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NEUTRON AND MUON SHIELDING CALCULATIONS FOR STORAGE RINGS HERA AND PETRA

by

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Abstract

Dose equivalent due to neutrons and absorbed dose due to muons from proton-electron storage rings HERA and PETRA have been estimated by Monte Carlo codes CASIM and CASIMU and an analytical code MUSTOP.

Dose dependence on target size and incident proton energy has also been investigated. Brief description on the computer codes is given.

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Introduction

HERA storage ring facility aims at studies in elementary particle physics through lepton-hadron interaction. Its details can be seen in one of the publications for its proposal [1]. The HERA ring tunnel, which will be 6.3 km long and buried some 10 - 20 m from the ground surface, installs two storage rings, one for 820 GeV/c protons and the other for 30 GeV/c electrons. Existing electron-positron storage ring PETRA will be used as an injector to the HERA ring and accelerate protons up to 40 GeV/c in the same vacuum tube as for electrons and positrons.

Environmental radiation safety studies against the beam from HERA have been reported by Dinter and Tesch [2]. In their work they have estimated the doses from neutrons and muons by analytical calculations. Since then some Monte Carlo (MC) codes have become usable at DESY for dose estimation due to hadrons and muons. Moreover, some machine parameters have been given further in detail. These facts have made us reconsider some of the previously calculated results.

In the present work we have used hadron cascade MC code CASIM for estimating the dose equivalent due to neutrons and its muon part (CASIMU) and an analytical code MUSTOP for muon problems. Brief description of these codes is given in the next chapter.

Simple geometries have been chosen throughout this paper because of the simplicity in calculation, and the whole protons have been assumed to impinge on a cylindrical target at the center. The total number of protons filled in the HERA main ring is expected to be 6.3×10^{13}, thus the calculated results concerning the HERA ring are given per 1×10^{14} protons incident on a target. For PETRA ring the filling condition is more complicated and the results are given per one incident proton. In application of these results to the actual problems, the data of beam loss is necessary.

This report presents simply the results of shielding calculations and it is not concerned with any safety aspects aroung the accelerators. Simple geometries in the calculation are not indicating that we think such situations are realistic or physically and technically possible.

2. Some remarks on the computer codes

Although the computer codes used here are well known among some people in the radiation protection groups in high energy physics laboratories, no descriptions on the codes have been officially published so far. Thus, a brief explanation of each code, including some of its physical background, is given below.

2.1 CASIM

CASIM is a MC code developed by Van Ginneken [3] in the Fermi Lab in order to study the average development of internuclear hadronic cascades when high energy hadrons (protons, neutrons or pions) are incident on large targets or shields. The program outputs such concerns as star densities (i.e. number of strong interaction per cm^3), momentum spectra of interacting particles and energy deposited by the cascades.

2.1.1 Physical background of CASIM

CASIM is based on the thermodynamical model of Hagedorn and Ranft [4]. The thermodynamical model has been formulated only for p-p collisions. A number of parameters in the model were determined by empirical fits. A discussion of Ranft [5] on the p-nucleus collision has been included in the code. The program includes low energy component representing knock-out nucleons based on the fact that nuclear effects seem to be significant only for low energy secondaries. In addition such nuclear effects as excitation and binding energy are approximately taken into account.

The particles concerned in the program are nucleons and pions. No distinction is made between π^+ and π^-. The π^0 are not considered in the propagating cascade, but they are taken into account in calculating energy deposition. Kaons and other less frequently produced particles are not implicitly included.

The star densities in CASIM pertain only to the particles exceeding a certain threshold energy, typically 0.3 GeV/c, below which hadrons are not followed. The value of this cut-off energy, however, is important to determine the conversion factors for star densities to the dose equivalent. To include such low energy contributions and obtain the dose equivalent from the calculated star densities with CASIM, a following technique is applied.

According to calculations from ORNL, it can be said that the shape of the spectrum for low energy particles is rather independent of the location within the shield, incident energy or even shielding material (as long as the hydrogen content is essentially the same). Based on this fact, the kinetic energy spectrum of hadrons calculated by Gabriel and Santoro [6] is assumed to be representative of an equilibrium spectrum. It is fitted to the spectrum around 300 MeV/c in order to take into account the low energy particle effect that is not included in CASIM and finally to obtain the dose equivalent.

Above mentioned features are described more in detail in ref. 7. The resulting conversion factor of star density (stars/cm^3) to dose equivalent (rem) varies more greatly with radial location than forward location since the cascade develops almost uniformly in the forward direction.

Graphs in ref. 7 depict conversion factors as a function of radius at several depth ranges for incident protons of 30 GeV/c and 1000 GeV/c. Those factors for radial positions at larger distances than 50 cm from the beam axis can be taken as almost constant. Furthermore, the lateral distances at which we are interested in the dose calculations are far larger than this border. Based on these facts the conversion factor of (the total) star densities in concrete and sand to the dose equivalent is chosen as $9.0 \cdot 10^{-6}$ rem $\cdot$ $star^{-1} \cdot cm^3$ in this paper. (Quality factor QF = 6.)

2.1.2 Geometry used in CASIM (and CASIMU)

The geometry used for CASIM (and CASIMU) in the present report is so called "cave geometry" and is depicted in fig. 10. It is cylindrically symmetric and a solid target is located along the center line of a cave. Beam profile of a Gaussian form can be specified but the beam must hit the target on the face.

The whole structure is divided into 2500 volume bins delineated by 50 equally spaced depths and 50 equally spaced radii. The output star densities, as well as deposited energies, are given in each bin.

Because of such a simple geometry that CASIM (and CASIMU) can handle, the dose calculation with these codes usually needs some geometrical and physical simplifications of the actual problem.

2.1.3 Dependence of dose equivalent on target size and incident proton energy

Neutron dose equivalent to be calculated is dependent on the target size. As an example Fig. 2a $\sim$ c shows the dose equivalent obtained with CASIM as a function of iron target radius at a radial position of 2 m from the target. The tunnel radius is 1.5 m, and 0.5 m concrete shield lies between the target and this position. The proton momentum incident on the target is 7.5, 40, and 820 GeV/c, respectively. The target length is 50 cm for 7.5 GeV/c and 40 GeV/c and 2 m for 820 GeV/c. The prints represent the maximum dose equivalent along the longitudinal distance.

The figure shows that the maximum dose is achieved at radius 5 $\sim$ 10 cm for all cases. Partly from this fact the target radius has been fixed to 10 cm in almost all calculations in this paper.

Figs. 3 and 4 depict the neutron dose equivalent calculated with CASIM at a radial distance 2 m (0.5 m concrete shield) and 3 m (1.5 m concrete), respectively, as a function of the proton energy incident on iron target. Open circles are for 10 cm radius x 2 m and 0.5 m long targets and closed circles are for the 3 m long target with the same radius.

Liu et al [8] have recently summarized experimental values of the Moyer model parameter H_o which describes the energy dependence of the neutron dose equivalent behind a shield on primary energy of protons incident on an arbitrary target.

In equation H_o is expressed as

$$H_o = C \cdot E^m \quad . \qquad (1)$$

Their regression analysis has given a best value for the exponent m of 9.77 ± 0.26, but has not rejected m = 1 (with probability 20%).

Above calculations by CASIM with 3 m long target give for the same parameter m = 0.88 at radius 2 m (0.5 m concrete shield, Fig. 3) and m = 0.92 at radius 3 m (1.5 m concrete shield, Fig. 4). The value of the parameter m is smaller when shorter target is used, where cascades are not fully developed (open circles in Fig. 4).

2.1.4 Comparison of dose equivalent calculated by CASIM with semiempirical estimates

Based on some experimental data Tesch [9] has recently given some values for the parameters in the simple expressions describing the dose equivalent near a point source and a line source. He estimates the dose equivalent H from a point source at a point around 90^o from beam axis as follows:

$$H = 8.3 \cdot 10^{-6} \frac{L}{\gamma^2} e^{-\frac{d}{\lambda}} \qquad (2)$$

where
- H is the dose equivalent in mrem
- L is the primary proton energy in GeV
- γ is distance from the target in cm
- d is the shield thickness in $g \cdot cm^{-2}$

The parameter λ is given as:

$\lambda = 110\ g \cdot cm^{-2}$ for sand and ordinary concrete

$\lambda = 135\ g \cdot cm^{-2}$ for heavy concrete (density: $3.7\ g\ cm^{-3}$)

Comparison between the values calculated with CASIM and those estimated by above semiempirical formula has been made for many cases, and the results are listed in Table 1. The values obtained with CASIM are means in several runs in the maximum region along the longitudinal direction at a fixed radius. Errors indicate one-third of the value from the mean to the maximum on the minimum at that point.

The ratios of doses calculated by CASIM to those obtained by the semiempirical equation are given in the last column of the same table. They show that both corresponding values agree with each other within a factor of 5, the mean value of the ratio is 1.5. The agreement seems somewhat better in the cases with primary proton momentum of 40 GeV/c, where 1 m long target might be the optimum size to develop fully the hadron cascade within itself.

2.1.5 Comparison with measurements at 350 GeV

In order to show a validity of CASIM calculations, Cossairt et al [10] have made some measurements of absorbed dose rate using tissue equivalent and proportional chambers. Several test cases involving lateral concrete and soil shield up to 660 cm were selected, and the primary proton beam at 350 GeV was dumped on several types of target. They have compared their measured values with CASIM calculations, and they concluded that the code can predict absorbed dose within a factor of about 3 in situations where geometry and beam loss mechanism are well understood.

2.2 CASIMU

The so called CASIMU [11] is the muon part of CASIM. Therefore, the physical background for simulating the development of hadron cascades is the same as in the latter. It would, however, be worthwhile to mention to some extent the mechanism of the muon production in the code. The geometry that CASIMU can handle is the same as CASIM.

2.2.1 Physical background of CASIMU

Muons around high energy proton accelerators are produced mainly through the decay of pions and kaons generated by the interaction of the incident protons with nuclei or through these direct interactions. The muons originating from the former are called decay muons and those from the latter prompt muons.

As mentioned just above, CASIMU is the muon section of the MC code CASIM. Similar to CASIM, the program CASIMU handles the internuclear cascade that occurs throughout the entire volume within the problem boundaries. It includes both prompt muons as well as decay muons from pions and kaons. Muon yield is determined by an empirical formula [12]. As for the material data needed in the program, the parameters compiled by Grote, Hagedorn and Ranft [13] are used.

A conversion factor of $3.2 \cdot 10^{-9}$ mrem per one muon $\cdot$ m^{-2} has been used throughout this paper. This value is in good agreement with the value suggested by Stevenson [14].

2.2.2 Dependence of absorbed dose on target size

Figs. 5 - 8 show the absorbed dose calculated with CASIMU due to muons produced by 820 GeV/c protons on aluminum target of various sizes. Tunnel radius is 1.2 m and shield material is sand of density $1.6\ g \cdot cm^{-3}$. The graphs are given at several radii. Error bars indicate statistical fluctuation (standard error) around each mean value.

The nuclear interaction length for Al is $106.4\ g \cdot cm^{-2}$ (39.6 cm). In the case of 30 cm long target (Fig. 5) the cascades are not fully developed and the absorbed dose due to muons at any position is smaller than that in the case of 1 m long target (Fig.6). If we compare the cases for 1 m and 10 m long target with the same 10 cm radius (Figs. 6 and 7), the dose in the latter case is much higher than the former case near the target regions but it decreases drastically as a function of longitudinal distance. This feature is explained by the fact that in such a long target the pions produced in the forwardly developed cascades are self-absorbed by the target (captured by target atoms) thus generating less muons. If the target radius is as large as 0.5 m (Fig. 8) the dose near the target is also suppressed.

2.2.3 Comparison with experimental values

A comparison between measurements of muons at 10, 15 and 19 GeV/c and MUSTOP (see next section) calculations has been made by Höfert and Yamaguchi [15] at CERN. The measurements were carried out using high pressure filled argon chambers aligned in the beam axis behind iron and concrete shields.

The result is reproduced in Fig. 9, where the values recently calculated by the author with CASIMU are added. They show excellent agreement with each other.

2.3 MUSTOP

MUSTOP is an analytical program originating from Keefe and Nohle [16] and modified by Stevenson [17] to improve the running time, to increase the options available such as production formula, geometries, etc., and to make the input easier.

2.3.1 Muon production in MUSTOP

In MUSTOP muons are considered to be the decay products of pions (contribution from kaon decay is not included).

The pi-mu decay length is taken to be the distance between the target and the shield. When there is no target and the protons impinge directly on a shield, only the first pions generated in the initial layers of the shield are considered and the decay length available to the pions is assumed to be 1.8 times of the interaction mean free path of pions in the shield (in Fe i.m.f.p. $\sim$ 17 cm). Prompt muons are not considered in the code.

Ranft formula [18] has been chosen in the code for muon production throughout the calculations presented here. The formula agrees with the predictions of the thermodynamical model and has the correct Feynman scaling behaviour.

2.3.2 Geometry used in MUSTOP

Two types of geometrical situations are existing in MUSTOP: 1) backstop (beamstop) geometry (Fig. 1b), and 2) tunnel geometry (Fig. 1c).

