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Shielding Calculations Using FLUKA

— comparison with simple equations—

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Abstract:

The dose equivalent on the surface of concrete shielding has been calculated using the Monte Carlo code FLUKA86 for incident proton energies from 10 to 800 GeV. The results have been compared with some simple equations. The value of the angular dependent parameter in Moyer's equation has been calculated from the locations where the values of the maximum dose equivalent occur.

Key words: Transverse Shielding, FLUKA Calculations, Dose Equivalent, Moyer's Equation.

1. Introduction

The maximum energy of particles that has been achieved at various accelerator facilities has been increasing year by year [1]. Since a significant amount of the construction cost of a high-energy accelerator facility involves shielding, a reliable and practicable estimation of the shielding cost is always required. However, the energy increases of planned accelerators are often so drastic that shielding estimations must depend on calculations rather than on a few numerical results of shielding experiments.

It is a common practice to use computer programs written with Monte Carlo (MC) techniques to estimate the shielding thickness at high-energy accelerator laboratories. The MC technique is most powerful when the concerned accelerator structures and/or shielding configurations are complicated. Not every person can, however, easily handle complex MC codes which usually require a large computer.

Based on experimental data some people have suggested the use of simple equations to estimate the dose equivalent on the surface of a shield of simple geometry [2-8]. Calculations with MC codes also support these simple equations as long as the values of the maximum dose equivalent on the shield surface is concerned [9-12]. In this report the results are listed of MC calculations using the FLUKA86 code [13] and a comparison is made with the values obtained from simple equations above referred.

2. Calculations

Calculations with the FLUKA code were carried out for the same cylindrical geometry (fig. 1) that is mentioned in ref. 8. An Fe target of various radii (2.5-7.5 cm) and 2 or 3-m length was located at the center of a 1-m radius tunnel surrounded by a concrete shielding with a density of 2.5 g cm^{-3}. The target radius and length were determined so that the maximum star density would be produced at the shield surface (see second column of Table 1). The shielding thickness was 1.02, 1.40, 2.88 and 3.36-m, over which a region was located filled with water with thickness of two radial-bins (8.4-14 cm).

FLUKA, like other MC codes, outputs star and/or energy densities for each 50 x 50 geometrical bins (generally equally divided) in both radial and longitudinal directions. The star density was obtained from the outer-most bin in the concrete shielding region, while the energy density was obtained from the water region. For a shielding thickness of 3.36-m, three runs with different random-number seeds were carried out for a maximum CPU time of 60 min for each on a HITAC 280-H; the corresponding values were summed together in order to improve the statistics of the results.

3. Results

3.1 Star and energy densities

Fig. 2 shows the maximum star density (stars cm^{-3}) in the outermost bin of a concrete shielding of various thicknesses as a function of the incident proton energy E_p. Each point is the mean value for 10 - 20 bins. The error bars represent statistical errors, which range from 25 to 70 %. They represent the standard deviations calculated in the usual manner, assuming that each bin produces a statistically independent phenomenon. This procedure corresponds to first order polynomial fitting to the data when higher order polynomial fittings are more appropriate [18]. Thus, the actual error for the mean value would be somewhat smaller. Fig. 3 gives the maximum energy density (GeV cm^{-3}) in the water layer located just above the concrete shielding, as described in the previous section.

The dose equivalent behind concrete or sand at an angle nearly perpendicular to the beam can be expressed by a simple equation [2, 4]:

$$H = H_1 \frac{e^{-d/\lambda}}{r^2} , \qquad (1)$$

where d is shield thickness, λ the attenuation length, and r the distance from the target. Parameter H_1 is energy-dependent, and can be expressed as [6]:

$$H_1 (E_p) = H_0 E_p^x, \qquad (2)$$

where H_0 is a constant.

Substituting eq (2) into eq (1), we obtain

$$H = H_0 (E_p)^x \frac{e^{-d/\lambda}}{r^2} . \qquad (3)$$

Based on several experimental data, Tesch and Dinter [8] have assigned the parameters in eq (3) as

$$H = 1.5 \cdot 10^{-14} (E_p)^{0.8} \frac{e^{-d/107}}{r^2} , \qquad (4)$$

where H is in Sv, E_p is in GeV, d is in g cm^{-2} and r is in m. According to their analysis, eq (4) is valid for a shielding thicknesses greater than about 100 g cm^{-2} and for E_p in the range 1 GeV to 1 TeV. The error in H, estimated from deviations in the equations from which eq (4) was derived, is approximately a factor of 2 in both directions. It has also been shown that the agreement of eq (2) with experimental data of Cossairt et al. [14] with 800 GeV protons is within a factor of 2, if a quality factor QF = 5 is assumed.

Table 1 summarizes the results of FLUKA calculations. The listed values are: The star density S (stars cm^{-3}), the dose equivalent H_{TD} (Sv) calculated from the equation of Tesch and Dinter (i. e. eq. (2)), the values of $k_1 = H_{TD}/S$, the energy density in the water layer ΔE (GeV cm^{-3}), the dose equivalent H_{FL} (Sv) calculated from the values of ΔE (assuming QF = 5), and the values of $k_2 = H_{TD}/H_{FL}$.

The mean of all the values for k_1 in Table 1 is (6.8 ± 1.2) 10^{-8} Sv $star^{-1}$ cm^3. This value is the star-density-to-dose-equivalent conversion factor for FLUKA86. The mean of all k_2 values is 0.95 ± 0.13. Taking into account the large statistical errors in the values of FLUKA calculations, the agreement between the values of the dose equivalent calculated from eq (2) and those calculated from the star and/or energy densities using the FLUKA code is excellent.

