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DESIGNING ACCELERATORS WITHOUT THE PERFECT SIMULATION CODE

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ABSTRACT

Detailed computer programs which follow the development of cascades induced by the interaction of high-energy particles in matter have been available since the late 1960s. They have only reached a high degree of sophistication and accuracy in the last few years. The radiological safety of most proton accelerators was therefore guaranteed without the use of these programs. This paper illustrates the methods then used, their successes and their limitations.

1 Introduction

The first high-energy proton accelerators to achieve energies of over 1 GeV came into operation in the early 1950s. Most of the computer codes which simulate high-energy radiation transport had their beginnings in the late 1960s. Thus most proton synchrotrons were built before any cascade simulation code became available.

In the 20 years from 1930, most of the elementary particles which are of importance in radiation problems were discovered. However even today, many codes still do not consider the transport of kaons and therefore lack completeness. Charm was discovered in the mid 1970s, and this is of great importance in determining muon shielding requirements for >300 GeV accelerators. Muon production via charmed-D decay has only very recently been included in transport codes. In addition, only in the last few years have a few of the available simulation codes reached the stage where they are able to predict radiologically important quantities to a significant degree of accuracy (to better than about 50%). Thus even during the construction of the most recent generation of accelerators one has had to rely on less than perfect cascade simulation programs for predicting radiation levels.

Over the years, a considerable body of knowledge based on practical experience has been developed. It is the purpose of this paper to illustrate the extent of this knowledge, to point out its strong points, but also where these approximations can lead to mistakes. This knowledge can also be used to check the predictions of the modern transport codes.

2 Shielding of proton synchrotrons

The weak-focussing protons synchrotrons, the Cosmotron and the Bevatron were originally designed with no or very little shielding since expected beam intensities were low. With time, the intensities slowly increased, with concomitant increases in stray radiation levels. In contrast the NIMROD accelerator in the UK and the CERN PS were expected to run at high intensities with internal targets. Shielding predictions for these machines were based on cosmic-ray attenuation studies in the atmosphere and a high degree of conservatism was introduced into the calculations. As a consequence of this initial over-shielding the CERN PS now operates with a circulating proton intensity some four orders of magnitude higher than those obtained initially without any excessive radiation levels outside its main shielding.

The first physically significant shielding calculations for high-energy proton accelerators were made by B. Moyer for the Bevatron upgrade. He developed a line-of-sight shielding model which now bears his name [1, 2]. His expression for the dose equivalent per interacting proton, H, from hadrons at a point outside the shielding is:

$$H = \frac{1}{r^2} \int F(E)\, B(E,\theta) \times \exp[-x(\theta)/\lambda(E)]\, \frac{\mathrm{d}^2 n(E,\theta)}{\mathrm{d}E\mathrm{d}\Omega}.\mathrm{d}E$$

where r is the distance from the source, E is the energy of the neutron causing the dose, F converts neutron fluence to dose equivalent, x is the shield thickness, λ is an effective removal mean free path, B is a build-up factor and $\mathrm{d}^2n/\mathrm{d}E\mathrm{d}\Omega$ is the yield of neutrons per unit solid angle at θ per unit energy interval at E. Since λ is approximately independent of energy above 150 MeV, and particles with E>150 MeV can be regarded as *Cascade Propagators*, the integral over E can be replaced by the fluence of all hadrons with energies greater than 150 MeV. In general one is only interested in the angular range $60^\circ < \theta < 120^\circ$, and one replaces $B(E,\theta)$ by a multiplicity $m(E_p)$, where E_p is the incident proton energy. The angular distribution of secondaries can be written:

$$\int \frac{\mathrm{d}^2 n(E,\theta)}{\mathrm{d}E\mathrm{d}\Omega}.\mathrm{d}E = g(\theta) = C\exp(-\beta\theta)$$

Over a wide variety of spectra, dose equivalent in an equilibrium cascade is proportional to the high-energy fluence with a constant of proportionality k. Thus

$$H = k\, C\, m(E_p)\, \exp(-\beta\theta)\, \exp(-x/\lambda)\, /r^2$$

where Moyer was able to estimate all the constants from first principles.

Shielding of the Fermilab accelerator and the CERN SPS was based on early FLUKA and CASIM simulations which predicted star densities in different configurations [3, 4]. These were confirmed by O'Brien's one-dimensional analytical solutions to the Boltzmann equation [5]. However most importance in the design of hadron shielding at these two accelerators was given to extrapolations from experimental data.