Target length is about one nuclear interaction mean free path in the target material. Only one shielding material is allowed in MUSTOP.

2.3.3 Dependence of absorbed dose on target material

Fig. 10 shows the absorbed dose calculated with MUSTOP due to muons produced from protons of various energies incident on copper and berillium target as a function of distance from the target at radius 3.2 m. The tunnel geometry was used with 1.2 m tunnel radius. The shield was 2 m sand. The dose is normalized to 10^{14} incident protons.

No significant differences have been found in the muon absorbed doses between Cu and Fe target. For Al target the dose is slightly ($\lesssim$ 20%) smaller.

2.3.4 Comparison with experiment

As mentioned in sub-section 2.2.3 MUSTOP calculation has shown a very good agreement with measurement in the beam axis in the forward direction.

3. HERA ring

The HERA ring tunnel will be built at least 10 m under the ground surface in order to shield secondary particles produced internuclear cascades of protons that are lost in the tunnel and interacting with various machine components inside as well as the shielding materials outside.

3.1 Dose equivalent due to neutrons

3.1.1 Neutron dose above the tunnel

The surface dose equivalent 10 m above the HERA tunnel calculated with CASIM is given in Fig. 11 as a function of longitudinal distance from the target. The dose is expressed in mrem per 10^{14} protons incident on 10 cm radius x 2 m long iron target. The incident proton energy was 820 GeV. The target radius was determined assuming shielding effects by one of the HERA dipole magnets. The tunnel radius was 1.6 m and the shielding material was sand of density 1.6 g $\cdot$ cm^{-3}. The error bars indicate statistical fluctuation (standard deviation) in several program runs with different random number generation seeds. The data points carrying the bars represent a total of 50 equally separated longitudinal points.

The dose equivalent takes the maximum value of 0.04 mrem per 10^{14} incident protons at a longitudinal distance of 5 m. Only neutrons contribute to the dose after passing through such a thick shield.

3.1.2 Neutron dose in HERA experimental hall

The basic shielding in the HERA experimental hall at a location where no detector is installed is made with 2 m thick heavy concrete of density 3.65 g $\cdot$ cm^{-3}. Fig. 12 shows the dose equivalent calculated with CASIM for 820 GeV/c incident proton momentum as a function of longitudinal distance at 4 m radial distance. The target face is 3 m inside the tunnel entrance.

The dose equivalent curve shows maximum at about 3.5 m from the proton impinging point.

Another situation to be considered in the HERA experimental hall is the dose equivalent in the pass-through tunnel that is planned on both sides of the hall for persons to cross under the beam line to the other side of the hall (see Fig. 13). The ceiling of the tunnel will be made of 1.9 m heavy concrete, while the outside walls, part of the building walls, are made of normal concrete.

CASIM was used to estimate the dose equivalent under the ceiling and on the floor of the pass-through tunnel. Since the code can handle only such a simple situation as the cave geometry (see sub-section 2.1.2), the tunnel radius in the calculation was chosen as 0.6 m which is equal to the distance from the beam axis to the top of the ceiling of the pass-through tunnel. The target was 9.2 cm radius x 2 m long iron cylinder.

Fig. 14 depicts the results of the calculation. Radius 4.5 m corresponds to a position on the floor of the pass-through tunnel, or of the experimental hall. In each curve the maximum of the dose equivalent is seen at 3 $\sim$ 4 m from the target face.

3.2 Absorbed dose due to muons

3.2.1 Muon dose above the HERA tunnel

The absorbed dose due to muons 10 m above the HERA tunnel was calculated with MUSTOP. The Monte Carlo code CASIMU was not used for this case because of bad statistics at such a long radial distance.

The first situation that we have to consider is the case where one of the dipole magnets in the tunnel can be a muon producing source. MUSTOP was run with its tunnel geometry (Fig. 1c). The target was Cu, and tunnel radius was 0.86 m, which is equal to the distance between the HERA proton dipole magnet and the tunnel ceiling. The shield was sand of density 1.6 g $\cdot$ cm^{-3}.

The result is given in Fig. 15. The dose increases rapidly up to a distance of 100 m, then reaches almost an equilibrium state.

The second situation is concerned with a contribution from vertically deflecting magnets for protons in the tunnel. Two deflector magnets shall be located at about 50 m and 170 m downstream of each experimental hall. The proton beam axis between these magnets makes an angle of 7.44 mrad with respect to the tunnel axis (see Fig. 16). The absorbed dose above the tunnel due to decay muons generated from pions produced by the interactions of lost protons with the deflector magnet at 170 m was estimated using MUSTOP with its backstop geometry (Fig. 1b). Deflection of pions and muons by the magnet was not taken into account. The decay length d is the distance between the magnet and the tunnel ceiling along the extrapolated proton trajectory, and now d = 190 m was assumed. Since the tunnel is not constructed horizontally, the effective thickness, D, of the soil shielding is different from one place to another.

Fig. 17 shows the muon dose calculated with MUSTOP as a function of depth in the soil (density 1.6 $g \cdot cm^{-3}$). The abscissa indicates the effective thickness D and the corresponding radial thickness in m. At radial distance of 10.5 m muons produced from 820 GeV/c reach their maximum range.

3.2.2 Muon dose in the HERA experimental hall

The distance between the proton beam and the tunnel wall is different from one point to another in the tunnel. In the following calculations this distance is chosen as 1.2 m independent of the position inside the tunnel (see sub-sections 2.1.2 and 2.3.2).

Fig. 18 depicts the muon absorbed dose calculated by CASIMU and MUSTOP at various radial positions as a function of distance from the target. In both calculations the tunnel (or cave in CASIMU) geometry was used. Tunnel radius was 1.2 m and the shielding material was sand (density 1.6 g $\cdot$ cm^{-3}). Target was Cu cylinder of 10 cm diam. x 1 m long.

Discrepancies between CASIMU and MUSTOP calculations are fairly large near the target region where radial development of the hadron cascade plays an important role. They are explained by the fact that in MUSTOP only the pions generated by the primary interactions of the incident protons are concerned and that the prompt muons are not taken into account.

With present energy of the incident protons MUSTOP calculations show gradual increase in the absorbed dose as a function of distance from the target up to 160 m, while CASIMU calculation gives somewhat maxima in the dose at longitudinal positions around 20 m for radius 2 - 5 m. This feature is more prominent when the target is larger because of the self-absorption of the forwardly developed hadron cascades by the target.

The values of both calculations come closer at larger distances from the target. The result of ref. 15 confirms this, where muons were measured along the extrapolated beam axis and the agreement among the measurements and calculations by MUSTOP and CASIMU was excellent.

4. PETRA ring

The existing PETRA electron-positron storage ring will be used as a proton accelerator for HERA leaving the magnets as they are. PETRA will accelerate proton injected at 7.5 GeV/c up to 40 GeV/c. The PETRA ring is partly buried underground and partly shielded by soils. The similar dose calculations done for the HERA ring against neutrons and muons were performed for the PETRA ring as well.

4.1 Dose equivalent due to neutrons

Figs. 19 - 22 show the absorbed dose equivalent calculated by CASIM as a function of longitudinal distance at several radial positrons for 7.5 GeV/c and 40 GeV/c incident protons. The target was Fe of 20 cm diam. x 1 m long located 1 m from the entrance of the tunnal of 1.5 m radius. The shielding material was sand (density: 1.6 g · cm^{-3}) or normal concrete (density: 2.35 g · cm^{-3}).

4.2 Absorbed dose due to muons

4.2.1 Muon dose above the PETRA tunnel

MUSTOP was run for Cu target and 40 GeV/c incident protons to estimate the absorbed dose due to muons coming out through the 3 m sand shielding above the PETRA tunnel. The problem was treated with two geometries, i.e. tunnel geometry and backstop geometry, as for the HERA ring.

Fig. 23 shows the absorbed dose due to muons as a function of distance from the target at a radius of 4.25 m or 3 m sand shield calculated with tunnel geometry. The graph shows a prominent peak at a distance around 20 m.

The PETRA tunnel is not straight and the pions produced by the interaction of protons with accelerator components decay into muons while they are running towards the tunnel wall. This case was treated with backstop geometry. The decay length was assumed as the distance between the target and the point where the tangential line at the target of the proton beam hit the wall (see Fig. 24).

The result is given in Fig. 25 as a function of the distance from the point of the tunnel wall above mentioned. The curve also indicates maximum at a distance around 18 m which is at a radial distance of 70 cm from the tunnel wall.

The problems were handled with CASIMU as well, but the bad statistics in the results have refrained us from reproducing the data.

4.2.2 Muon dose beside the PETRA tunnel

Muons produced in front of a dipole magnet will be deflected by the magnetic field as shown schematically in Fig. 26. Assuming two dimensional behaviours, the muon trajectories can be grouped as follows:

A: Muons fly straight and hit the tunnel (1).

B: When muons hit the return yoke of the magnet, positive muons are diverged towards outside of the ring (2), while negative muons towards center of the ring (3).

C: When muons enter the magnet gap at its field center, negative muons are diverged towards outside of the ring but after they hit its return yoke, they are converged back to the other direction twice as strongly as before (because magnetic field in the return yoke is in the opposite direction and twice as strong as that between the magnet gap) (4). While positive muons are deflected towards the center of the ring (5).

D: Muons fly straight and hit the tunnel wall (6).

Fig. 27 shows the momentum spectra for positive muons calculated by MUSTOP at various angles from the beam axis which correspond to the angles in the above grouping of the muon behaviour. Negative muon spectra look similar.

Cases (1) and (6): Muons are not affected by the magnetic field, and high energy muons that are emitted forward can be treated by MUSTOP with its tunnel geometry.

The result is given in Fig. 28. In this calculation 40 GeV/c protons impinge on the iron target, and not only muons corresponding to the present cases (1) and (6) but also all others are included because of the simplicity of calculation. Therefore, the result is far more overestimated as can be understood from the momentum spectrum in Fig. 27.

Case (3): If we consider the muon energy-range relation (Table 2) and particle deflection radius in the magnetic field (4.8 m for 1 GeV/c muon in the air gap) negative muons with energies smaller than 2 GeV/c are stopped in the magnet yoke. Those with higher momentum may escape the magnet yoke converged forward or to the center of the ring tunnel with their momentum degraded up to 1 GeV/c. The former, the forwardly deflected high energy component can be considered as included in the overestimated calculation carried out for the cases (1) and (6) above. The latter has momentum smaller than 1 GeV/c and can be stopped completely by the 6.5 m thick lateral shield of sand (corresponds to 2 GeV/c muon range).

Case (4): The magnetic field inside the yoke is about twice as strong as in the magnet air gap, moreover, the muon momentum is degraded in the yoke. Negative muons whose momentum is less than 3 GeV/c are stopped within the yoke as in the case (3). Those with higher momentum may leave the magnet without hitting the yoke with an angle to the beam axis smaller than 0.08 radian (4.5°). These muons can be considered as included in the calculation for the cases (1) and (6). The muons deflected toward the center of the ring tunnel have momentum less than 1 GeV/c and are stopped by the 6.5 m thick lateral sand shield as those in the case (3).

Case (2): Positive muon momentum spectrum for this case is depicted in curve B in Fig. 27. Depending upon the incident point to the magnet yoke, positive muons 1 $\sim$ 2 GeV/c of their momentum before they excape the yoke. No muons with momentum less than 3 GeV/c can penetrate the shield. If we shift the momentum spectrum B in Fig. 27 by 3 GeV/c toward lower energy side, the intensity is reduced by a factor of 10.

Muons with momentum higher than 3 GeV/c are diverged a very small angle even taking into account the energy loss in the yoke, and therefore they are included in the calculation for the case (1).

Case (5): In this case there is no momentum loss in the magnet structure. As in the previous case muons with less momentum than 2 GeV/c are stopped by the 6.5 m sand shield. Those with the same momentum leave the magnet field with an angle of 0.14 radian (8.5^{o}), thus almost all muons of our interest are forwardly transported. Therefore, we consider this case is included in the calculation for the case (6).

4.2.3 Muon dose outside PETRA experimental hall

Muon dose outside the experimental hall (see Fig. 29) was estimated with MUSTOP and CASIMU. MUSTOP was run with tunnel geometry. Nearer to the beam, the higher the absorbed dose. Table 3 shows the absorbed dose at radius 1.3 m and 3 m.

