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SIMILARITIES AMONG THE RADIATION FIELDS AT DIFFERENT TYPES OF HIGH ENERGY ACCELERATORS*

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Introduction

In 1965, DeStaebler presented a paper at the Brookhaven Conference entitled "Similarity of Shielding at Electron and Proton Accelerators."[1] The purpose of the lecture today is to update and expand on this theme, as well as to point out the equally important dissimilarities that exist between the two. To illustrate this, let us consider a typical shielding exercise commonly performed at SLAC.

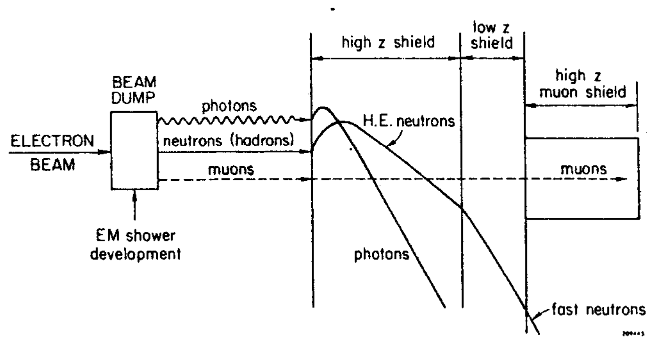

Fig. 1. Typical shielding geometry at high energy electron accelerator.

Figure 1 shows a source-shielding geometry whereby a high energy electron beam strikes a device, such as a beam dump, dissipating its energy in an electromagnetic cascade shower. Bremsstrahlung photons, neutrons and muons emanate from the device to attenuate in the shield.

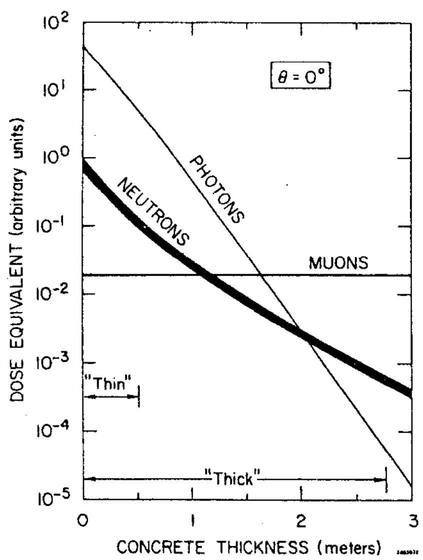

Fig. 2. Various contributions to the dose equivalent in the forward direction at an electron accelerator as a function of shield thickness.

In Fig. 2 the transmission of the three radiation components is shown in the forward direction. Arbitrary "thick" and "thin" shield dimensions are indicated. For thick shields, muons completely dominate in this example, followed by neutrons and then photons. A comparable situation for a proton accelerator[2] is shown in Fig. 3 where we have again indicated arbitrary shield thicknesses. For

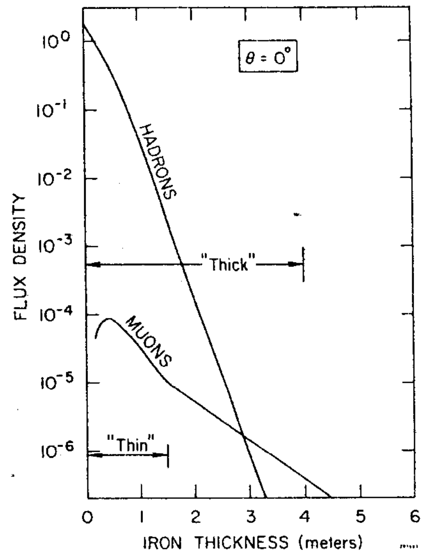

Fig. 3. Longitudinal development of strongly interacting particle and muon flux densities of a nuclear-meson cascade initiated by 25 GeV/c protons in iron in the forward direction.[2]

thick shields muons again dominate in the forward direction, neutrons are next important, and the photon component is absent. This is not meant to suggest that photons are nonexistent at proton accelerators. Indeed, they have been observed near the proton beams both at NIMROD[3] and at CERN,[4] probably from the electromagnetic cascade caused by high energy photons from the decay of π^0's. However, their relative magnitude is much less severe than at electron accelerators. The overall conclusion is that thick shielding situations are similar, although not necessarily comparable in magnitude, at both types of accelerators.

The thin shield case is quite different. For the electron accelerator we note that photons dominate, followed in importance by neutrons and then muons. For the proton accelerator, however, neutrons dominate because there are essentially no photons. We conclude, therefore, that the two machines have different radiation environments when the shields are relatively thin.

