PREDICTION OF RADIATION EFFECTS ON ACCELERATORS USING HADRON CASCADE CALCULATIONS

J. Ranft
Sektion Physik, Karl-Marx-Universität,
Leipzig, DDR

Summary

Radiation effects, especially radiation heating, radiation doses and induced activities on accelerator components as septa, targets, beam dumps and accelerator and beam line magnets are predicted using hadron cascade calculations. There is good agreement to measurements in the 10-20 GeV energy range, the same is found in a comparison to first measurements at 300 GeV at NAL.

1. Hadron cascade calculations

Hadron cascade calculations and their application to radiation problems around high energy accelerators were described in detail by Ranft.[1] Here we report on recent experimental comparisons and applications of these calculations.

The cascades considered are initiated by primary hadrons in the energy range of tens and hundreds of GeV. The characteristic feature of collisions in this energy range is the abundant production of new hadrons, a process which is rather independent on wether Hydrogen or heary material like Fe or Cu is used as target material. The number of newly produced secondary particles rises logarithmically or with a small power of the laboratory energy of the primary particle

$$n_s \approx \log E_p \quad \text{or} \quad n_s \approx E_p^{1/4} \qquad (1)$$

In extended matter these secondaries produce in turn more particles in their collisions and so on. This process comes to an end only when finally the energies of all particles are small enough so that particle production is no longer possible.

In most materials the cascade of high energy hadrons is the dominant mechanism of energy transport. For many applications of hadron cascade calculations nuclear excitation processes like the intranuclear cascade and nuclear evaporation, which give rise to large numbers of low energy secondaries - mostly neutrons - are relatively unimportant and can be treated approximately. In the well developed cascade the fluxes of these low energy particles are related to the flux of high energy particles, collisions of high energy hadrons are the main source of the low energy component.

There are three dominant mechanisms of energy deposition by the hadron cascade. These are:

(i) the ionization energy loss of high energy charged hadrons,

(ii) electromagnetic cascades initiated by γ quanta from π^0 decay and

(iii) low energy nuclear fragments depositing the energy component which we call nuclear excitation energy.

The three mechanisms are roughly of equal importance. The proportion of energy deposited by the electromagnetic cascade rises with energy and the proportion of nuclear excitation energy decreases with primary energy.

For most applications the three dimensional development of the cascade initiated by a narrow beam of primary particles is of interest. The elementary events in the cascade are rather complicated, particle production is strongly anisotropic. There are different kinds of processes to be considered, elastic and inelastic collisions, ionization energy loss, electromagnetic cascades etc. Different kinds of particles are involved, we consider protons, neutrons, and charged and neutral pions.

In this situation three dimensional analytic calculations are extremely difficult no such calculations have been performed yet. Analytic calculations of the one dimensional development of the hadronic cascade using a simplified description of the contributing processes were however performed.[2] Such calculations are valuable for the general understanding of the cascade process but only of limited use for practical applications.

Physical input data for the cascade calculations are the following: elastic and inelastic cross sections of hadrons on nuclei, inclusive particle production cross sections for hadrons colliding with nuclei and ionization energy losses, multiple Coulomb scattering, nuclear excitation energies and energy deposition by the electromagnetic cascade. All input data used are discussed in Ref.[1] and [3]. Technical details of the Monte Carlo calculation are discussed in Ref.[1,3,4] and[5].

Computer programs using different methods, for different applications and for different geometries are available[5-9].

The most important results of the hadron cascade calculations are presented in the form of three dimensional hadronic cascade star densities and energy deposition densities. Star densities are of use to estimate the production of radioactive isotopes in the material and from this the remanent dose rates from induced radioactivity after the end of irradiation by the high energy particles. Energy deposition densities are related to direct radiation dose and to heat deposition in the material as well as to signal size in scintillation detectors.

2. Recent comparisons of results of hadron cascade calculations with experimental data

The confidence in the predictive power of the rather complex hadron cascade calculations is to be justified by comparison of the results with experimental data obtained in a wide variety of situations. Such comparisons done up to 1971 were reported in[1], here we discuss recent work done since the completion of the paper.[1]

The computer programme FLUKA[5,8] was used by Henny and Potier to calculate the heat deposition in external targets. The results of the calculation were compared with experimental data obtained at the CERN-PS with a proton beam of 24 GeV/c incident on external targets with the length l = 180 mm and a diameter of 12 mm. In Table 1 we compare the measured heat deposited by a beam of 10^{12} protons with the hadron cascade results.

It is to be noted that the heat deposition in heavy materials is up to five times larger than due to the ionization energy loss of primary particles alone. The calculated heat depositions agree rather well with the experimental data.