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References

1) HERA A proposal for a large electron-proton colliding beam facility at DESY, DESY HERA 81/10, July 1981

2) H. Dinter and K. Tesch, Untersuchung über den Schutz der Umwelt gegen Strahlung am Speicherring HERA. DESY HERA 80/04 May 1980

3) A. Van Ginneken, CASIM: program to simulate transport of hadronic cascades in bulk matter FNAL, FN-272 (1975)

4) R. Hagedorn, Suppl. Nuovo Cim. 3, 147 (1965); R. Hagedorn and J. Ranft, Suppl. Nuovo Cim. 6, 169 (1968); H. Grote, R. Hagedorn, J. Ranft, "Atlas of Particle Spactra", CERN, Geneva (1970)

5) J. Ranft, Secondary particle spectra according to the thermo dynamical model. A fit to data measured in p-Nucleus collisions, TUL 36, Karl Marx Univ., DDR (1970)

6) T. A. Gabriel and R. T. Santoro, Calculation of the long lived activity in soil produced by 500 GeV protons, ORNL-TM-3762 and Nucl. Instr. Meth. 95, 275 (1971)

7) A. Van Ginneken and M. Awschalom, High energy particle interactions in large targets: Vol. 1, Hadronic cascades shielding, energy deposition, FNAL Batavia, Illinois, USA

8) K. Liu, G. R. Stevenson, R. H. Thomas and S. V. Thomas, The variation of the Moyer model parameter, H_o, with primary proton energy, LBL-13150 (1982)

9) K. Tesch, Comments on the determination of transverse shielding for proton accelerators, Health physics 44, 79 (1983)

10) J. D. Cossairt, N. V. Mokhov and C. T. Murphy, Absorbed dose measurements external to thick shielding at a high energy proton accelerator: comparison with Monte Carlo calculations, Nucl. Instr. Meth. 197, 465 (1982)

11) A. Van Ginneken, Penetration of prompt and decay muon components of hadronic cascades through thick target, TM-630 Fermi National Accelerator Lab. (1975)

12) A. Van Ginneken, private communication (1983)

13) H. Grote, R. Hagedorn and J. Ranft, The Atlas of particle production, CERN (1970)

14) G. R. Stevenson, Dose and dose equivalent from muons, CERN TIS-RP/099 (1983)

15) M. Höfert and C. Yamaguchi, Measurements of muons at 10, 15 and 19 GeV/c and comparison with calculations, CERN HS-RP/TM/80-42 (1980)

16) D. Keefe and C. M. Noble, Radiation shielding for high-energy muons, UCRL-18117 (1968)

17) G. Stevenson, A users guide to the MUSTOP program CERN HS-RP/TM/79-37 (1979)

18) J. Ranft, CERN Lab. II-RA/71-1 (1971)
G. R. Stevenson, The radiation environment of proton accelerators and storage rings, CERN 76-04 (1976)

19) C. Richard-Seere, Evaluation de la perte d'energie unitaire et du parcours pour des muons de 2 a 600 GeV dans un absorbant quelconque, CERN 71-18 (1971)

20) P. M. Joseph, Range energy tables for high energy muons, Nucl. Instr. Meth. 75, 13 (1969)

Table 1 Comparison of the dose equivalent calculated by CASIM with that estimated by the semiempirical equation in ref. 9

Case no.	Primary proton momentum (GeV/c)	Fe target size		Distance from target (m)	Shielding		Dose equivalent (mrem/proton)		Ratio I/II
		Radius (cm)	Length (m)		Material	Thickness (m)	I. CASIM (max)	II. Tesch (ref. 9)	
1	820	10	2	11.6	Sand	10	$(4.0^{+1.0}_{-0.8})\ 10^{-16}$	$2.4 \cdot 10^{-15}$	0.2
2	820	9.2	2	2.5	Concr	1.9	$(1.5^{+3.0}_{-0.9})\ 10^{-9}$	$1.9 \cdot 10^{-9}$	0.8
3	820	9.2	1	2.5	Concr	1.9	$(3.8^{+3.2}_{-1.7})\ 10^{-9}$	$1.9 \cdot 10^{-9}$	2
4	820	9.2	2	4.9	Concr	4.3	$(1.4^{+1.6}_{-0.9})\ 10^{-11}$	$2.9 \cdot 10^{-12}$	5
5	820	9.2	1	4.9	Concr	4.3	$(8.5^{+6.0}_{-1.5})\ 10^{-12}$	$2.9 \cdot 10^{-12}$	3
6	820	9.2	2	4.5	Concr	3.9	$(1.1^{+8.5}_{-0.6})\ 10^{-11}$	$8.1 \cdot 10^{-12}$	1.4
7	820	9.2	2	2.5	heavy Concr	1.9	$(4.2^{+2}_{-1.8})\ 10^{-10}$	$7.2 \cdot 10^{-10}$	0.6
8	820	9.2	2	4.9	heavy Concr	4.3	$(7.0^{+3}_{-3})\ 10^{-14}$	$3.3 \cdot 10^{-13}$	0.2
9	40	10	1	4.5	Sand	3.0	$(9^{+6}_{-3})\ 10^{-12}$	$2.0 \cdot 10^{-11}$	0.5
10	40	10	1	7.5	Sand	6.0	$(7^{+3}_{-2})\ 10^{-14}$	$1.0 \cdot 10^{-13}$	0.7
11	40	10	1	2.0	Concr	0.5	$(2.4 \pm 0.2)\ 10^{-9}$	$2.7 \cdot 10^{-9}$	0.89
12	40	10	1	3.0	Concr	1.5	$(1.2^{+0.3}_{-0.1})\ 10^{-10}$	$1.4 \cdot 10^{-10}$	0.86
13	40	10	1	4.5	Concr	3.0	$(2.2^{+1.2}_{-0.9})\ 10^{-12}$	$2.2 \cdot 10^{-12}$	1.0
14	7.5	10	1	3.0	Sand	1.5	$(8.5^{+0.5}_{-1.0})\ 10^{-11}$	$7.0 \cdot 10^{-11}$	1.2
15	7.5	10	1	4.5	Sand	3.0	$(3.2^{+0.6}_{-0.6})\ 10^{-12}$	$3.4 \cdot 10^{-12}$	0.94
16	7.5	10	1	6.5	Sand	5.0	$(8^{+2}_{-3})\ 10^{-14}$	$9.5 \cdot 10^{-14}$	0.84
17	7.5	10	1	2	Concr	0.5	$(6.0^{+0.5}_{-0.5})\ 10^{-10}$	$4.6 \cdot 10^{-10}$	1.3
18	7.5	10	1	3	Concr	1.5	$(3.4^{+0.8}_{-0.6})\ 10^{-11}$	$1.4 \cdot 10^{-11}$	2.4
19	7.5	10	1	4.5	Concr	3.0	$(1.4^{+1.4}_{-0.6})\ 10^{-12}$	$3.7 \cdot 10^{-13}$	3.8

Table 2 Range of muons in iron and normal concrete (after refs. 19 and 20).

Energy (GeV)	Range in Fe ($g\ cm^{-2}$)	(m)	Range in sand ($g \cdot cm^{-2}$)	(m)
0.1	43.61	0.06		
0.2	108.8	0.14		
0.5	310.4	0.39		
1	631.2	0.80		
2	1237	1.57	1061	6.63
4	2370	3.01	2048	12.8
6	3551	4.52	2994	18.7
8	4501	5.73	3916	24.5
10	5530	7.04	4822	30.1
20	10450	13.30	9194	57.5
30	15100	19.21	13400	83.8
40	19600	24.94	17500	109

*) Values for muons < 1 GeV are taken from ref. 20

Table 3 Absorbed dose equivalent outside experimental hall in mrem per 40 GeV/c proton incident on Cu target calculated by MUSTOP and CASIMU

Point	Distance from beam axis (m)	Absorbed dose equivalent $(mrem \cdot p^{-1})$	
		MUSTOP	CASIMU
A	1.3	$2.1 \cdot 10^{-12}$	$(3.4 \pm 4.0)\ 10^{-12}$
B	3.0	$3.0 \cdot 10^{-15}$	$(1.2 \pm 0.7)\ 10^{-15}$

Figure Captions

1. Types of the geometry used in the computer codes CASIM, CASIMU and MUSTOP

2. Neutron dose equivalent calculated with CASIM at radial position 2 m (50 cm concrete shield). Target length is 50 cm for 7.5 GeV/c incident protons and 2 m for 40 GeV/c and 820 GeV/c.

3. Neutron dose equivalent calculated with CASIM. Radial distance 2 m (0.5 m concrete shield of density 2.35 g $\cdot$ cm^{-3}).
   Fe target: 10 cm radius x 2 m long (open circles),
   10 cm radius x 3 m long (closed circles)

4. Neutron dose equivalent calculated with CASIM. Radial distance 3 m (1.5 m concrete). Fe target:
   10 cm radius x 0.5 m long (open circles)
   10 cm radius x 3 m long (closed circles)

5. Muon absorbed dose calculated with CASIMU (820 GeV/c) Al target 5 cm radius x 30 cm long. Tunnel radius 1.2 m.

6. Muon absorbed dose calculated with CASIMU (820 GeV/c). Al target 5 cm radius x 1 m long. Tunnel radius 1.2 m.

7. Muon absorbed dose calculated with CASIMU (820 GeV/c). Al target 5 cm radius x 10 m long. Tunnel radius 1.2 m.

8. Muon absorbed dose calculated with CASIMU (820 GeV/c). Al target 0.5 m radius x 10 m long. Tunnel radius 1.2 m.

9. Comparison between measurements of muons at 10, 15 and 19 GeV/c and calculations with CASIMU and MUSTOP (from ref. 15).

10. Muon absorbed dose calculated with MUSTOP for Cu and Be target.

11. Neutron dose equivalent 10 m above the HERA tunnel calculated with CASIM (820 GeV/c).

12. Neutron dose equivalent calculated with CASIM (820 GeV/c). Target is iron. Shield is heavy concrete of density $3.65\ g \cdot cm^{-3}$.

13. Side view of one of HERA experimental halls.

14. Neutron dose equivalent calculated with CASIM (820 GeV/c).

15. Muon absorbed dose calculated with MUSTOP (820 GeV/c).

16. Side view to show schematically the vertically deflecting magnets in the HERA tunnel.

17. Muon absorbed dose calculated with MUSTOP (820 GeV/c). Target is Cu.

18. Muon absorbed dose calculated with CASIMU (dashed lines) and MUSTOP (solid lines) for 820 GeV/c incident protons. Target is 5 cm radius x 1 m long Cu. Tunnel radius is 1.2 m.

19. Neutron dose equivalent calculated with CASIM (7.5 GeV/c). Shield: sand.

20. Neutron dose equivalent calculated with CASIM (7.5 GeV/c). Shield: normal concrete.

21. Neutron dose equivalent calculated with CASIM (40 GeV/c). Shield: sand.

22. Neutron dose equivalent calculated with CASIM (40 GeV/c). Shield: normal concrete.

23. Muon absorbed dose 3 m above PETRA tunnel (MUSTOP: tunnel geometry, 40 GeV/c)

24. Top and side views to show geometry used in MUSTOP calculation.

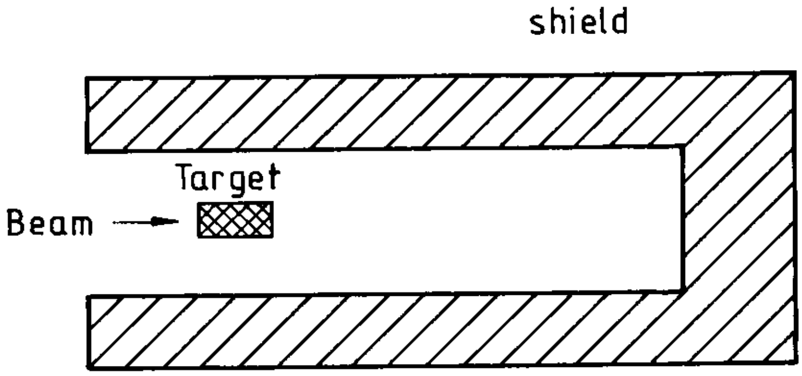
25. Muon absorbed dose 3 m above PETRA tunnel (MUSTOP: backstop geometry, 40 GeV/c).

26. Behaviour of muons deflected by the PETRA dipole magnet field.

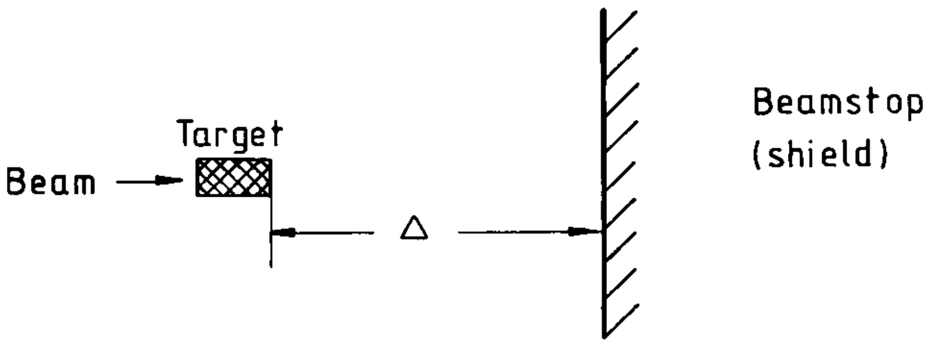
27. Muon momentum spectra at various angles from the beam axis.