Even today simulation programs for high-energy cascades are unable to provide any direct solution to the lateral shielding problem without employing severe weighting techniques which themselves depend on intuition derived from extrapolations of experimental data. Initial estimates of hadron shielding for the SSC and LHC have been based on a simple extension of Moyer's ideas. There is a considerable body of experience from practical measurements and Monte-Carlo simulations which allows one to propose a simple model for predicting the *maximum* effective dose rate at a given radial distance in a dump configuration [6].

$$H = H_0 \left(\frac{E_p}{E_0}\right)^{\alpha} \frac{1}{r^2} \exp(-d/\lambda)$$

The radial thickness of the shield is d and the radial distance r. E_p is the proton energy in GeV and E_0 is 1 GeV. This formula is valid for an "*optimum*" target, *i.e.* one in which the cascade develops fully but in which there is little or no lateral attenuation and is therefore very conservative.

There are four sets of parameters H_0 and λ: two come from extrapolations of cascade simulations, FLUKA and CASIM, one is based on the experimental data used to obtain the Moyer Model constants and one is based on an assessment of both data and simulations (DESY). It should be noted that these constants are based on the old QF-LET values multiplied by a factor of two.

Table 1: Shielding parameters

Method	H_0 (Sv.m^2)	$\lambda_{concrete}$ (g/cm^2)	λ_{iron} (g/cm^2)
FLUKA	1.4×10^{-14}	133	164
CASIM	2.6×10^{-14}	113	141
Moyer	2.6×10^{-14}	114	160
DESY	3.0×10^{-14}	105	200

Figure 1 indicates that maximum shield thickness required for the loss of protons from one ring of the LHC (0.5 mSv from 5×10^{14} protons, or an attenuation requirement of 10^{-18} Sv) is essentially independent of the model used. However there remain uncertainties in the required shielding for very high attenuation factors.

3 Radioactivation at proton accelerators

Detailed calculations of radioisotope production in accelerator components were made for the Fermilab accelerator with HETC, see for example [7]. However, star density predictions made from very rudimentary cascade simulations (based on inelastic cross-sections, multiplicities in inelastic reactions and energy conservation) can be used to predict dose rates from induced radioactivity with a fair degree of accuracy through the so-called ω-factors [2, 8, 9]. Partial cross-sections allow one to determine the production of light elements such as ^3H and ^7Be from star densities. Because the presence of small amounts of light materials does not perturb the fluence distribution in a cascade in a dense iron accelerator component, isotope production in air or water can be determined from the star densities in surrounding massive objects, see for example [10]. Thus it is not necessary to follow in detail all aspects of the intra-nuclear cascade and evaporation in an inelastic interaction in order to estimate the production of most isotopes of radiological significance.

However the calculation of star densities cannot lead to an accurate assessment of the production of isomeric states. In addition, codes which simulate the production and transport of neutrons down to thermal energies are essential in order to estimate correctly the production of isotopes from (n,γ) reactions. The proximity of large metallic