Fortunately, photons are efficiently attenuated by means of high-Z materials such that the thick-shield situation may be quickly realized for photons even though, as we shall see later on, such high-Z shields might be considered thin for neutrons. DeStaebler[1] stresses these points when he makes the statement, "..... the electron-photon cascade must not dominate." He also brings out another fact in his discussion, namely, that high energy electron and proton accelerators do not have comparable thick-shield radiation magnitudes unless the electron machines operate at high beam powers as well. One means of showing this is to compare the high energy neutron yields (neutrons with energies greater than 150 MeV) from the two types of accelerators. One finds that the two spectra are fairly similar at the source, but for equal incident beam powers, the neutron yield from 6.3 GeV protons is about 400 times greater than that from 20-GeV electrons (for example).

SLAC is considered a high power, as well as a high energy, electron accelerator, so the thick-shield similarity with existing proton accelerators is apparent, even on a magnitude scale. In Fig. 4, we have reproduced a figure taken from the textbook by Freytag,[5] which shows various

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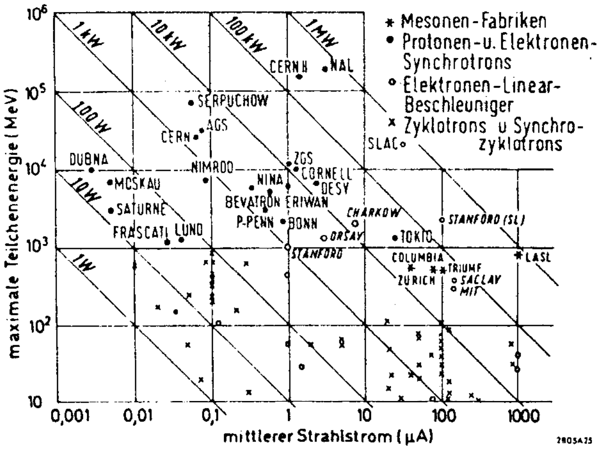

Fig. 4. Various high energy electron and proton accelerators throughout the world represented in terms of their maximum energy and average beam current.[5]

accelerators throughout the world in terms of two of their most important parameters, maximum energy and maximum average current. The SLAC beam power of 670 kW can be scaled down by a factor of 400 and a parallel line drawn at 1.7 kW. One would expect, from this line of reasoning, that the magnitude of the neutron component outside thick shields at SLAC should be comparable to those outside thick shields at the CERN Proton Synchrotron, the Brookhaven AGS and the Bevatron at the Lawrence Berkeley Laboratory. While this may be a valid statement in general, one must exercise some caution in making it, for there are many parameters that can be introduced into the picture that will affect the generalization, particularly shield composition and ducts.

Electromagnetic versus Hadronic Cascades

Electromagnetic cascades, or soft showers as they are often called, are initiated by high energy photons, electrons, or positrons. It is important to note that all of the intrinsic processes in the electromagnetic shower are extremely well understood and are predictable by formulae of quantum-electrodynamics. In the interactions of high energy electrons with matter, only a small fraction of the energy is dissipated as a result of collision processes, such as ionization and excitation, while a large fraction is spent in the production of high energy photons (bremsstrahlung). The secondary photons, in turn, undergo materialization into electron-positron pairs or make Compton collisions. Either process results in the electrons having energies comparable to the photons, and the process continues until more and more electrons fall into the energy range where radiation losses no longer can compete with collision losses. Eventually the energy of the initiating particle is completely dissipated in excitation and ionization of atoms. The end result is heat, which sometimes causes difficulties for our engineering friends. Because shower maximum occurs at such relatively shallow depths and since the longitudinal and transverse extent of the energy deposition is also relatively small, the term "soft shower" is most appropriate. Electromagnetic cascade shower phenomena are quite characteristic of electron accelerators although they play a role in high energy hadron cascades as well.

Hadronic cascades, characteristic of high energy proton machines, are initiated by charged and neutral hadrons (p, n, $\pi^{\pm}$, etc.). They are also called nuclear cascades or "hard showers," the latter name obviously a result of the fact that the penetration into the medium is relatively deep and the lateral spread is more extensive than for the electromagnetic case. Unlike the electromagnetic interactions, the nuclear processes are not as well understood, and therefore semi-empirical approaches are usually necessary for most calculations.