28. Muon absorbed dose after 6.5 m sand shield (MUSTOP: tunnel geometry, 40 Gev/c).

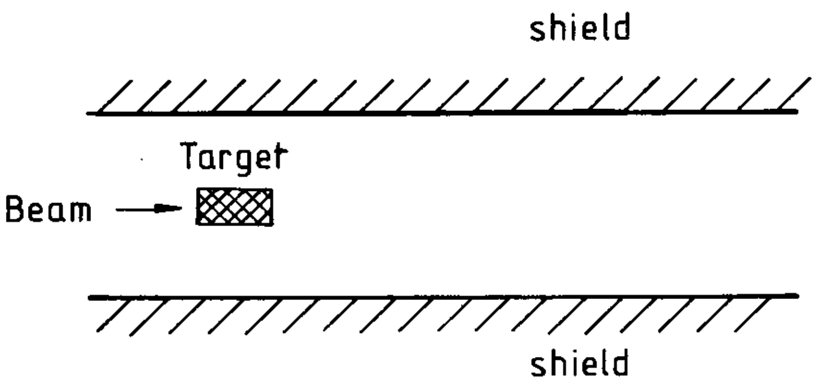
29. Shielding layout around PETRA experimental hall.



a) Cave geometry used in CASIM and CASIMU



b) Backstop (beamstop) geometry used in MUSTOP



c) Tunnel geometry used in MUSTOP

Fig. 1

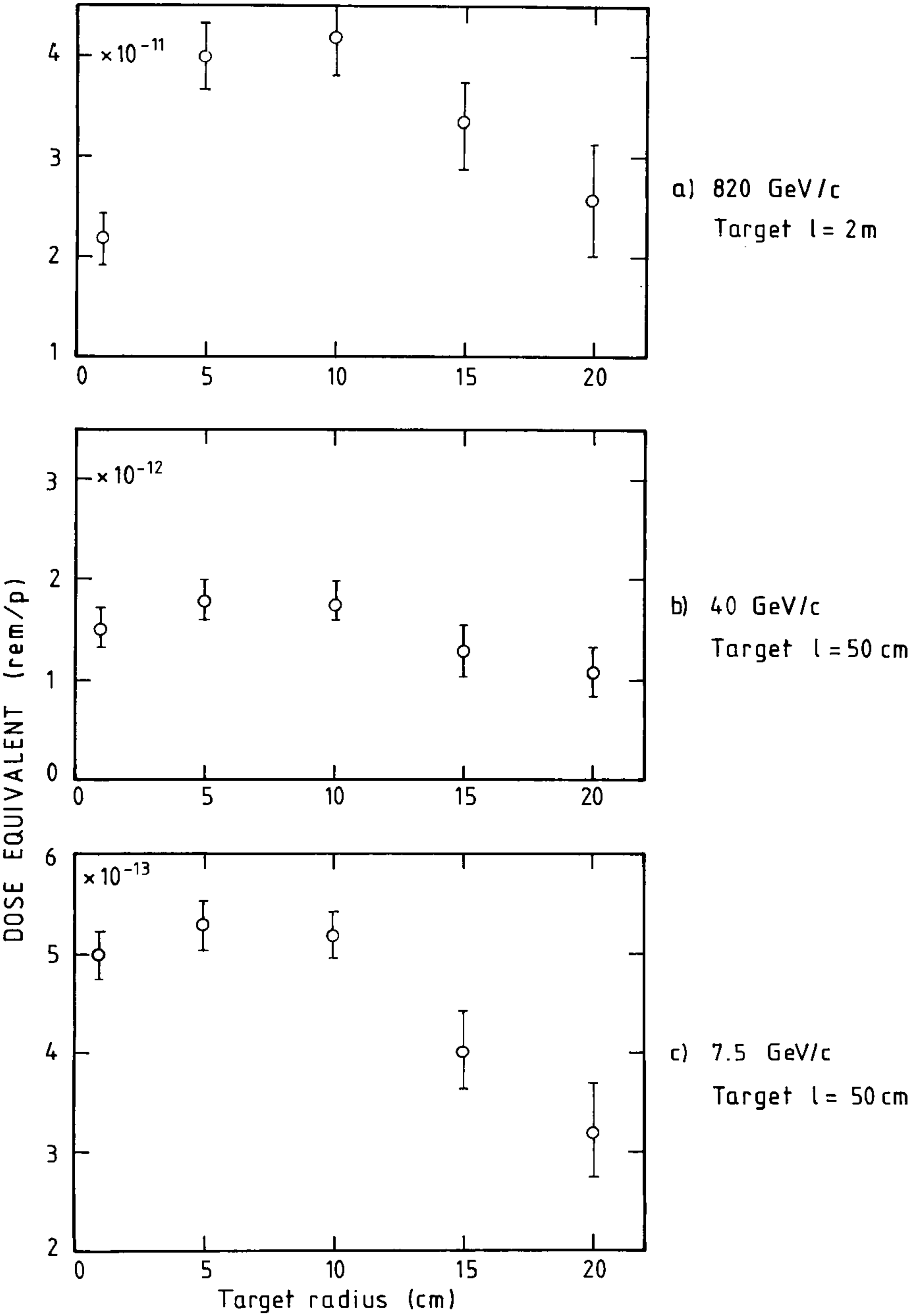

×10^-11
a) 820 GeV/c
Target l = 2m
×10^-12
b) 40 GeV/c
Target l = 50 cm
×10^-13
c) 7.5 GeV/c
Target l = 50 cm
DOSE EQUIVALENT (rem/p)
Target radius (cm)
0
5
10
15
20
1
2
3
4
0
1
2
3
2
3
4
5
6

Fig. 2

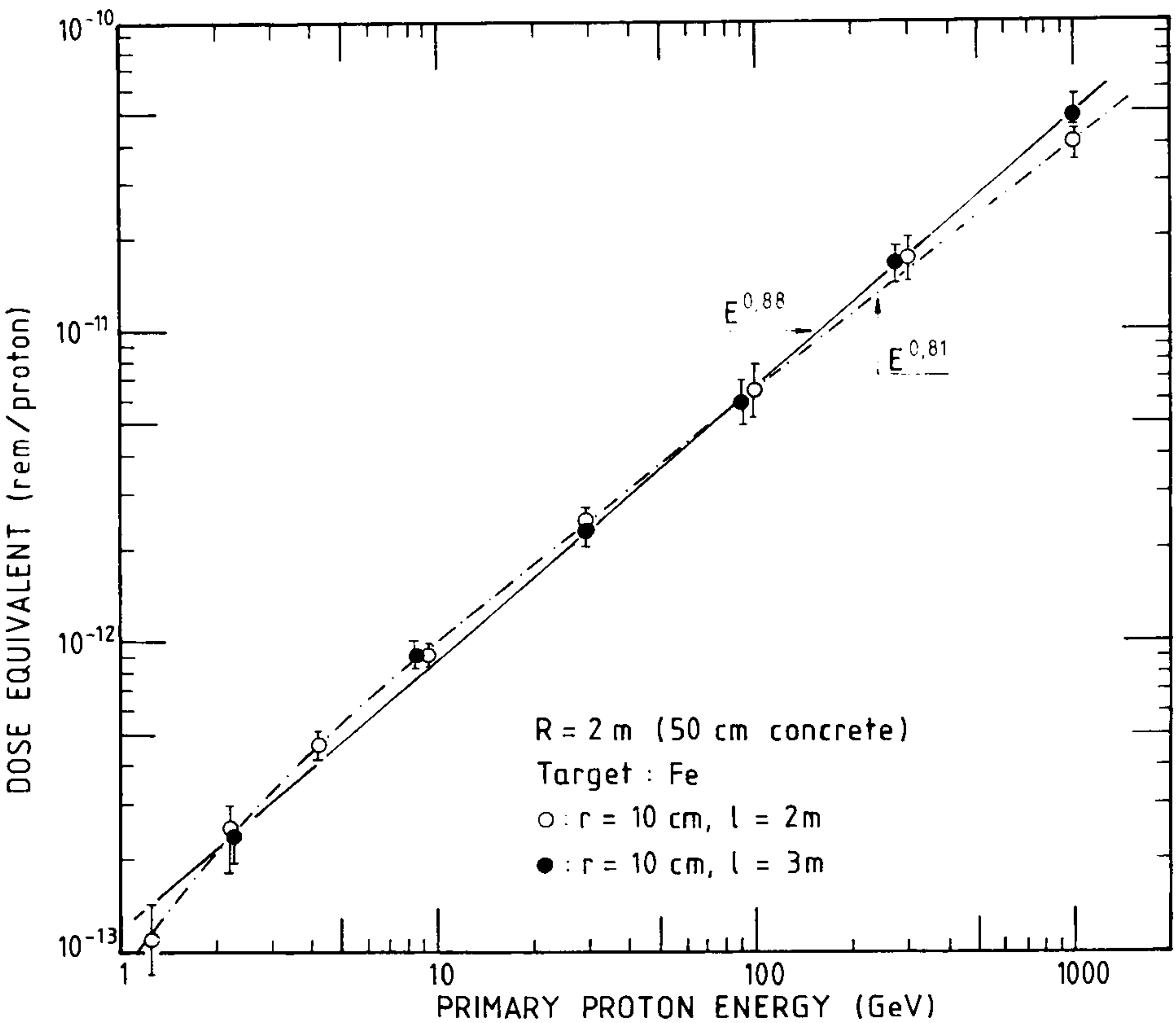
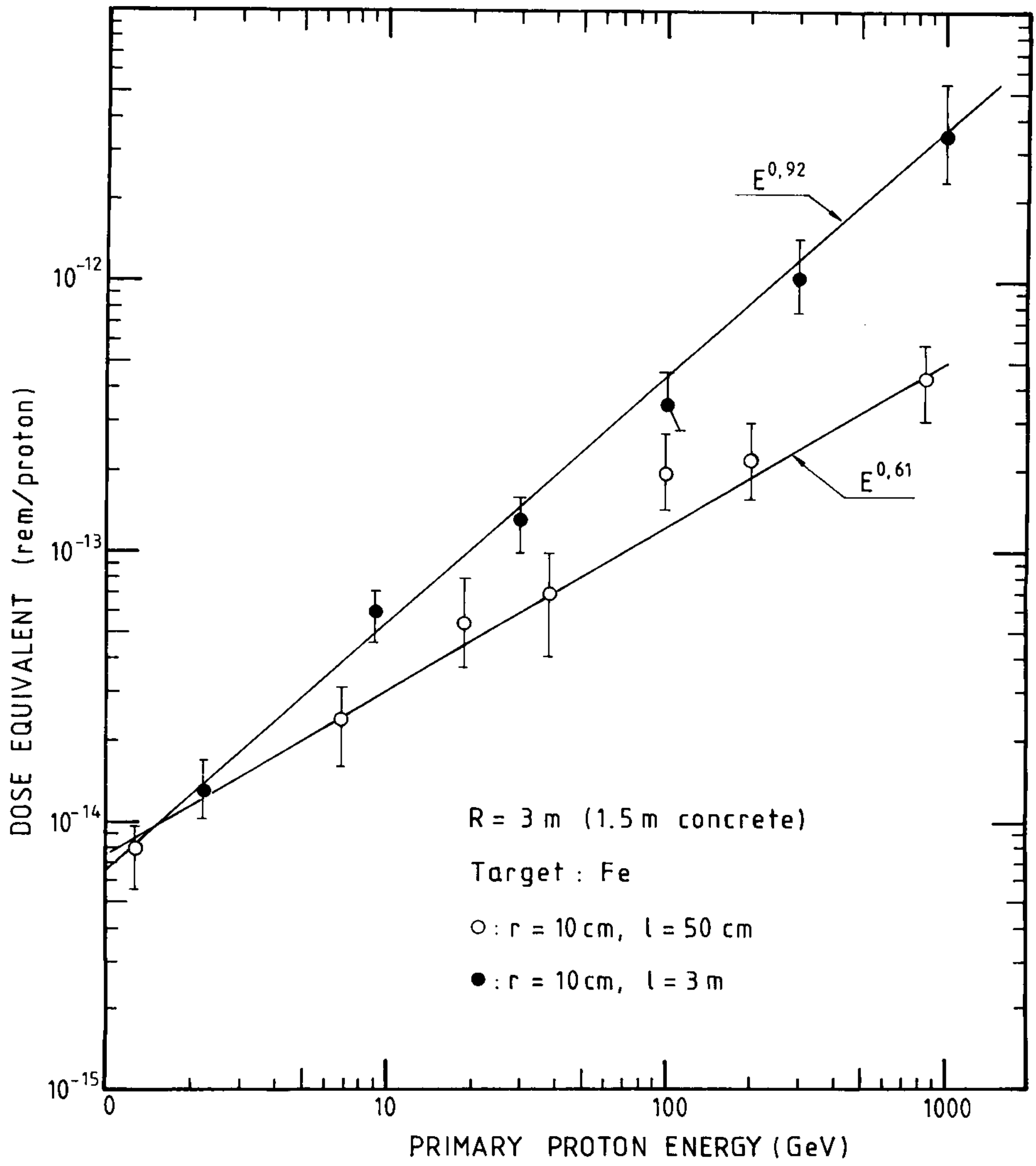

DOSE EQUIVALENT (rem/proton)
PRIMARY PROTON ENERGY (GeV)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1
10
100
1000
$E^{0.88}$
$E^{0.81}$
R = 2 m (50 cm concrete)
Target : Fe
○ : r = 10 cm, l = 2m
● : r = 10 cm, l = 3m