3.2. Energy dependent parameter x

The energy dependency of the dose equivalent on the primary proton has been described as in eq (3). The slopes of the straight lines in Figs. 1 and 2, which were drawn by eye, give the values of parameter x in eq (3). Because of the large statistical errors of each point, we can modestly say that the values of parameter x for the present cases are

$$x = 0.83 \pm 0.03. \qquad (5)$$

Several investigations on parameter x have been reported by several authors based on regression analyses of experimental data [6, 7] or on the results of Monte Carlo simulations [10, 11]. The latest value of x given by Thomas and Thomas is 0.80 ± 0.10 [7], while Yamaguchi's values based on CASIM calculations ranged from 0.83 ± 0.02 to 0.95 ± 0.06, depending on the shield thicknesses [11]. The value of x obtained from the present calculations agrees well with both of these assignments.

3.3. Three parameter fitting

Three parameters must be defined when eq (3) is applied. The value of each parameter necessarily has some ambiguities. We have calculated the values of k_1 and k_2 (see section 3.1) for various combinations of the values of the three parameters in eq (3): H_0, λ and x. For each set of parameter values there are, in the present calculations, 20 values of k_1's corresponding to the calculated data points, i.e. 4 (shielding thicknesses) x 5 (incident energies) = 20. The same is true for k_2.

The values were output in order of C. V. (coefficient of variance), expressed by

$$C.\,V. = \frac{\sigma}{\bar{k}} \times 100\,\%, \qquad (6)$$

where,

$$\sigma = \sqrt{\frac{\sum_{i}^{n} (k_i - \bar{k})}{n-1}}\,, \quad (n = 20) \qquad (7)$$

k_i is the i-th value of k_1 or k_2,

$\bar{k}$ the mean of twenty k_i's, and

n the number of data point (= 20).

The range of parameter values were: H_0 ($1.0 - 1.6 \cdot 10^{-14}$ Sv m^2), λ (105-117 g cm^{-2}) and x (0.80-0.86).

The results show that with any combination of the parameter values, within the range given above, the agreement between the values of the dose equivalent calculated by eq (3) and those obtained by using the FLUKA code is within 20 % for the examined beam energies and shield thicknesses.

3.4 Locations of the maximum dose equivalent and Moyer's equation

Fig. 4 (a-e) shows the locations at which the maximum values of the maximum star and energy densities occur in the FLUKA calculations for various incident energies. The longitudinal locations at which the maximum energy density in water occurs are 0.6 - 0.9 m closer to the target for each incident energy than the locations at which the maximum star density in the concrete shielding occur.

In 1961 Moyer developed a semi-empirical method [15, 16] for estimating the shield thicknesses required for Bevatron — a 6 GeV proton synchrotron. Detailed descriptions of Moyer's equation have been presented, for example, in a text book [17]. Assuming a point source, the dose equivalent on the outside surface of the shielding is estimated by

$$H = H_0 (E_p)^x e^{-\beta\theta} \frac{e^{-(d/\sin\theta)/\lambda}}{r^2}, \quad (8)$$

where θ is the angle subtended between the beam line and a line joining the point source and the point of interest. It can clearly be seen that Moyer's equation is characterized by an angular-dependent term, exp $(-\beta\theta)$, without which the equation is the same as eq (3). The transverse shield thickness d in eq (3) now appears in eq (8) as $d/\sin\theta$, indicating an effective slant shield thickness. Summarizing the measured values of the angular distribution parameter, Stevenson et al. obtained best values of 2.3 ± 0.1 for β [3].

In order to determine the agreement between Moyer's equation and the MC calculations, it would be necessary to fit the whole function of eq (8) to the dose equivalent curves obtained from the MC calculations for various shield thicknesses. However, the values of both eq (8) and the corresponding MC results range over several orders of magnitude as the longitudinal distance from the target surface changes from 0 to several meters. Moreover, it is said that eq (8) is valid for any angle $60° < \theta < 120°$ [3], or around the maximum dose equivalent regions where our interest is concentrated owing to radiation-safety aspects. Thus, as one of the preliminary studies, we attempt below to determine the value of β from the longitudinal distances at which the values of the maximum dose equivalent occur.

The value of the angle θ at which the maximum dose equivalent occurs, θ_m, in Moyer's equation is given by

$$2 \cot\theta_m - \beta + \ell \cot\theta_m / \sin\theta_m = 0, \quad (9)$$

where $\ell = d/\lambda$ is the shield thickness measured in units of the attenuation length λ. Thus, it would be possible to calculate β from the value of θ_m.

One of the difficult features, however, in measuring the angle θ is that a point source is assumed in Moyer's equation, while in actual cases the radiation source is distributed within the target. If a thin target is used in an experiment for measuring

parameter β, the hadron cascade does not fully develop within the target and the validity of eq (8) would be uncertain.

Assuming that a point-like radiation source is located at Z_S-m inside (from its face) the target, we have calculated from Fig. 4 (a - e) the values of β as a function of Z_S. Figs. 5a and 5b show the values of β obtained from the star and energy density peaks, respectively, for various incident energies and two different values of the attenuation length λ. The error bars represent the uncertainties for four different shield thicknesses.

Since the longitudinal locations at which the maximum energy density in water occurs are much closer to the front face of target than the locations at which the maximum star density occurs, the values of β deduced from the energy density data are much smaller than those from the star density data. In either case, however, the higher the incident energy, the larger the value of β. Naturally, the values of β decreases as a function of Z_S. They are slightly larger for $\lambda = 117$ g cm^{-2} than for $\lambda = 107$.

The present values of β for $Z_S = 0$ obtained from the star density peaks are smaller than the value of β estimated by another MC code, CASIM [12], but they are much larger than the value of 2.3 radian^{-1} given by Stevenson et al. [3]. It should be noted here that in CASIM cascades develop too sharply in the forward direction because of various simplifications in the program, resulting in higher values of β than those obtained from FLUKA. The values of β in the present calculations come closer to the value of Stevenson et al. for larger value of Z_S. The values of β obtained from the energy density peaks are about 2.5 for $Z_S = 0$ and are very close to the value of Stevenson et al. However, it is not realistic that the total incident energy is deposited at a point on the front surface of the target, and the value of β could be smaller than the above values.