Table 1

Heat deposition in cal/10^{12} protons by a proton beam of 10^{12} particles incident on targets of l = 180 mm length and 12 mm diameter[10]

Target material	Al	Ti	Cu	Mo	W
primary ionization alone	3.5	5.5	10.5	11.2	19.0
experiment	4.7	10.8	38.0	47.0	93.5
hadron cascade calculation, FLUKA	7.0	13.3	28.6	38.8	89.0

Deep penetration hadron fluxes measured with activation detectors and dose meters in the large muon filter of the CERN neutrino experiment were compared by Goebel, Ranft and Routti[11] with hadron star densities and energy deposition densities calculated with the programme TRANKA.[5] Good agreement of experimental and calculated results was found up to a depth of 400 cm in iron and up to radial distances of 200 cm from the beam axis. The hadron fluxes in this region are attenuated by about 7 decades. This agreement was found in spite of the rather inhomogenous composition of the muon back stop used.

In the same paper Goebel, Ranft and Routti compare the results of TRANKA with activation detector measurements in a more homogenous Fe backstop irradiated with 28 GeV protons at BNL.[12] In Fig. 1 we compare the hadron flux density calculated with the BNL results. The data at r = 60 cm outside the beam axis might be influenced by the halo of the beam.

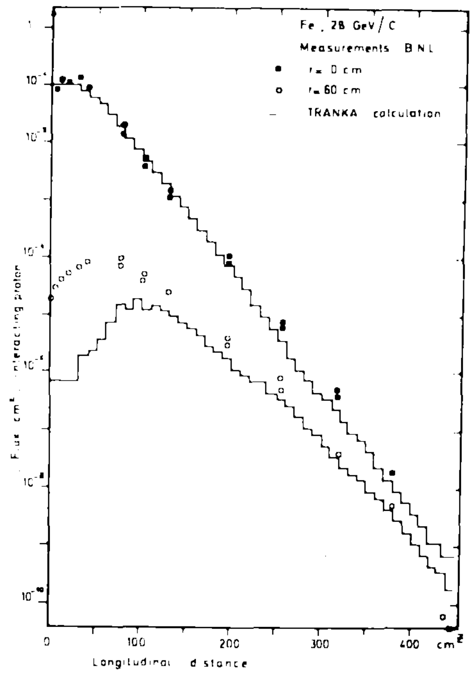

Fig. 1 Comparison of hadron flux densities calculated with the Monte Carlo programme TRANKA[5] with BNL measurements using ^{11}C activation detectors.[12]

As described in[1] and[5] the programme FLUKA can also be used to simulate the action of total absorption detectors. A modified version of FLUKA was used by Engler et al.[13] in order to optimise the energy resolution of neutrons or other strongly interacting particles with sampling total absorption counters (STAC). In Fig. 2 we compare the energy resolution measured by Engler et al.[13] using a particular STAC counter with the energy resolution calculated with the modified version of FLUKA by the same group.

A first experiment measuring the propagation of the hadron cascade initiated by 300 GeV protons interacting in a target which was positioned inside a beam line bending magnet was performed at NAL.[14] Preliminary results of this experiment were compared with hadron cascade calculations using the programme MAGKA.[8] In Fig. 3 we compare the energy deposition density as calculated by MAGKA with the results of dose measurements inside and outside the magnet yoke. Good agreement is found.

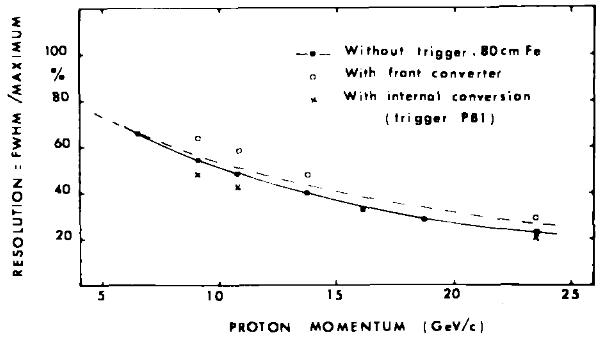

Fig. 2 The energy resolution measured with a sampling total absorption counter as function of the proton momentum for different trigger conditions. The full line is drawn through measured points without special trigger conditions. The dashed line was obtained from hadron cascade calculations using a modified version of the programme FLUKA.[13]

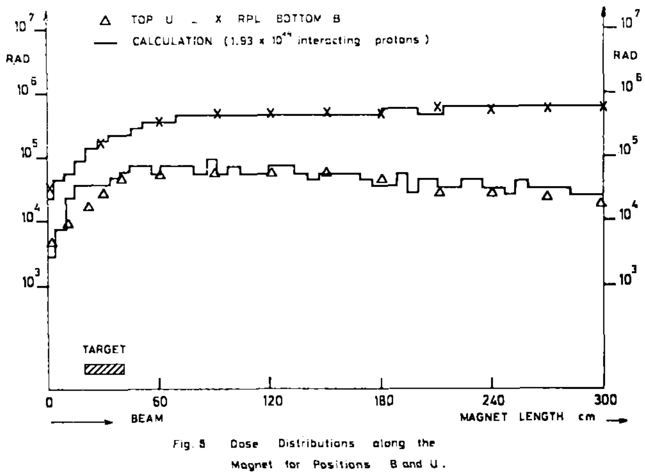

Fig. 3 Comparison of calculated and measured doses inside and outside the yoke of a beam line magnet. A target inside the magnet was irradiated with 300 GeV/c protons at NAL.[14,15]

Particle fluxes measured at large angles around massive targets in external proton beam lines were compared by Ranft and Routti[6] with results obtained with the computer programme FLUKU simulating the hadron cascade inside the target. Good agreement was obtained.