Fig. 3



DOSE EQUIVALENT (rem/proton)
10^-12
10^-13
10^-14
10^-15
0
10
100
1000
PRIMARY PROTON ENERGY (GeV)
E^0,92
E^0,61
R = 3 m (1.5 m concrete)
Target : Fe
○ : r = 10 cm, l = 50 cm
● : r = 10 cm, l = 3 m

Fig. 4

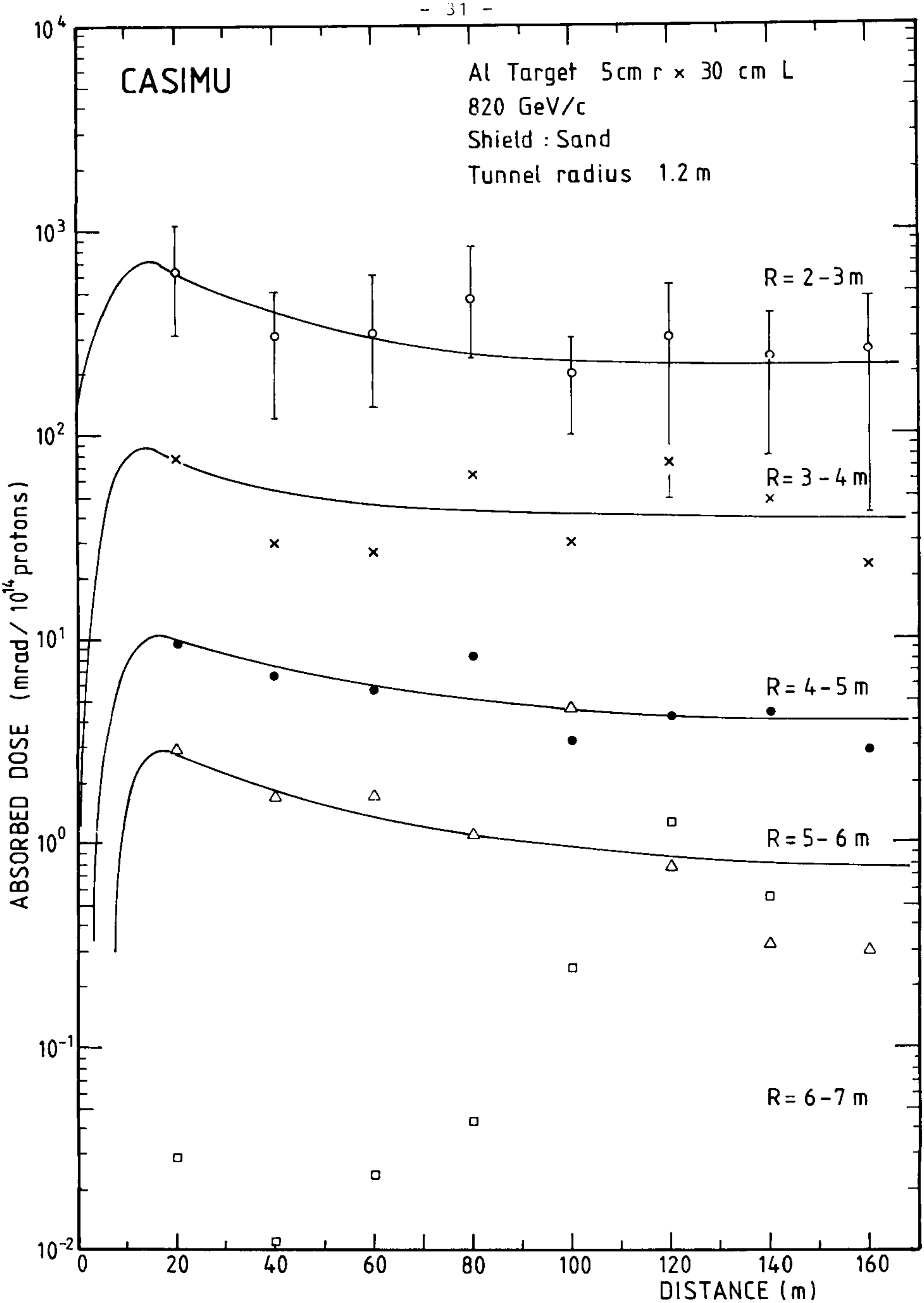

CASIMU
Al Target 5cm r × 30 cm L
820 GeV/c
Shield : Sand
Tunnel radius 1.2 m
R = 2-3 m
R = 3 - 4 m
R = 4 - 5 m
R = 5 - 6 m
R = 6 - 7 m
ABSORBED DOSE (mrad/ 10^14 protons)
DISTANCE (m)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120
140
160

Fig. 5

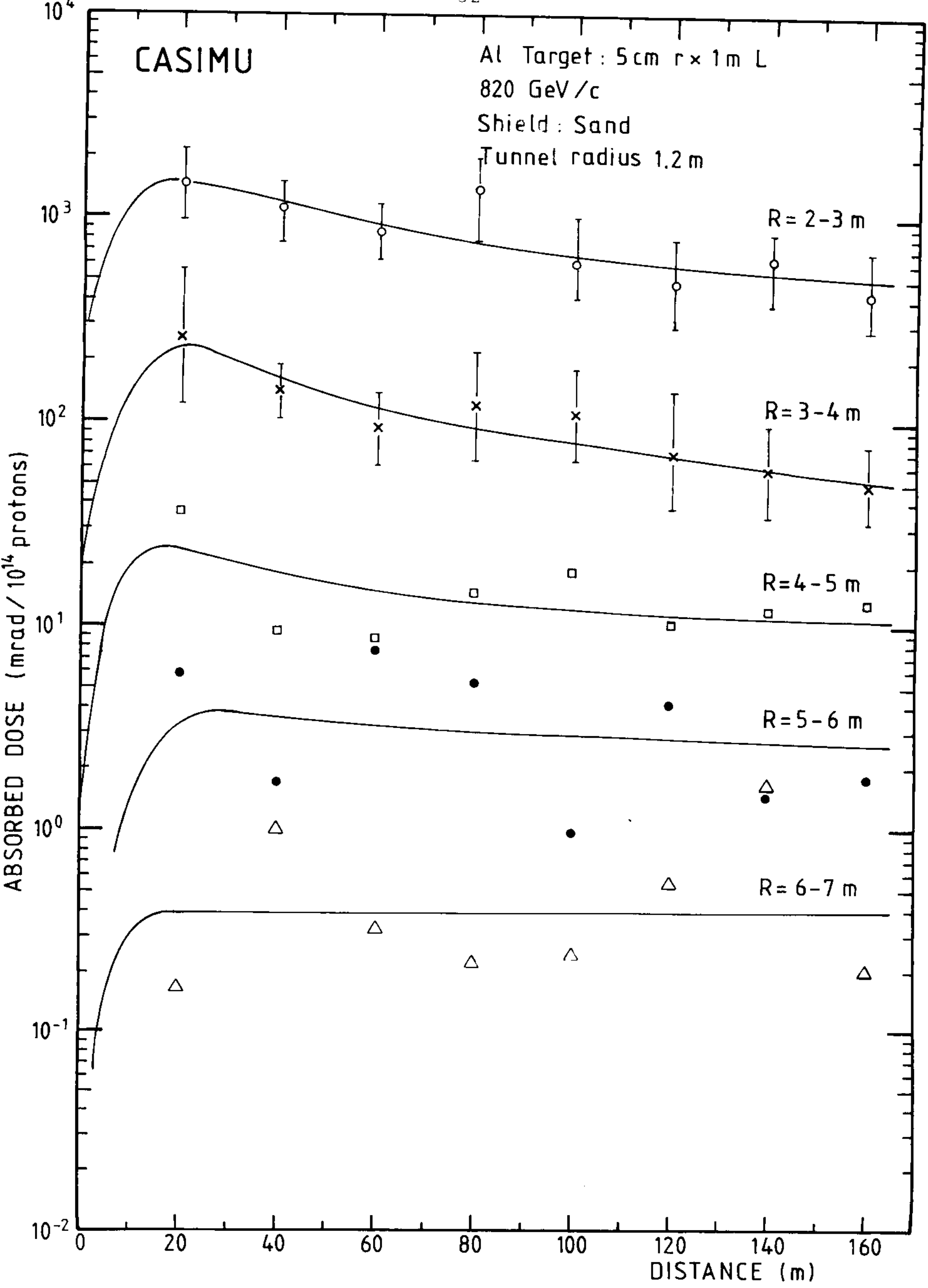

CASIMU
Al Target : 5 cm r × 1 m L
820 GeV/c
Shield : Sand
Tunnel radius 1.2 m
R = 2-3 m
R = 3-4 m
R = 4-5 m
R = 5-6 m
R = 6-7 m
ABSORBED DOSE (mrad/10^14 protons)
DISTANCE (m)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120
140
160

Fig. 6

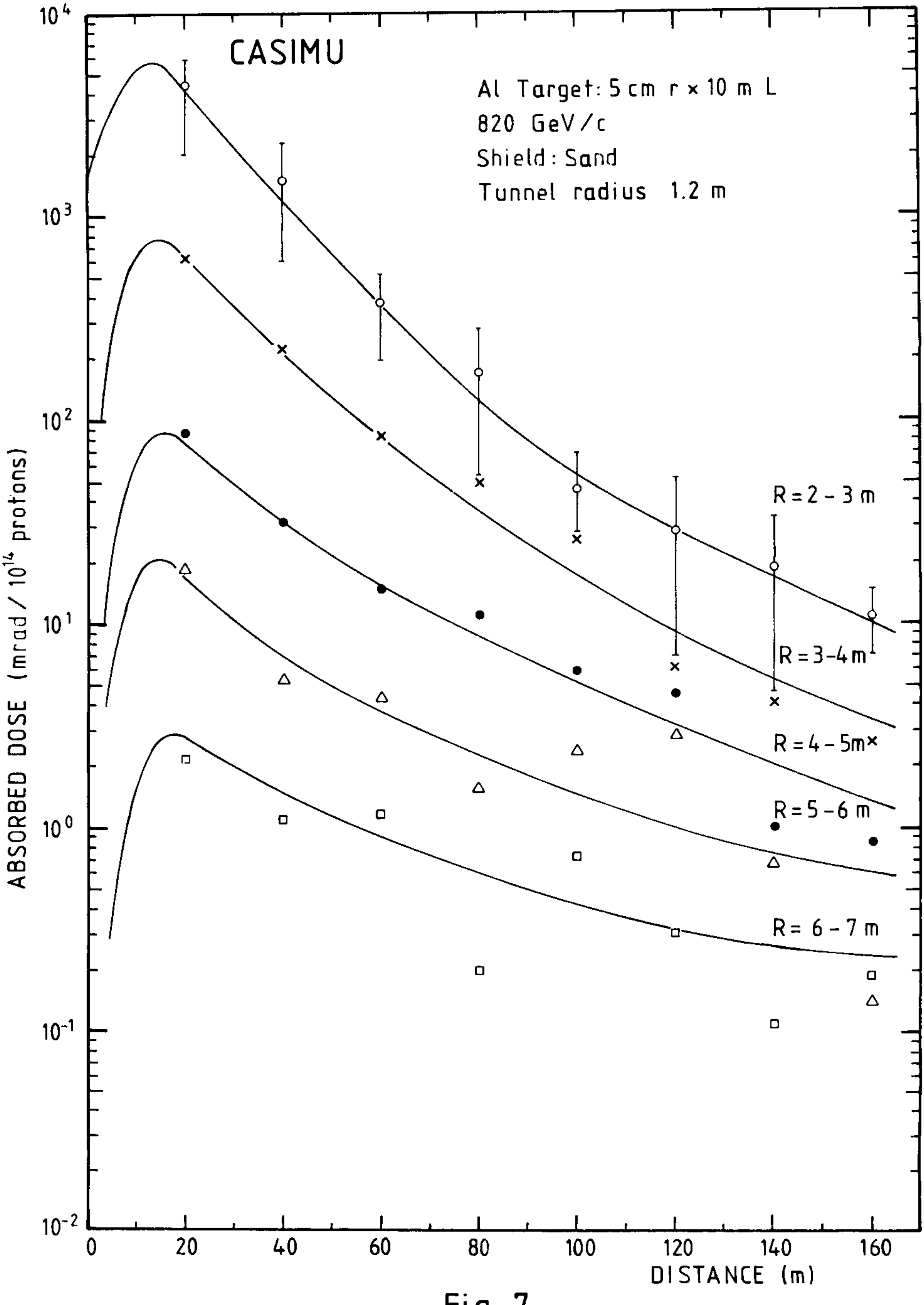

CASIMU
Al Target: 5 cm r × 10 m L
820 GeV/c
Shield: Sand
Tunnel radius 1.2 m
R = 2 - 3 m
R = 3-4 m
R = 4 - 5 m ×
R = 5 - 6 m
R = 6 - 7 m
ABSORBED DOSE (mrad / 10^14 protons)
DISTANCE (m)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120
140
160