4. Conclusions

It has been shown that the agreement is excellent, within 20 %, between the values of the dose equivalent calculated by a simple equation of Tesch and Dinter and those calculated from the maximum star and/or energy densities obtained using the MC code

FLUKA86 for a concrete shielding of thicknesses 1.0 - 2.4 m and for an incident energy range of 10 - 800 GeV.

The angular-dependent parameter β in Moyer's equation has been studied in terms of the locations at which the values of the maximum dose equivalent occur. It has been shown that β is a function of Z_s, the distance between the front surface of the target and the assumed point of total energy deposition of the incident proton. The parameter β is also a function of the incident proton energy E as well as the attenuation length λ. The values of β obtained from the FLUKA calculations are much smaller than those from similar calculations using CASIM.

Further studies are in progress.

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Figure Captions:

Fig. 1 Geometrical configurations for the present calculations.

Fig. 2 Maximum star density calculated using FLUKA for various thicknesses of concrete shielding as a function of the incident proton energy.

Fig. 3 Maximum energy density calculated using FLUKA for various thicknesses of concrete shielding as a function of the incident proton energy.

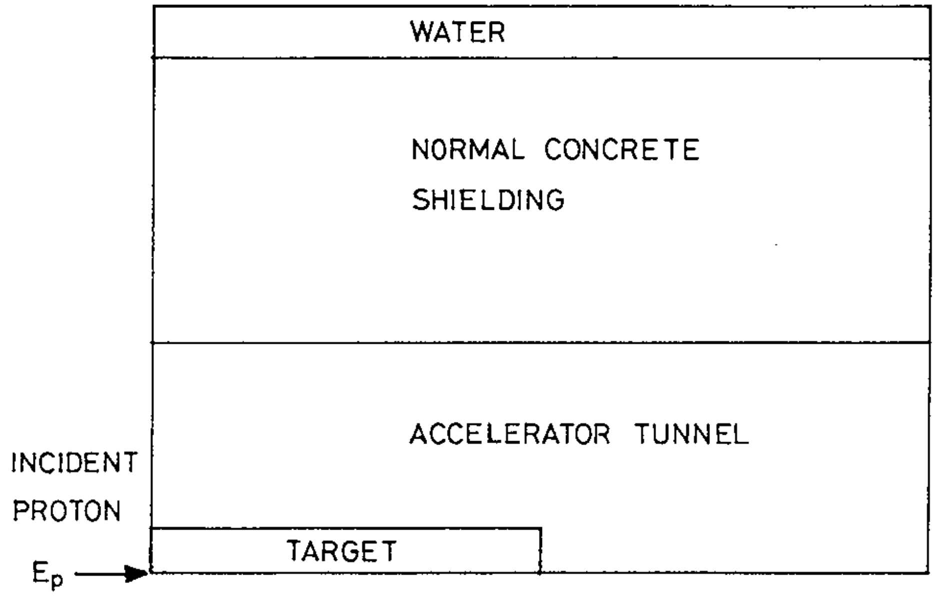
Fig. 4 Locations at which the maximum star and energy densities occur in the FLUKA calculations for various incident energies: a) 10 GeV, b) 25 GeV, c) 100 GeV, d) 300 GeV, e) 800 GeV.

Fig. 5 Values of the angular dependent parameter β in Moyer's equation as a function of the longitudinal distance, Z_S, between the front surface of the target and assumed point of total energy loss:

a) calculated from locations of the star density peaks,

b) calculated from locations of the energy density peaks.

Fig. 1



E_p (GeV)	Target (r x ℓ) (cm)	d (cm)	S(conc.) (stars cm^{-3})	H_{TD} (Sv)	k_1 (H_{TD}/S)	ΔE (H_2O) (GeV cm^{-3})	H_{FL} (Sv)	k_2 (H_{TD}/H_{FL})
10	5 x 200	102	2.8 E - 8	2.17 E - 15	7.7 E - 8	3.0 E - 9	2.4 E - 15	0.90
		140	7.8 E - 9	6.24 E - 16	8.0 E - 8	7.6 E - 10	6.1 E - 16	1.03
		188	1.6 E - 9	1.41 E - 16	8.8 E - 8	1.7 E - 10	1.4 E - 16	1.04
		236	6.1 E - 10	3.38 E - 17	5.5 E - 8	3.0 E - 11	2.4 E - 17	1.41
25	5 x 200	102	6.7 E - 8	4.51 E - 15	6.7 E - 8	6.0 E - 9	4.8 E - 15	0.94
		140	1.7 E - 8	1.30 E - 15	7.6 E - 8	1.6 E - 9	1.3 E - 15	1.01
		188	5.1 E - 9	2.94 E - 16	5.8 E - 8	4.3 E - 10	3.4 E - 16	0.85
		236	1.3 E - 9	7.03 E - 17	5.4 E - 8	9.7 E - 11	7.8 E - 17	0.91
100	7.5 x 200	102	1.7 E - 7	1.37 E - 14	8.1 E - 8	1.6 E - 8	1.3 E - 14	1.07
		140	5.3 E - 8	3.94 E - 15	7.4 E - 8	5.3 E - 9	4.2 E - 15	0.93
		188	1.3 E - 8	8.91 E - 16	6.9 E - 8	1.1 E - 9	8.8 E - 16	1.01
		236	4.4 E - 9	2.13 E - 16	4.8 E - 8	3.2 E - 10	2.6 E - 16	0.83
300	7.5 x 200	102	3.9 E - 7	3.30 E - 14	8.5 E - 8	4.4 E - 8	3.5 E - 14	0.94
		140	1.3 E - 7	9.48 E - 15	7.3 E - 8	1.4 E - 8	1.1 E - 14	0.85
		188	3.9 E - 8	2.14 E - 15	5.5 E - 8	3.5 E - 9	2.8 E - 15	0.77
		236	8.1 E - 9	5.13 E - 15	6.3 E - 8	7.1 E - 10	5.7 E - 16	0.90
800	7.5 x 300	102	9.3 E - 7	7.22 E - 14	7.8 E - 8	1.0 E - 7	8.0 E - 14	0.90
		140	2.9 E - 7	2.08 E - 14	7.2 E - 8	2.7 E - 8	2.2 E - 14	0.96
		188	9.0 E - 8	4.70 E - 15	5.2 E - 8	7.0 E - 9	5.6 E - 15	0.84
		236	2.0 E - 8	1.13 E - 15	5.6 E - 8	1.5 E - 9	1.2 E - 15	0.94