Hadron fluxes in a side shield near to a target in an external proton beam line were measured at BNL for 15.5 and 28 GeV/c incident protons.[16] The results of this experiment were compared by Ranft[7] with results of the hadron cascade programme MAGKO.

In situations where particle fluxes and doses perpendicular to the incident proton beam are of interest it is of advantage to use the programmes FLUKU[6] and MAGKO.[7] In these programmes the protons and neutrons resulting from the intranuclear cascade are considered in more detail than in other computer programmes.

3. Prediction of radiation effects around future accelerators using hadron cascade calculations

Many applications of hadron cascade calculations for the estimation of radiation problems around high energy accelerators are discussed in Ref.[3]. Such applications include estimation of dose to components and induced radioactivity in ejection regions and external target areas of proton accelerators, prediction of target heating and heat deposition in beam dumps, calculation of longitudinal and transverse hadron shielding requirements. We discuss here some recent applications mostly for problems around the 300 GeV accelerator of CERN-Laboratory II.

The thermal effects which accur in external targets when irradiated by fast and slow extracted beams of 400 GeV/c and 10^{13} protons per pulse were studied by Kalbreier, Middelkoop and Sievers[17] using the programme FLUKA.[5,8] Temperature and thermal stress distributions in targets of different materials were derived from the calculated energy deposition density. The incident beam was assumed with a Gaussian density distribution with 92% of all protons within a diameter of 2 mm. In Table 2 we give as an example temperatures calculated for targets with a length of one nuclear interaction length and 2 mm diameter.

Table 2

Target temperatures in °C for 10^{13} protons of 400 GeV interacting in a one interaction length, 2 mm diameter target compared to the melting temperatures of the target materials T_{melt}. T_o is the maximum temperature rise in the centre of the target for the case of a fast extracted beam. $\bar{T}$ is the average temperature rise at the end of a slow extracted pulse in the absence of cooling. T_R is the steady state temperature of the target at the end of the thermal cycle evaluated for cooling by radiation only. The maximum target temperatures are $T_R + \bar{T}$ for slow extraction and $T_R + T_o$ for fast extraction.

Material	T_o	$\bar{T}$	T_R	T_{melt}
Be	490	190	730	1280
BeO	950	420	830	2570
B_4C	1190	550	750	2430
C	1250	510	600	3320
SiC	840	310	910	2700
Al	670	400	660	660
Al_2O_3	1060	450	850	2040
Ti	1670	1070	880	1670
Cu	2900	1910		1080
Mo	9300	4000		2610
W	39000	20000		3380

The numbers in Table 2 exclude the use of heavy target materials and forced cooling by convection seems to be adviceable.
The dynamic stresses created in the targets due to the rapid heating in fast extracted beams have to be reduced by subdividing the total target length into several parts. In fast extracted beams also the quasistatic stress produced in the target due to the radial temperature gradient exceeds the elastic limit.

The thermal problems arising in beam dumps are also investigated using the hadron cascade programmes FLUKA and MAGKA.[18]

Dose to components and remanent dose rates from induced radioactivity were estimated at CERN-Laboratory II for the ejection region of the main ring and for the target areas in the West, North and Neutrino zones[19,20] using the programmes MAGKA and FLUKA. The results indicate very high dose and radiation levels in critical positions. Therefore it seems adviceable to develop special radiation hard components for these regions.

The remanent dose rates estimated for the CERN-SPS ejection region are in good agreement with the first experience around the NAL accelerator.[19]

The hadron cascade programmes MAGKA[8] and MAGKO[7] are well suited to study the effect of the heating due to beam losses in superconducting synchrotrons and storage rings. A preliminary study of this kind is beeing performed by Schönbacher and Van de Voorde.[21] The effect of radiation heating due to beam losses is not important for the refrigeration requirements but the sudden temperature rise due to the hadron cascade in the supraconducting windings can lead to a sudden loss of supraconductivity. The beam loss which can be tolerated depends on the arrangements of the supraconducting magnets but it seems that a loss of 10^{12} protons in or near to a s.c. magnet could affect its operation. For these reasons the operation of supraconducting synchrotrons and storage rings requires a control of beam losses well beyond the present state of the art.

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