Fig. 7

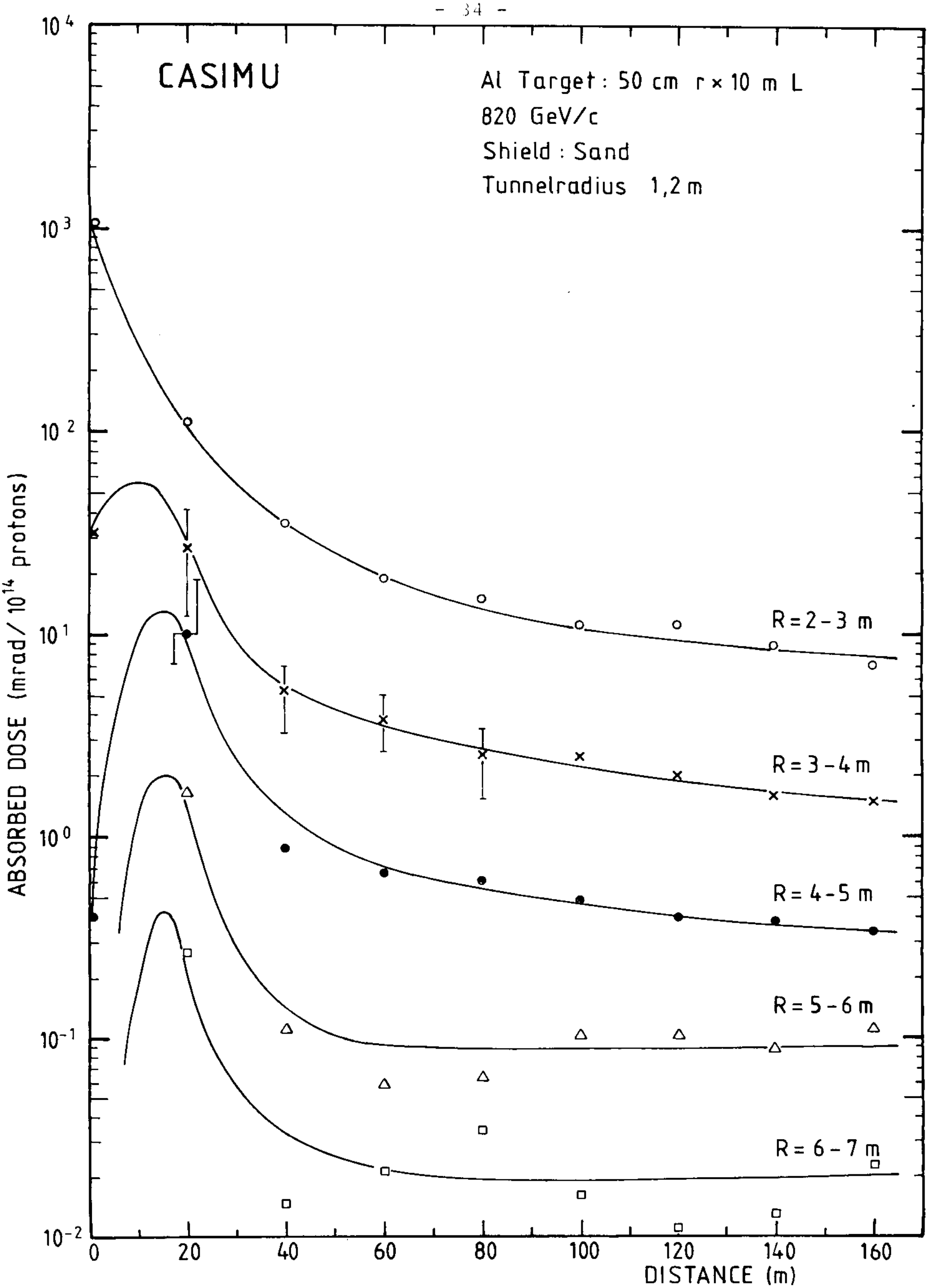

CASIMU
Al Target : 50 cm r × 10 m L
820 GeV/c
Shield : Sand
Tunnelradius 1,2 m
ABSORBED DOSE (mrad/ 10^14 protons)
DISTANCE (m)
R = 2 - 3 m
R = 3 - 4 m
R = 4 - 5 m
R = 5 - 6 m
R = 6 - 7 m
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120
140
160

Fig. 8

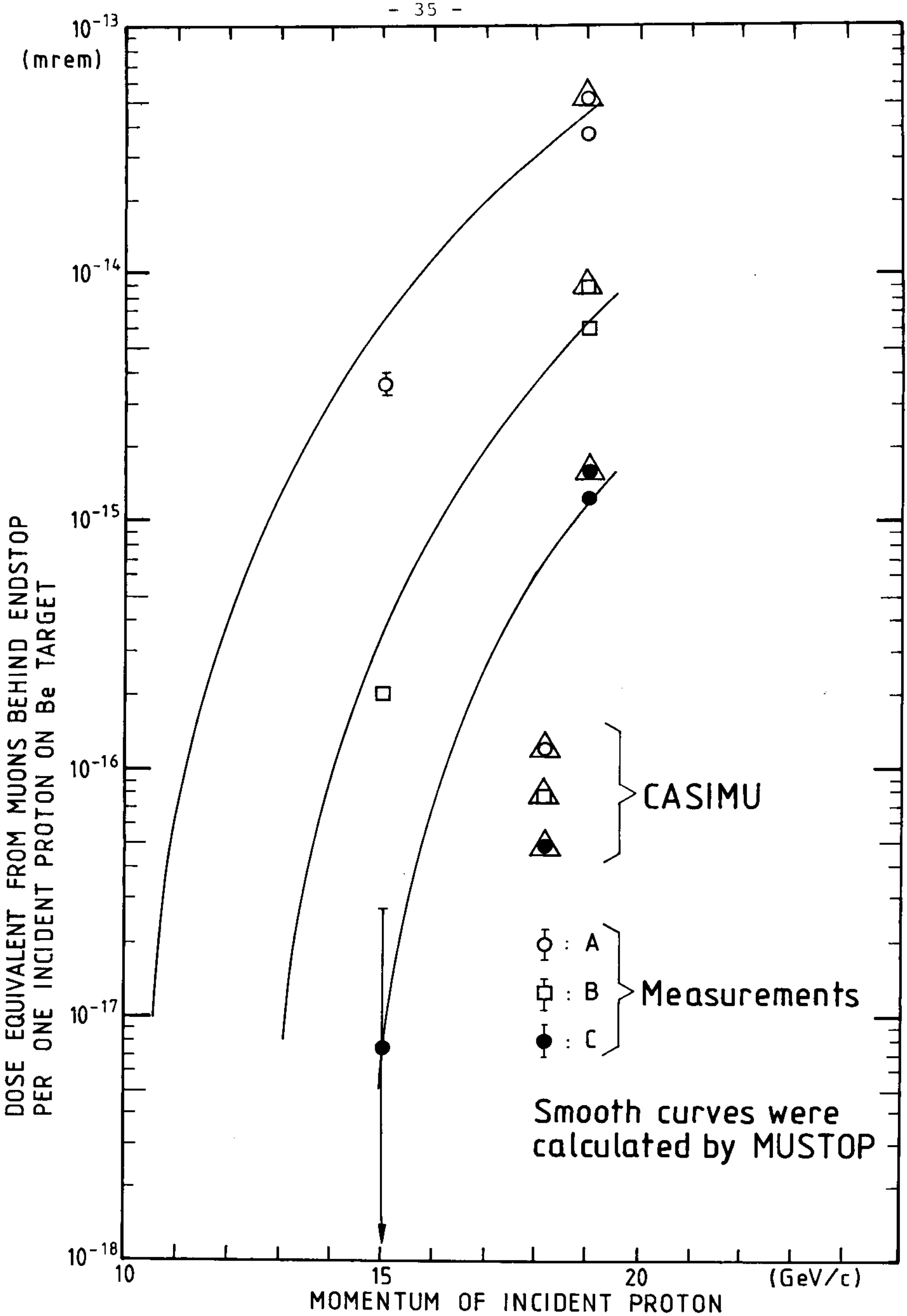

(mrem)
DOSE EQUIVALENT FROM MUONS BEHIND ENDSTOP PER ONE INCIDENT PROTON ON Be TARGET
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10
15
20
(GeV/c)
MOMENTUM OF INCIDENT PROTON
CASIMU
: A
: B
: C
Measurements
Smooth curves were calculated by MUSTOP

Fig. 9

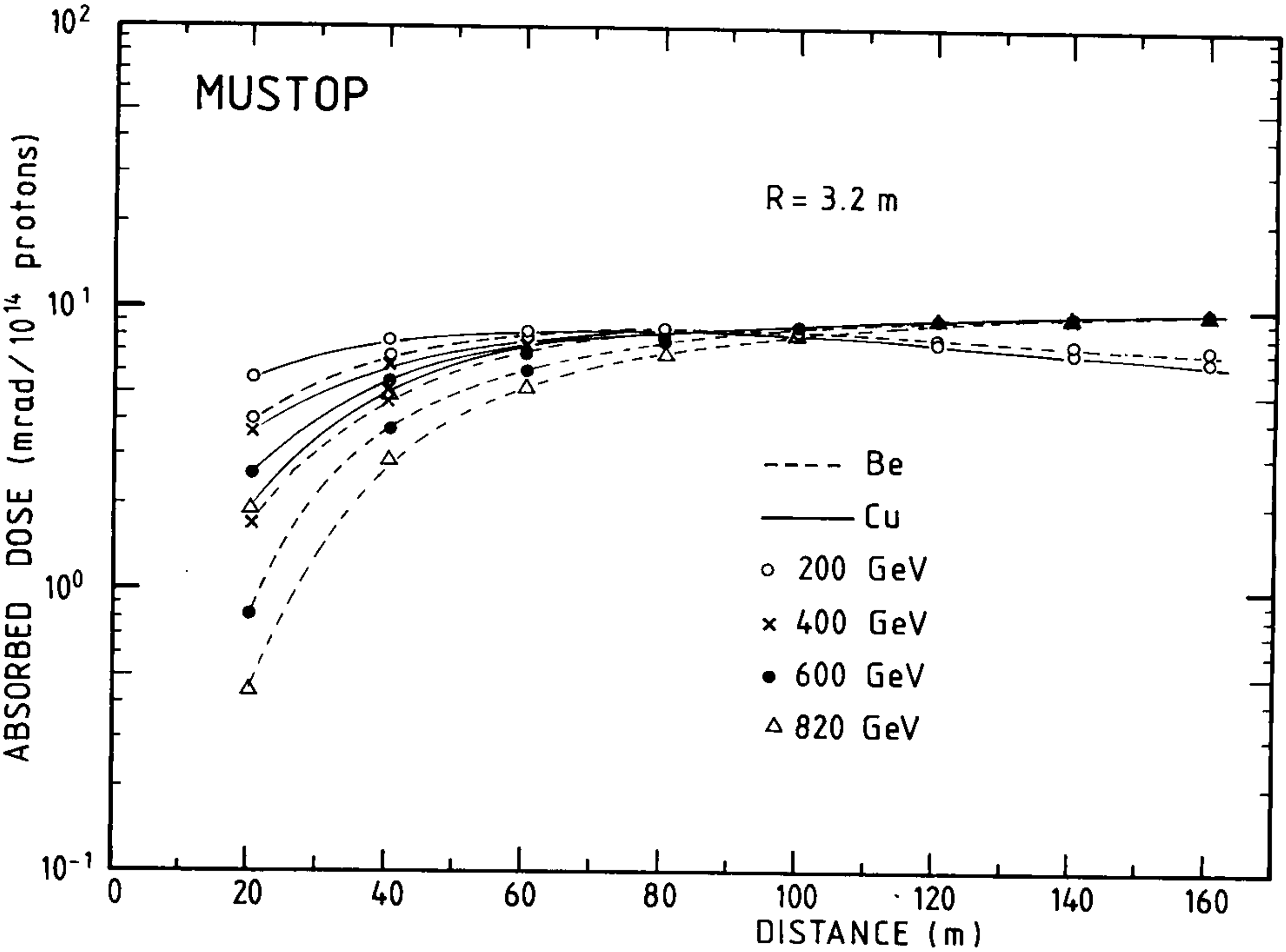
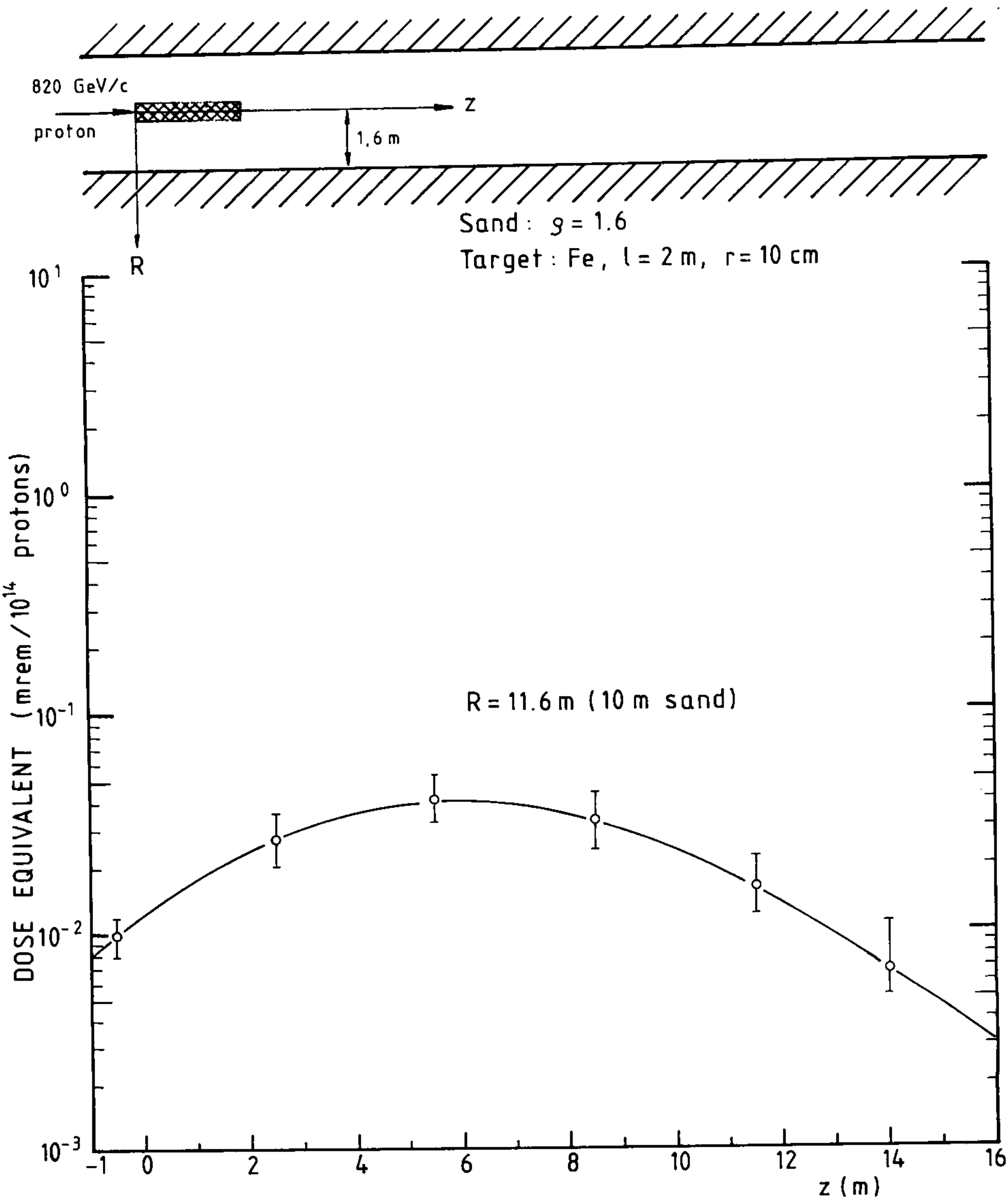