Table 1 Summary of the FLUKA calculations. S: Star density in stars cm^{-3}, H_{TD}: Dose equivalent in Sv calculated from Tesch and Dinter's equation in ref. 8., k_1: Ratio of H_{TD} to S, ΔE: Energy density in water region, H_{FL}: Dose equivalent calculated from energy density ΔE, k_2: Ratio of H_{TD} to H_{FL}.

Fig. 2

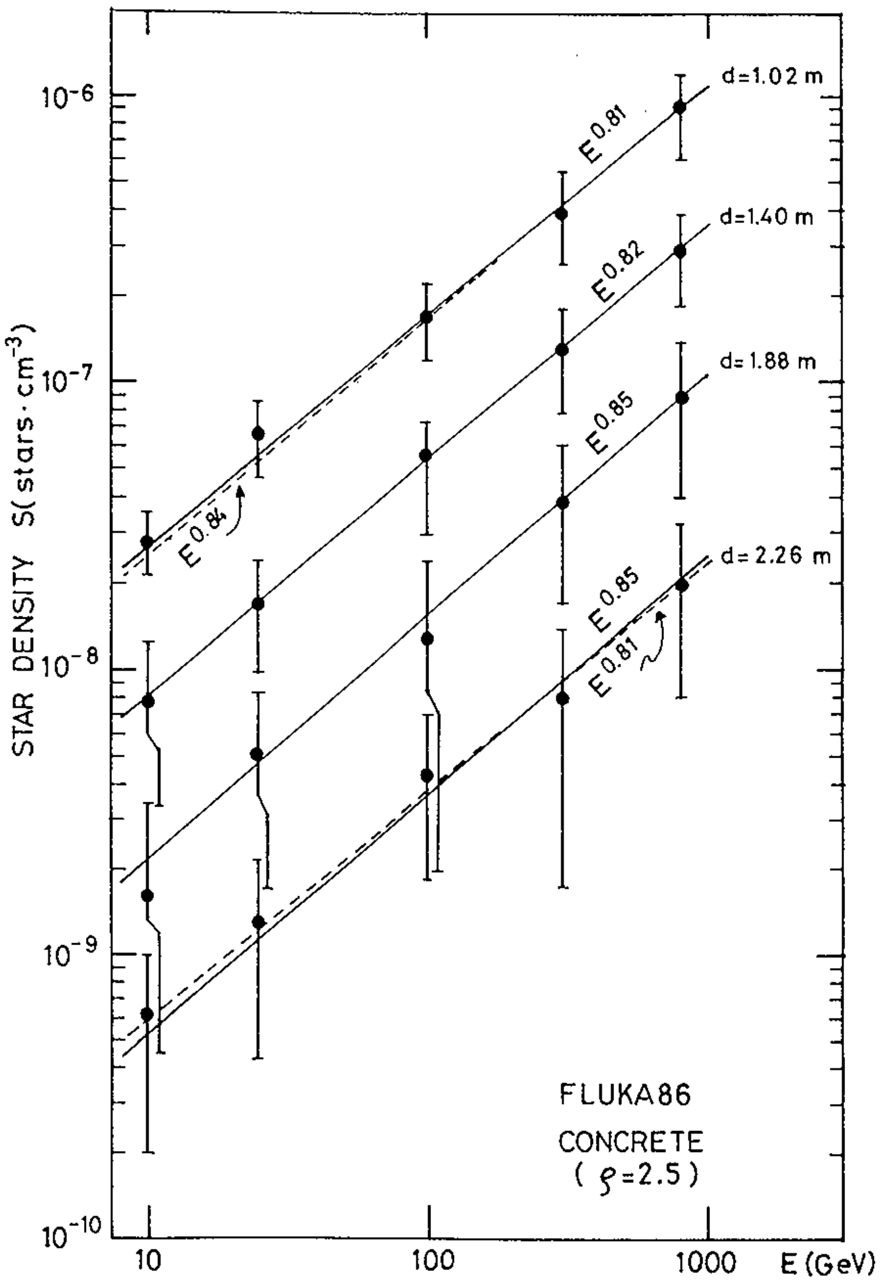

STAR DENSITY S(stars·cm^-3)
10^-6
10^-7
10^-8
10^-9
10^-10
10
100
1000
E (GeV)
d=1.02 m
d=1.40 m
d=1.88 m
d=2.26 m
E^0.81
E^0.82
E^0.85
E^0.85
E^0.81
E^0.84
FLUKA86
CONCRETE
(ϱ=2.5)