At large depths, the nuclear cascade is controlled by the most penetrating component, which turns out to be neutrons with energies above 150 MeV, where the inelastic neutron cross sections reach a constant minimum above 100-150 MeV. An analogous situation exists for the electromagnetic cascade where one would expect that the most penetrating component would be photons having energies near the Compton minimum.[6]

The role of the π^0 meson in the hadronic cascade is very significant. It decays very quickly (10^{-16} sec) into two photons (99% of the time) that in turn initiate electromagnetic showers. As the primary energy increases, the role of the electromagnetic cascade becomes increasingly important from an energy deposition (engineering) viewpoint. For radiation protection purposes, however, the electromagnetic cascade does not significantly contribute to the dose equivalent outside a proton accelerator.

Longitudinal and radial developments of both hadronic and electromagnetic cascades can be plotted for a number of different effects such as energy deposition and track density. Star densities, as well as residual radioactivity, are also a measure of hadronic buildup and attenuation. A number of parameters that characterize either type of shower are utilized in order to make extrapolation calculations. Figure 5 shows the parameters U, Λ, λ, B, and A that characterize

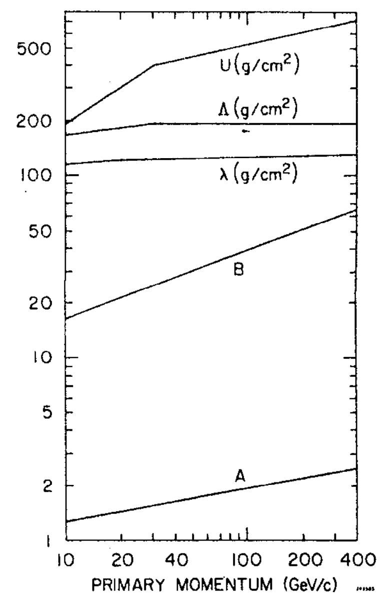

Fig. 5. The parameters B, Λ, A, U, and λ that characterize the proton star density as a function of the primary momentum.[7]

the proton star density as a function of the primary proton momentum.[7] In this figure, B is the buildup factor, obtained by extrapolating the laterally integrated star density back to zero depth, Λ is the attenuation length, which determines the slope of the laterally integrated star density, the parameter A is the maximum value reached in the transition curve, U is the depth, after the buildup, where the star density reaches unity again, and λ is like Λ except it is determined from peak values, not from laterally integrated data.

One can also plot characteristic parameters for electromagnetic showers. In Fig. 6 the radiation length (X_0), the attenuation length corresponding to the Compton minimum (Λ), and the Molière unit[6] (X_m) are plotted as a function of the atomic number.[18]

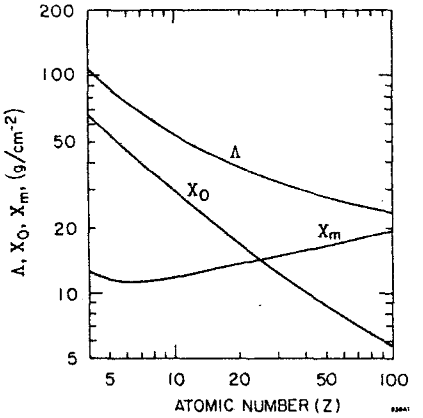

Fig. 6. The variation of Λ, X_0, and X_m with atomic number.[18]

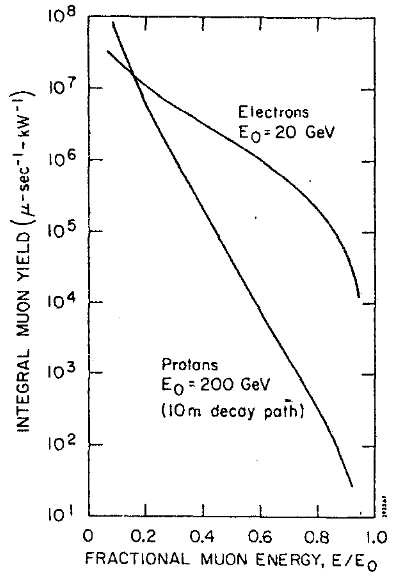

Fig. 7. Integral muon yield versus the fractional muon energy for incident 20-GeV electrons. Also included for comparison is the muon yield (from pion decay) that is expected from a 200-GeV proton beam.[1]

Muon Production and Shielding

In 1960, as a result of the calculations of Drell[8] and Ballam[9], it became apparent that a high-energy, high intensity electron accelerator could produce a high-intensity flux of muons by direct electromagnetic pair production. Muons can also be produced through the decay of pions. This is essentially the mechanism by which muons are produced at proton accelerator facilities. In either case, muons are peaked predominantly in the forward direction because, both in pair production and in nuclear pion production, the transverse momenta are on the order of the muon rest mass (106 MeV). Furthermore, in the pion decay case, the decay angle is quite small (0.2^{o} for 10 GeV pions). Consequently, muons are rarely a problem for transverse shielding.[10] On the other hand, they are a problem in the forward direction as a result of their weakly interacting nature. That is, muons with energies less than about 50 GeV lose energy essentially by ionization, and hence a fairly unique range is associated with each energy.[11] Above 10 GeV, interaction mechanisms other than ionization and excitation (collision loss) start to contribute.