MUSTOP
R = 3.2 m
Be
Cu
200 GeV
400 GeV
600 GeV
820 GeV
ABSORBED DOSE (mrad/10^14 protons)
DISTANCE (m)
10^2
10^1
10^0
10^-1
0
20
40
60
80
100
120
140
160

Fig. 10



820 GeV/c
proton
Z
1,6 m
R
Sand: ρ = 1.6
Target: Fe, l = 2 m, r = 10 cm
DOSE EQUIVALENT (mrem / 10^14 protons)
R = 11.6 m (10 m sand)
z (m)

Fig. 11

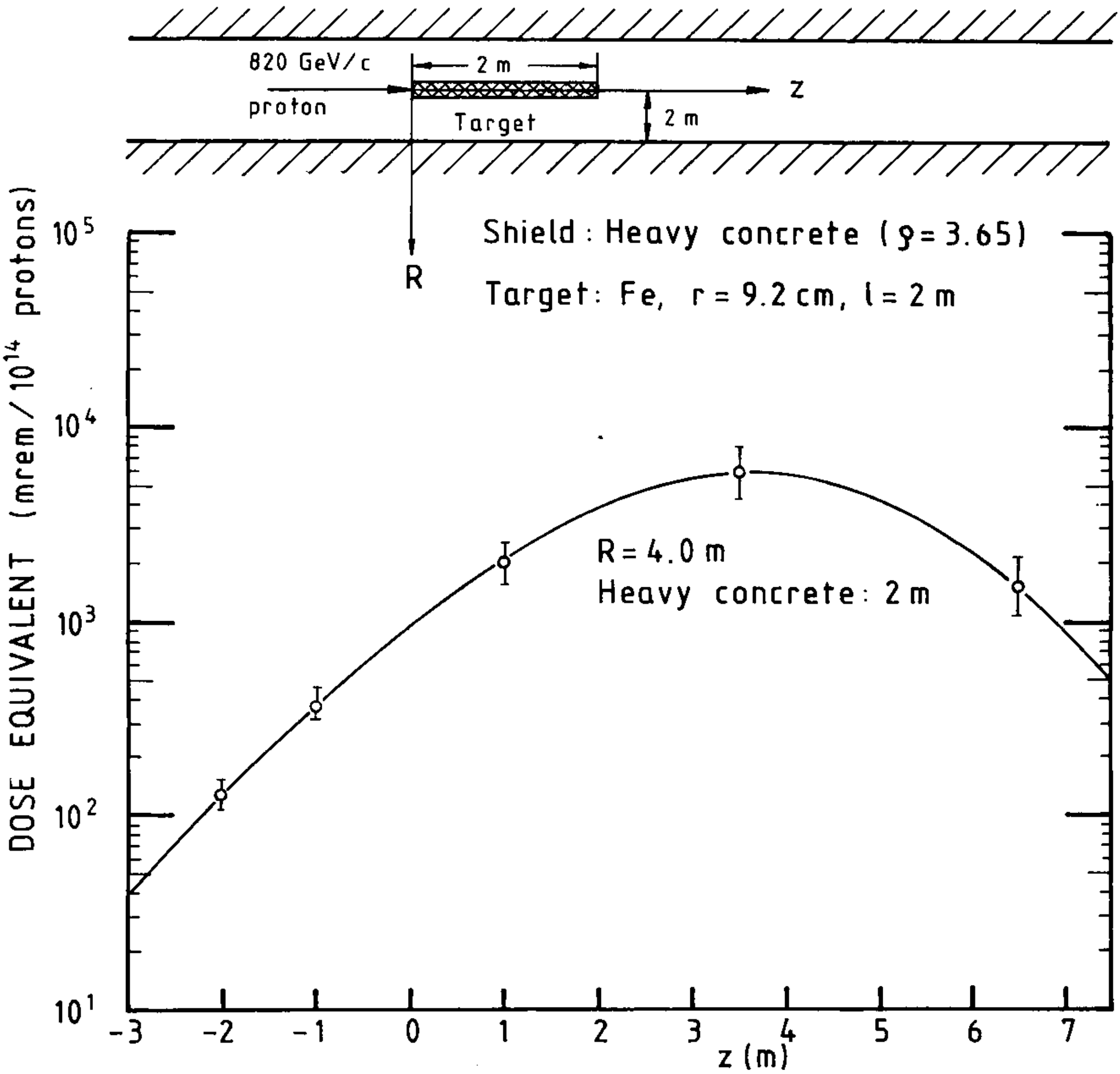

820 GeV/c
proton
2 m
Target
2 m
z
R
Shield : Heavy concrete (ϱ = 3.65)
Target: Fe, r = 9.2 cm, l = 2 m
R = 4.0 m
Heavy concrete: 2 m
DOSE EQUIVALENT (mrem / 10^14 protons)
10^5
10^4
10^3
10^2
10^1
-3
-2
-1
0
1
2
3
4
5
6
7
z (m)