Fig. 3

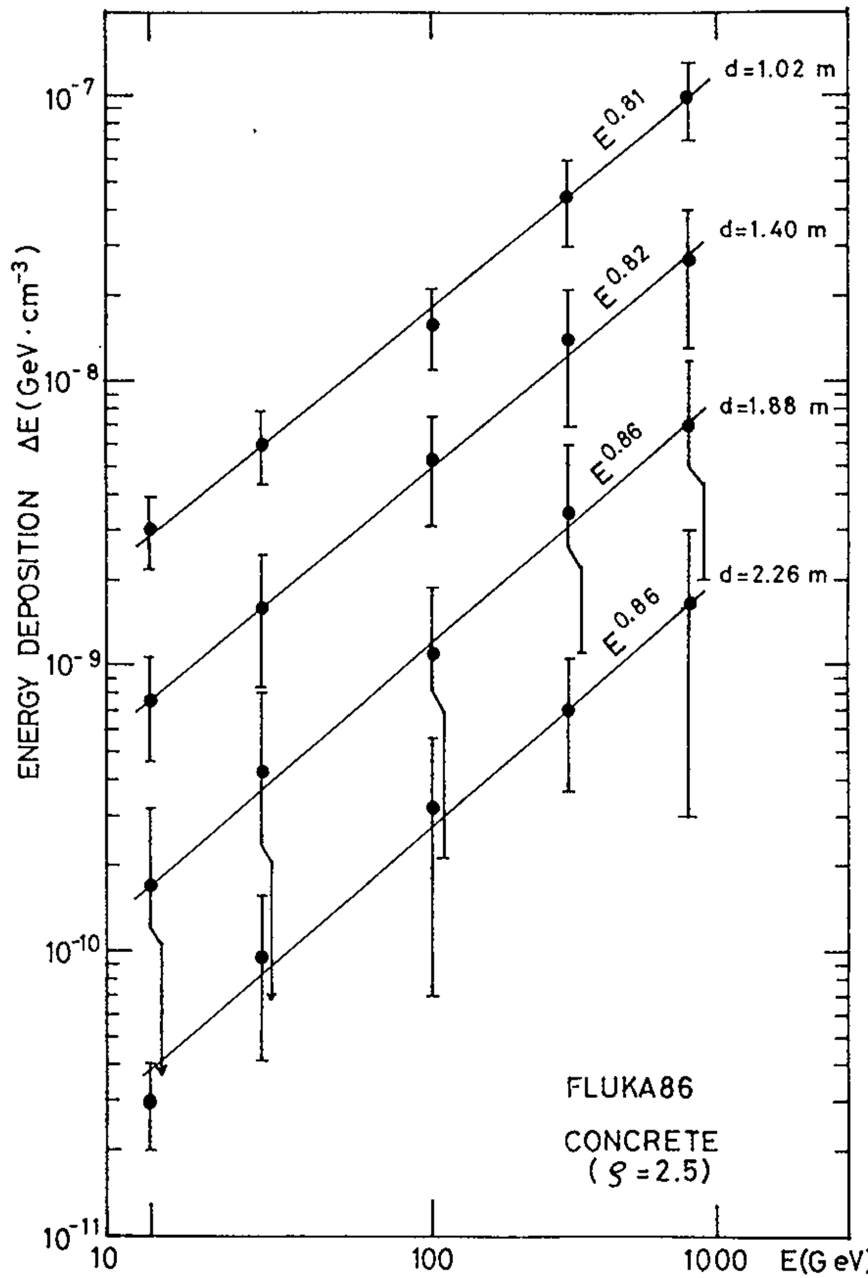
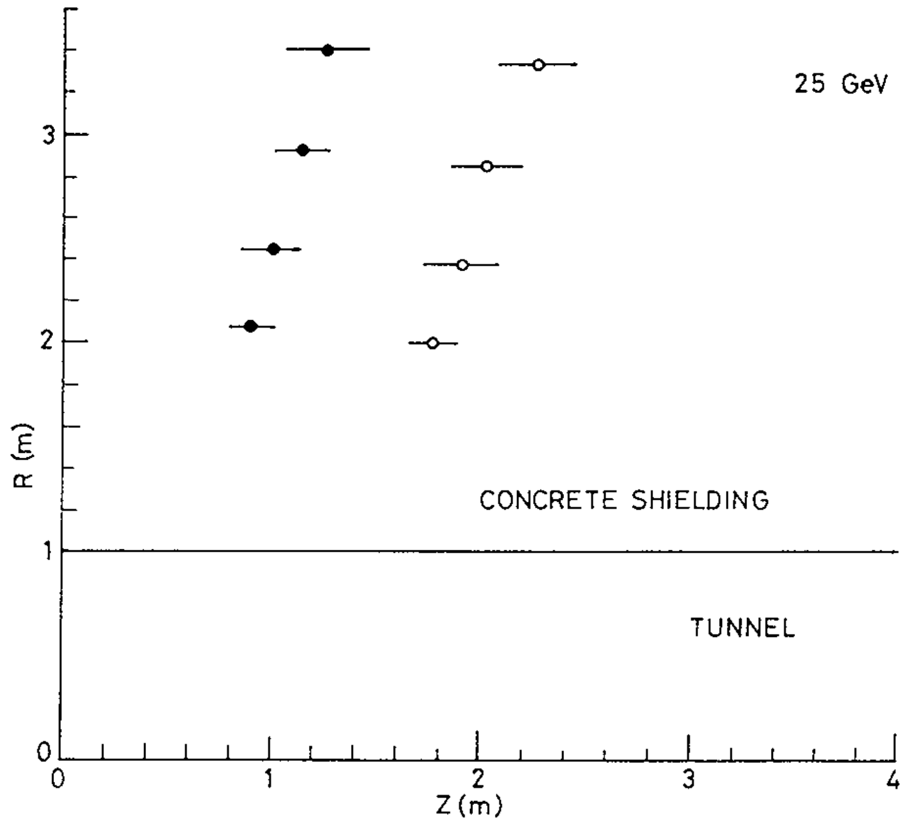
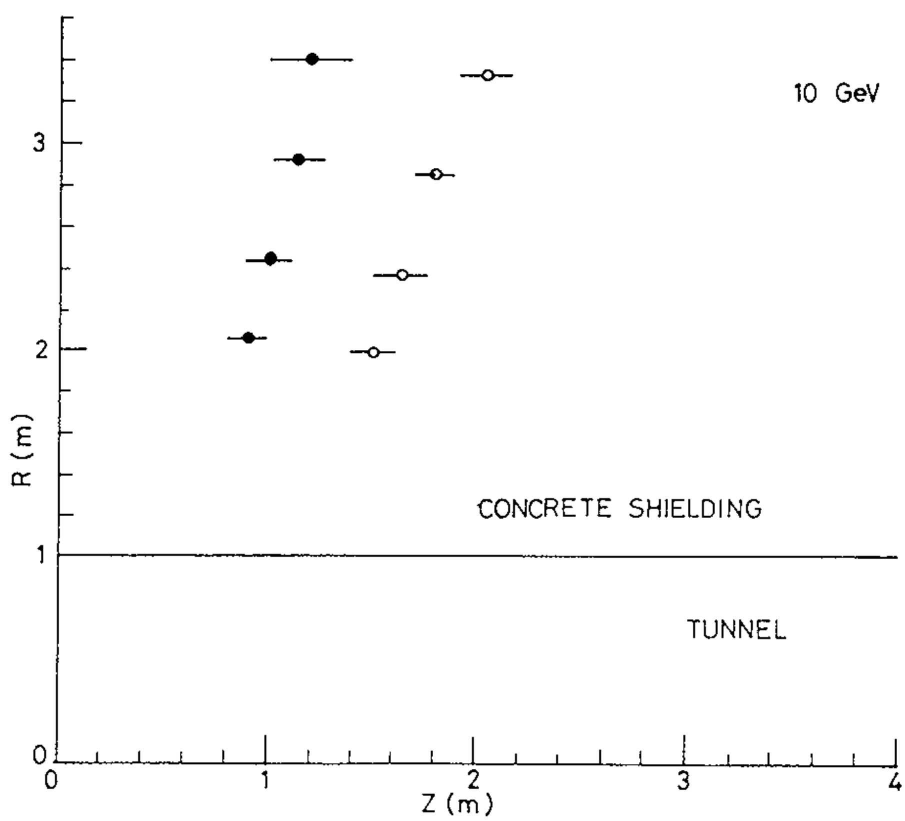

