[30,31]

C. Delta resonance

Above 140 MeV, the energy threshold for pion production, photonuclear interactions are characterized by excitation of the Δ-resonance. Most reactions end with a pion in the final state, but simple photon absorption can still take place via the quasi-deuteron mechanism. The total cross section has been shown to exhibit a simple scaling with atomic mass for all nuclei heavier than lithium (some smearing takes place with respect to the free proton cross section, due to Fermi motion of the bound nucleons).[32] The quasi-deuteron component has been estimated by subtracting the analytical expression of the deuteron photodisintegration cross section shown above from the evaluated fit of experimental data published in.[33]

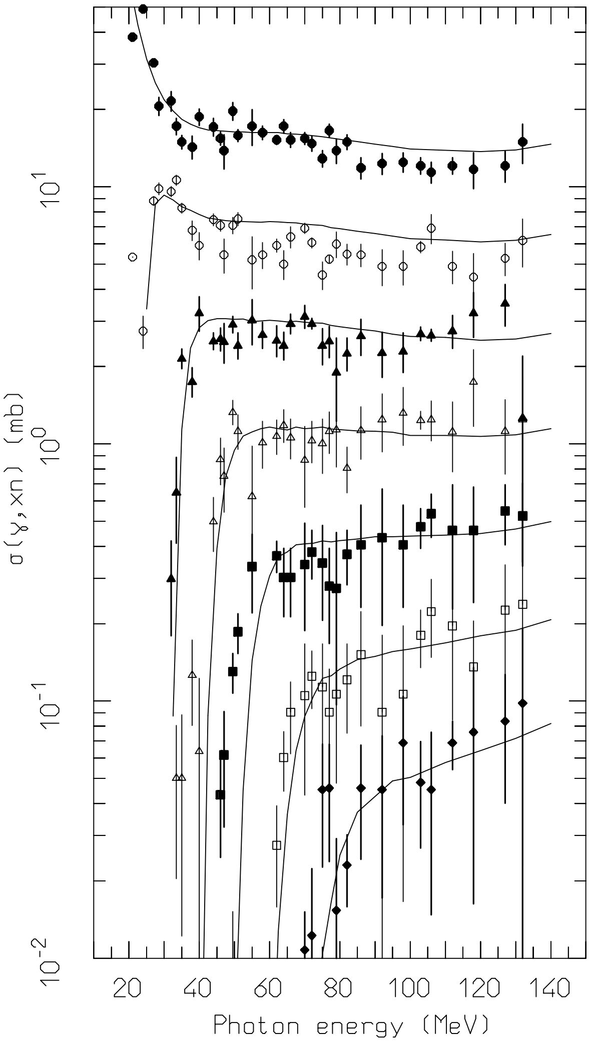

Figure 5: Excitation functions for emission of n or more neutrons from a lead target hit by monoenergetic photons. Symbols: experimental data, line: FLUKA results. From the top: $n = 2$; $n = 3 \times 1/2$, $n = 4 \times 1/4$, $n = 5 \times 1/8$, $n = 6 \times 1/16$, $n = 7 \times 1/32$ $n = 8 \times 1/64$

D. Vector Meson Dominance

In the high energy region above the delta resonance, the Vector Meson Dominance model,[34] already implemented in FLUKA some years ago,[15] has been kept and improved. The total cross section is obtained as $\sigma_T = N\sigma_n + Z\sigma_p$, where σ_n and σ_p are the photonuclear cross sections of the neutron and the proton, respectively. In the previous version, an analytical expression was used for σ_n and σ_p, but now it has been preferred to tabulate actual experimental data, taken from.[35] A "shadowing factor", dependent on A and energy, has been derived from experimental data reported in.[34] Such data are largely inconsistent, but the following expression has been found to reproduce at least the general trend:

$$f_{shadow}(A, E) = \frac{A^{0.068 \exp[E_\gamma(0.002A-0.66)]}}{A} \qquad (2)$$

with E_γ in GeV.