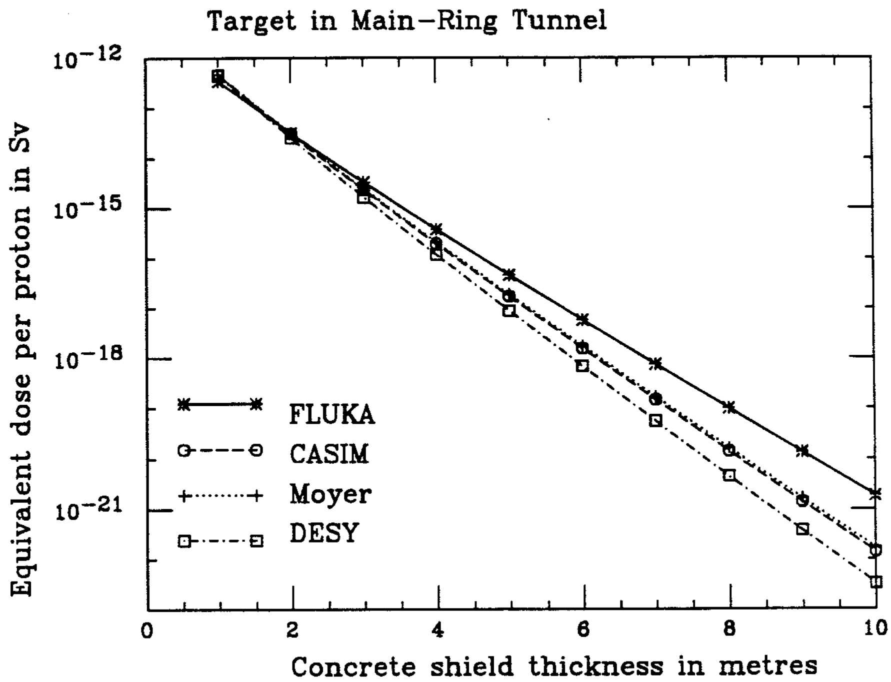

Figure 1: Hadron shielding for an optimum target in the LHC Main-Ring tunnel

or hydrogen-containing objects can introduce severe errors in values of the low-energy neutron fluence determined from empirical high-energy to low-energy fluence ratios.

4 Tunnel attenuation

A significant number of empirical recipes exist for determining the attenuation of neutrons in access-ways and ducts leading to high-energy proton accelerators. These are based on experimental data and Monte-Carlo calculations and are summarized in [2]. At CERN the use of so-called "Universal" curves has been developed, where the depth of the tunnel is measured in units of the square root of the cross-sectional area [11]. These curves can be used provided that this latter dimension is larger than several tens of centimetres. The experience of the authors is that these Universal Curves have survived repeated tests against both experimental data and sophisticated Monte-Carlo simulations, see for example [12], and so form a good basis for the design of access-ways without the need for new simulations.

5 Photon studies in LEP

The studies made during the design of the LEP collider at CERN illustrated two major points. Firstly, significant simplification of complex geometrical shapes such as that of the vacuum chamber did not affect estimations of dose to components close to the magnet structure. Secondly, it was possible to use the field close to the magnets calculated using an analogue code, EGS3, as a confirmation of the field determined by MORSE, used for the first time to study synchrotron radiation problems at an accelerator. This field was then used as input to a highly weighted MORSE estimation of the attenuation of complex labyrinth structures [13]. These calculations have since been verified by experimental measurements. It is also interesting to note that the attenuation of photons in the access ways could also be sufficiently well represented for design purposes by the same Universal attenuation curves as those determined for neutron attenuation at proton accelerators [14].

6 The need for detailed simulations

In the previous sections, arguments have been given to show that in a large number of cases, accelerators can be designed without full and detailed simulations of situations which could cause radiation problems. However when energy deposition in target structures is concerned, experience at CERN has shown that only detailed cascade simulations prevent serious incidents taking place. Targets have been vaporized and dump structures damaged by high intensity beams when insufficient care has been taken in the simulation. It is now standard practice to verify energy deposition in targets and dumps using the FLUKA program and to perform heat transport and stress analyses using these data as input. Although this prevents incidents arising from bad design, it cannot prevent accident situations where because of a fault in a magnet, a fast-extracted high-intensity beam could impinge on part of the accelerator structure which is not designed to receive such a beam, the usual result being at least a hole in the vacuum chamber.

7 Simulations

It is useful to recall several Golden-Rules when making detailed simulations of radiation transport for design purposes at an accelerator. One should *never trust a simulation* without a simple cross-check against *e.g.* Moyer model, energy conservation, universal curves, experimental data.......

It is easy to have:

- mis-typed the input
- made an error in your User-Code
- used the wrong units
- be suffering from poor statistics (not evident in weighted Monte-Carlo)
- used unfair biasing (energy/space cuts without protection)
- an artifact of the code (energy deposited in the middle of a step, accumulated events on boundary crossings *etc.*)
- have mis-interpreted approximations used in the code (*e.g.* fixed-angle bremsstrahlung, P3 Legendre expansion for single-scattering)

In all cases it should be remembered that simulations are only as good as the available experimental data.

However the simulation is probably the most accurate step in the assessment process. The beam-loss estimation is often less precise than the simulation. Thus in many cases a quick and purposely simplified simulation which is made in time may be more valuable than a detailed and accurate simulation which may be costly and take years to complete. In all cases the real cost of a detailed Monte-Carlo simulation must be balanced against the extra cost which might be engendered if conservative, empirical methods are used. However, it can in some cases be self-defeating even to offer such detailed simulations when other parameters in the problem are known with much less precision.

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