ENERGY DEPOSITION ΔE (GeV·cm^-3)
10^-7
10^-8
10^-9
10^-10
10^-11
10
100
1000
E(GeV)
d=1.02 m
d=1.40 m
d=1.88 m
d=2.26 m
E^0.81
E^0.82
E^0.86
E^0.86
FLUKA86
CONCRETE
(ϱ=2.5)

Fig. 4b



25 GeV
CONCRETE SHIELDING
TUNNEL
R (m)
Z (m)

Fig. 4a



10 GeV
CONCRETE SHIELDING
TUNNEL
R (m)
Z (m)

Fig. 4d

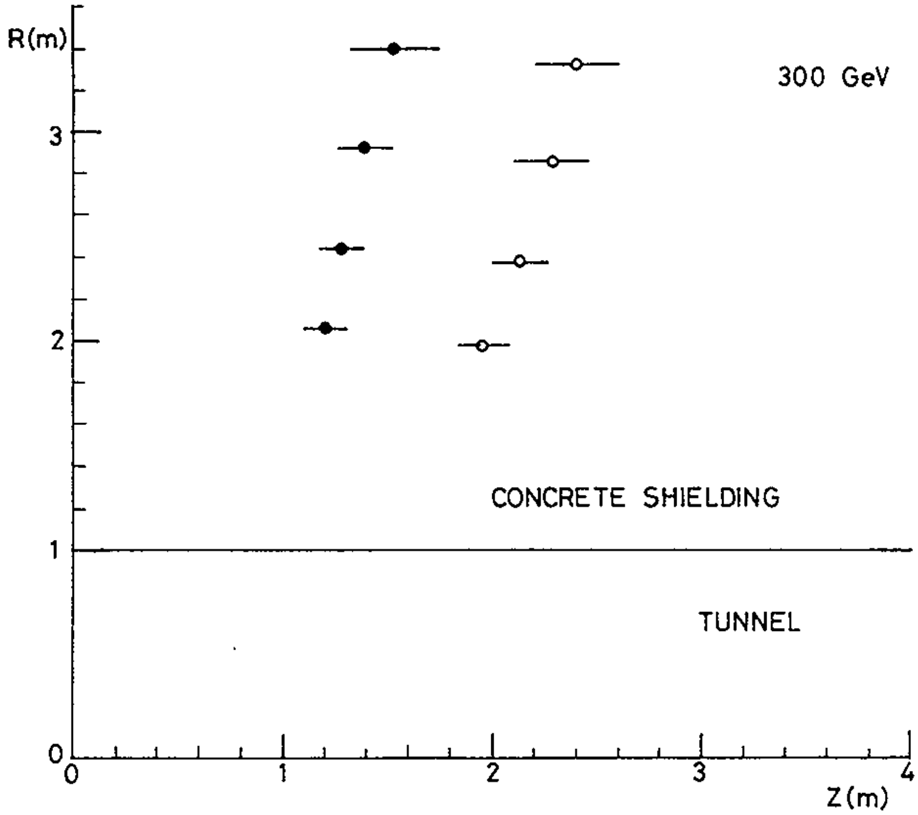

R(m)
300 GeV
CONCRETE SHIELDING
TUNNEL
Z(m)
0
1
2
3
4

Fig. 4c

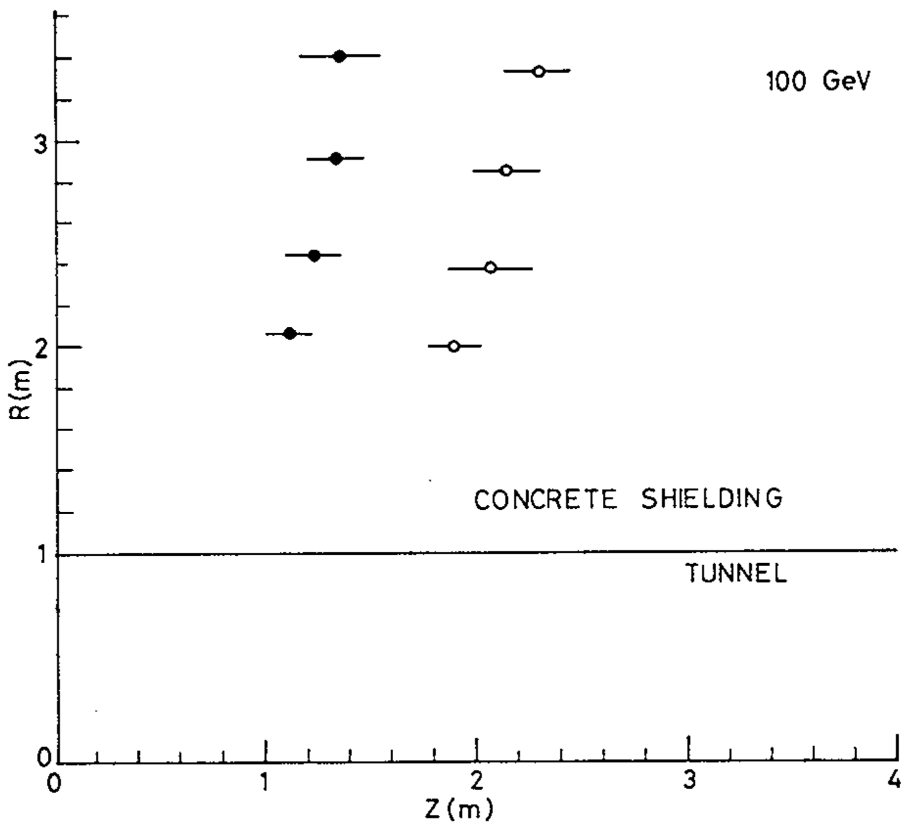

R(m)
100 GeV
CONCRETE SHIELDING
TUNNEL
Z(m)
0
1
2
3
4

Fig. 5a

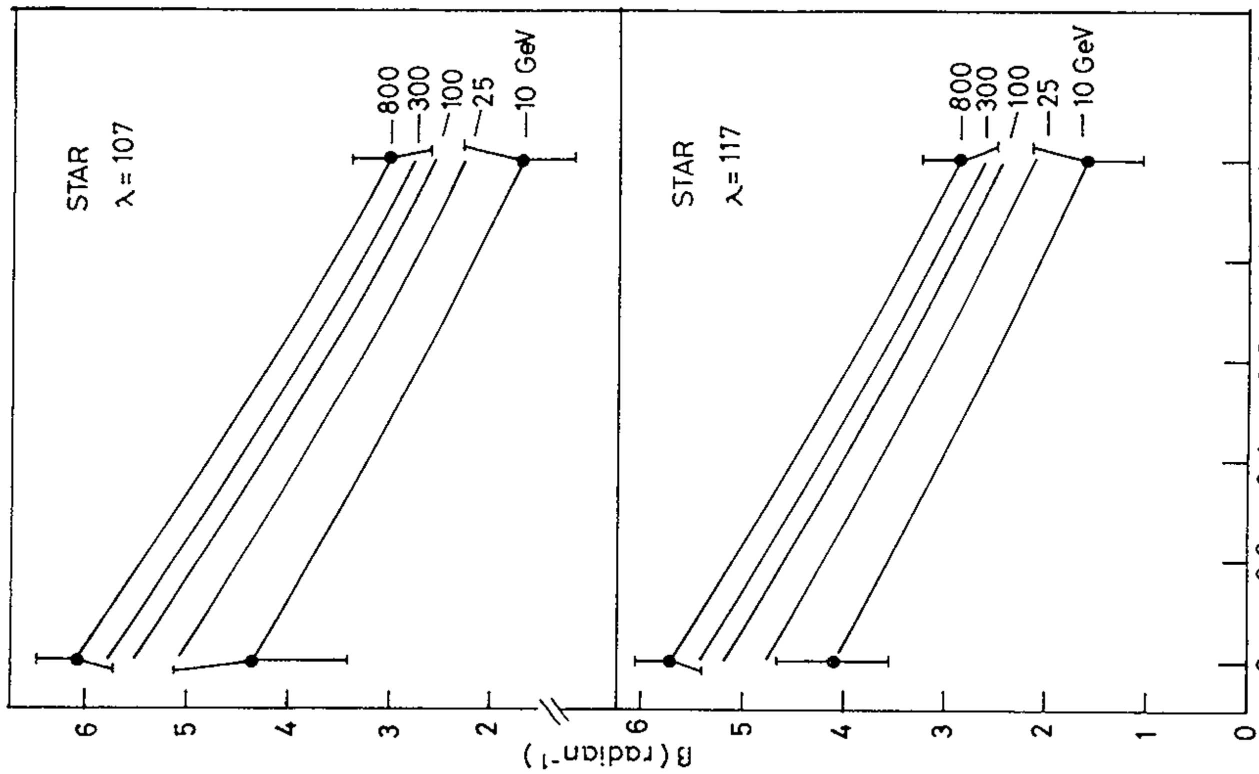

STAR
λ = 107
STAR
λ = 117
800
300
100
25
10 GeV
Zs(m)
β (radian⁻¹)