A second correction factor has been included, in order to account for the asymptotic increase of the total cross section at very large energies. Recent data from HERA[36] seem to indicate that such increase can be parametrized as $\sqrt{\ln(s)}$, where s is the square of the total energy in the center of mass system. This energy dependence has been introduced in FLUKA above 30 GeV. Some preliminary comparisons with experimental data on hadron production by 18 GeV electrons on a beryllium target (0.3 radiation lengths), are shown in fig 6, 7, 8. The data by Boyarski et al.[37] had already been shown to be consistently higher than those calculated by an earlier version of FLUKA[15] and such difference is confirmed by the present code. However, other data by Flatté et al.,[38] although limited to a few production angles, seem to indicate a much better agreement. More tests will be needed in future in order to settle this issue, of great importance for shielding of high energy electron accelerators.

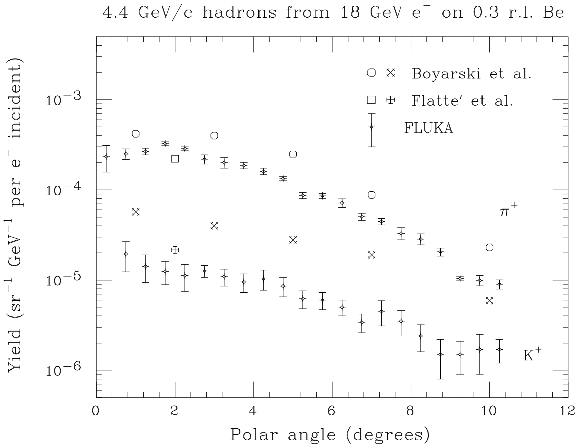

Figure 6: Yield of 4.4 GeV/c positive pions and kaons as a function of emission angle

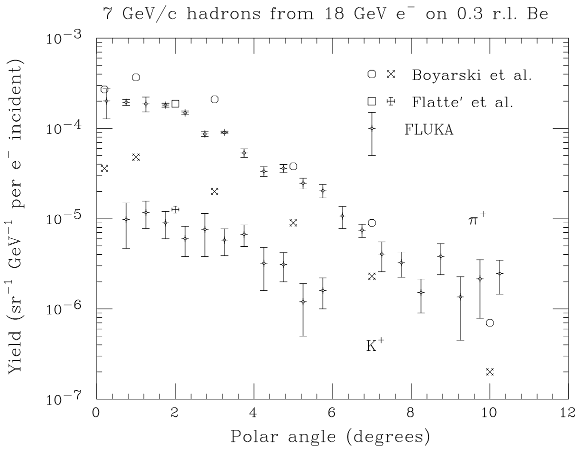

Figure 7: Yield of 7 GeV/c positive pions and kaons as a function of emission angle

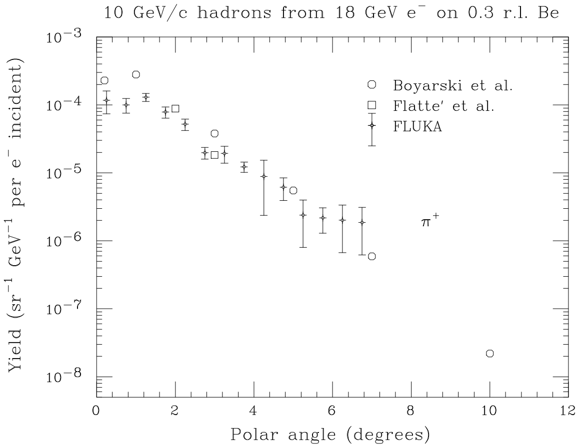

Figure 8: Yield of 10 GeV/c positive pions as a function of emission angle

III. CONCLUSIONS

With the inclusion of photonuclear reactions over the whole energy range, FLUKA is now on the way of becoming a truly complete radiation transport code, not comparable to any other Monte Carlo presently available. The work is still in progress and several refinements will be necessary, especially concerning the lightest nuclei and the transition regions between different models. However, the first benchmarks are very encouraging and in a not far future it should be possible for the first time to perform detailed calculations of electron accelerator shielding in the same way as it is normally done for proton accelerators.

ACKNOWLEDGMENTS

One of us (A. Fassò) would like to thank K. Kase and the other members of the SLAC Radiation Group, where part of this work was done.

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