Once muons are made, the transport descriptions are fairly similar around both types of machines. For the electron case, however, the muon source is essentially a point because the electromagnetic shower is "soft," as was indicated earlier. This is greatly emphasized for thick shields since the high energy muons that are capable of penetrating the shield must be produced by high energy photons in the shower, and most of the high energy muon production is accomplished in the first couple of radiation lengths. Muons are not necessarily produced at a point in a proton cascade. A comprehensive theoretical and experimental study of the production and the shielding of muons around electron accelerators has been made by Nelson and Kase.[11-13]

The slowing-down and scattering of the muons is generally treated as a diffusion process and the mathematical treatment is the same for either proton or electron accelerators,[11-14] although the source terms do differ. In Fig. 7, we have a comparison of the muon yields for a 20-GeV electron and a 200-GeV proton accelerator.[1] The yield from the proton machine is richer at lower energies partly because lower energy pions are more likely to decay.

Neutrons

The neutron production mechanisms at proton and electron accelerators are quite different. For proton accelerators the neutron spectrum can be synthesized into two parts: (a) neutrons above 20 MeV generated in the hadronic cascade, a process that occurs very rapidly, and (b) evaporation neutrons emitted at a later time by de-excitation of the residual nuclei. The neutron spectrum for electron accelerators may be synthesized into three parts: (a) neutrons from pions generated at photon energies above 150 MeV, (b) neutrons between 20 and 150 MeV from photodisintegration of the deuteron, and (c) giant resonance neutrons that are emitted isotropically by de-excitation of residual nuclei, as in the case of the evaporation process.

Earlier we pointed out that electron and proton accelerators have similar and, in some cases, comparable neutron radiation environments outside thick shields. This is so despite differences in the neutron spectra incident upon the inner surfaces of these shields, a fact that was recognized quite early by shielding physicists from cosmic ray studies.[15] Moyer[16,17] used the fact that the neutron inelastic cross section is essentially constant above 150 MeV and that lower energies have attenuation lengths substantially shorter. He ignored all neutrons with energies below 150 MeV, and set the removal mean free path to a constant value. He further assumed an equilibrium spectrum, after the innermost layers of a shield, allowing the total dose equivalent outside the shield to be determined in a relatively simple and straightforward manner.[18] This "Method of Moyer" has proved to be extremely workable at many accelerators, including SLAC. Thus, in most shielding applications, neutrons above 150 MeV are the only part of the spectrum that must be considered in the evaluation of shielding thickness. These high energy neutrons, which propagate the hadronic cascade in the shield, are accompanied by what Patterson and Thomas[19] call "camp followers," neutrons of much lower energies produced close to the shield surface from the cascade and evaporation processes. It is these lower energy neutrons that are most often measured by health physicists and which must be corrected by a suitable factor to determine total dose equivalent.

Even though an equilibrium spectrum is established early in the shield, it may not necessarily be the same as the cosmic ray spectrum nor will the spectra outside all thick shields at all accelerators be identical. Different shield compositions as well as voids in shields will alter the spectrum. In this context, a word of caution might be given which was alluded to in the introduction to this lecture. The use of a constant removal mean free path applied to neutrons above 150 MeV for medium and high-Z materials, simply removes neutrons from the high energy realm. High energy neutrons lose energy in the medium until they reach energies of a few MeV where the medium and high-Z elements are relatively transparent. These lower energy neutrons have a higher quality factor, and consequently will give a higher dose equivalent. Thus, it is always necessary to follow medium or high Z materials (used for photon attenuation, for example) by low Z materials to attenuate out these neutrons.

Summary

In this lecture we have attempted to draw comparisons between electron and proton shielding problems. The health physicist, charged with shielding either type of accelerator, must ask himself, "Am I faced with a thick or thin shield problem?" For the electron accelerator, he may be able to remove the photon component with medium or high Z materials close to the source, leaving a thick shield problem to solve. On the other hand, the health physicist at a proton accelerator always shields for hadrons; i.e., the photon component is always small. At both types of accelerators, muons may be a problem in the forward direction.

If the shields are thick, then similar spectra should be observed to the degree that shield compositions are the same. Thus it is possible for health physicists at various accelerators around the world to use similar shielding codes and methods, and to compare measurements regardless of type of accelerator.

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