Fig. 4e

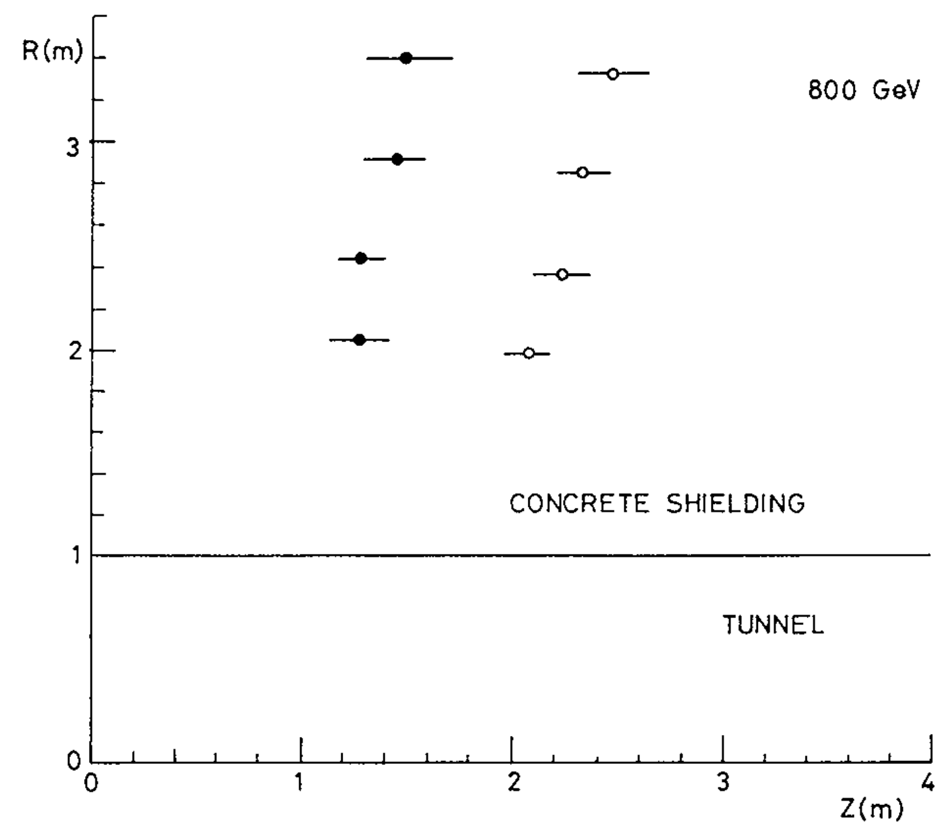
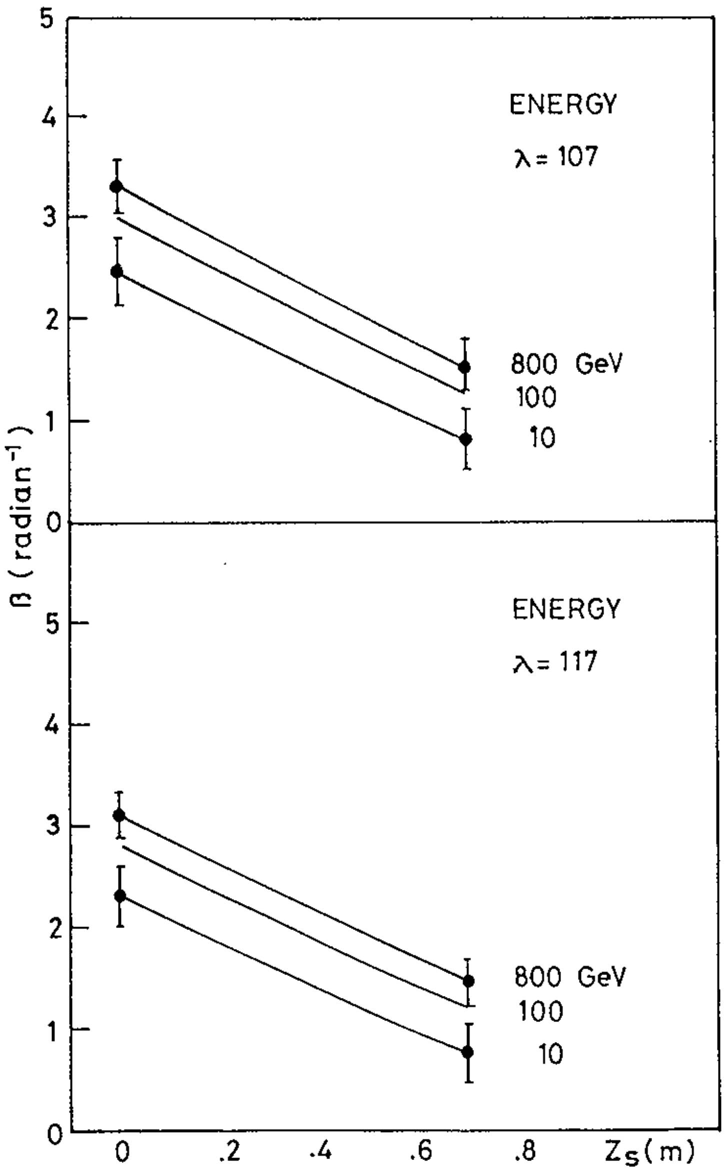

R(m)
800 GeV
CONCRETE SHIELDING
TUNNEL
Z(m)

Fig. 5b


ENERGY
λ = 107
800 GeV
100
10
ENERGY
λ = 117
800 GeV
100
10
β (radian⁻¹)
0
1
2
3
4
5
0
.2
.4
.6
.8
Zs (m)

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