Fig. 12

HERA - Experimentierhalle

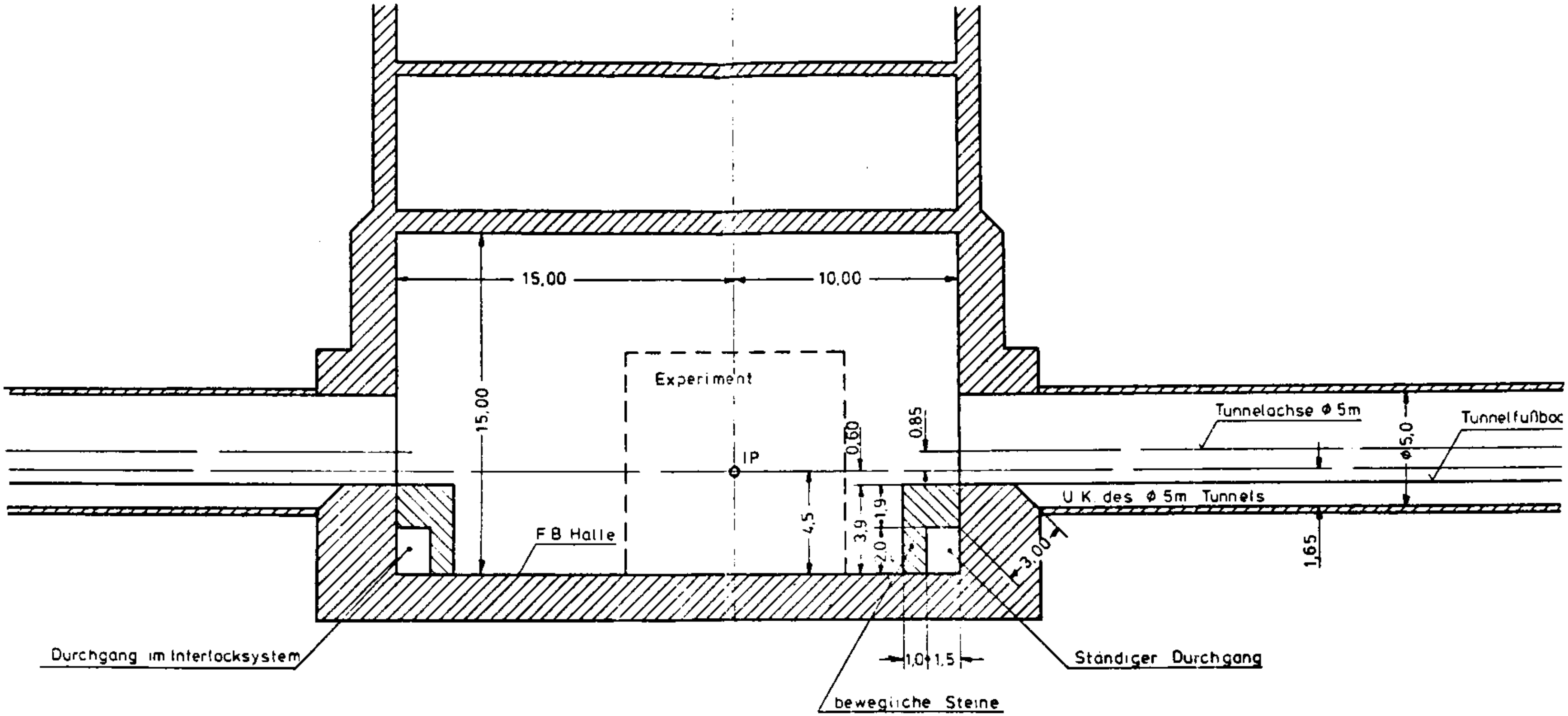


Fig. 13

382 8220 Bl. 4

Maßstab 1:200

2.8.82 / 29 9 82
Schulz -MHC-

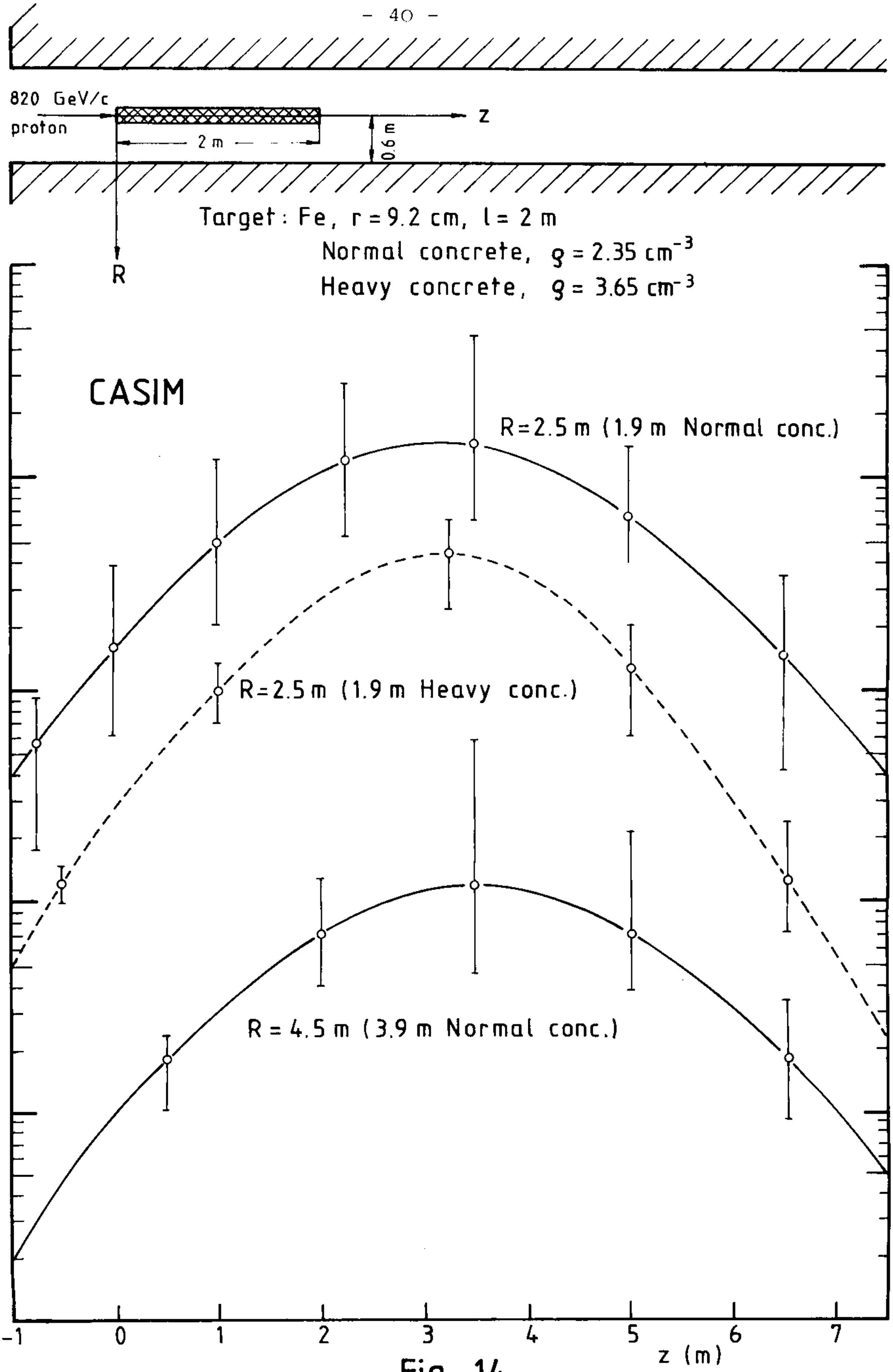

820 GeV/c
proton
z
2 m
0.6 m
R
Target: Fe, r = 9.2 cm, l = 2 m
Normal concrete, ρ = 2.35 cm⁻³
Heavy concrete, ρ = 3.65 cm⁻³
CASIM
R = 2.5 m (1.9 m Normal conc.)
R = 2.5 m (1.9 m Heavy conc.)
R = 4.5 m (3.9 m Normal conc.)
DOSE EQUIVALENT (mrem/10^14 protons)
10^6
10^5
10^4
10^3
10^2
10^1
-1
0
1
2
3
4
5
6
7
z (m)

Fig. 14

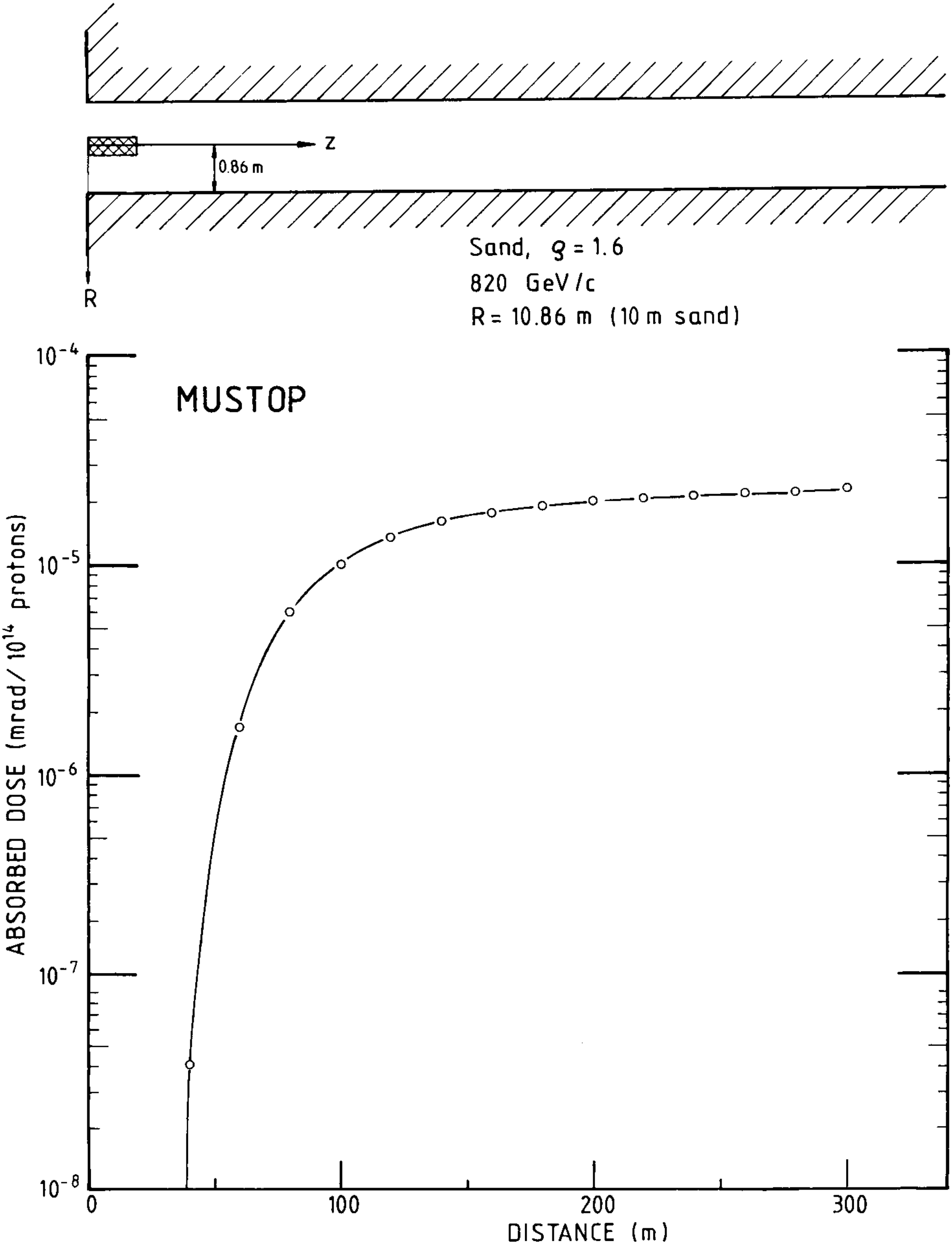
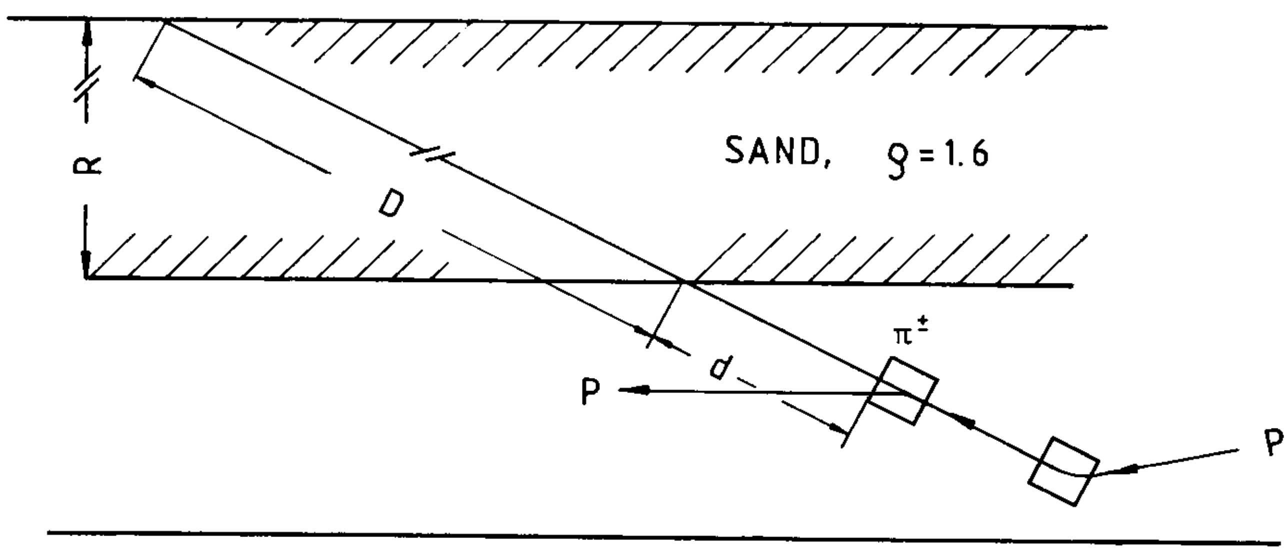

z
0.86 m
R
Sand, ϱ = 1.6
820 GeV/c
R = 10.86 m (10 m sand)
MUSTOP
ABSORBED DOSE (mrad/10^14 protons)
10^-4
10^-5
10^-6
10^-7
10^-8
0
100
200
300
DISTANCE (m)

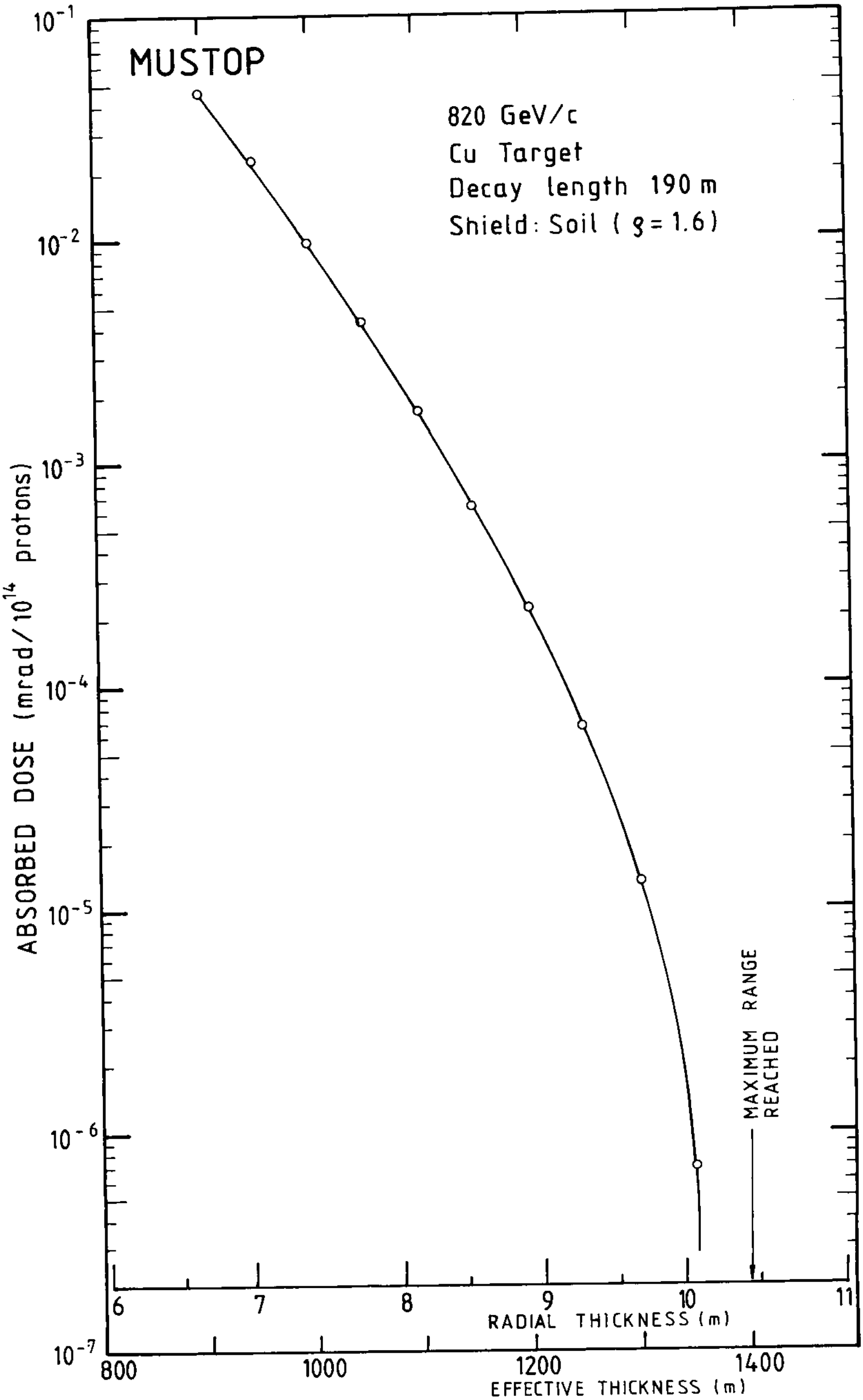
Fig. 15



d : decay length

D : effective shield thickness

Fig. 16



MUSTOP
820 GeV/c
Cu Target
Decay length 190 m
Shield: Soil (ρ = 1.6)
ABSORBED DOSE (mrad/10^14 protons)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
MAXIMUM RANGE REACHED
6
7
8
9
10
11
RADIAL THICKNESS (m)
800
1000
1200
1400
EFFECTIVE THICKNESS (m)

Fig. 17

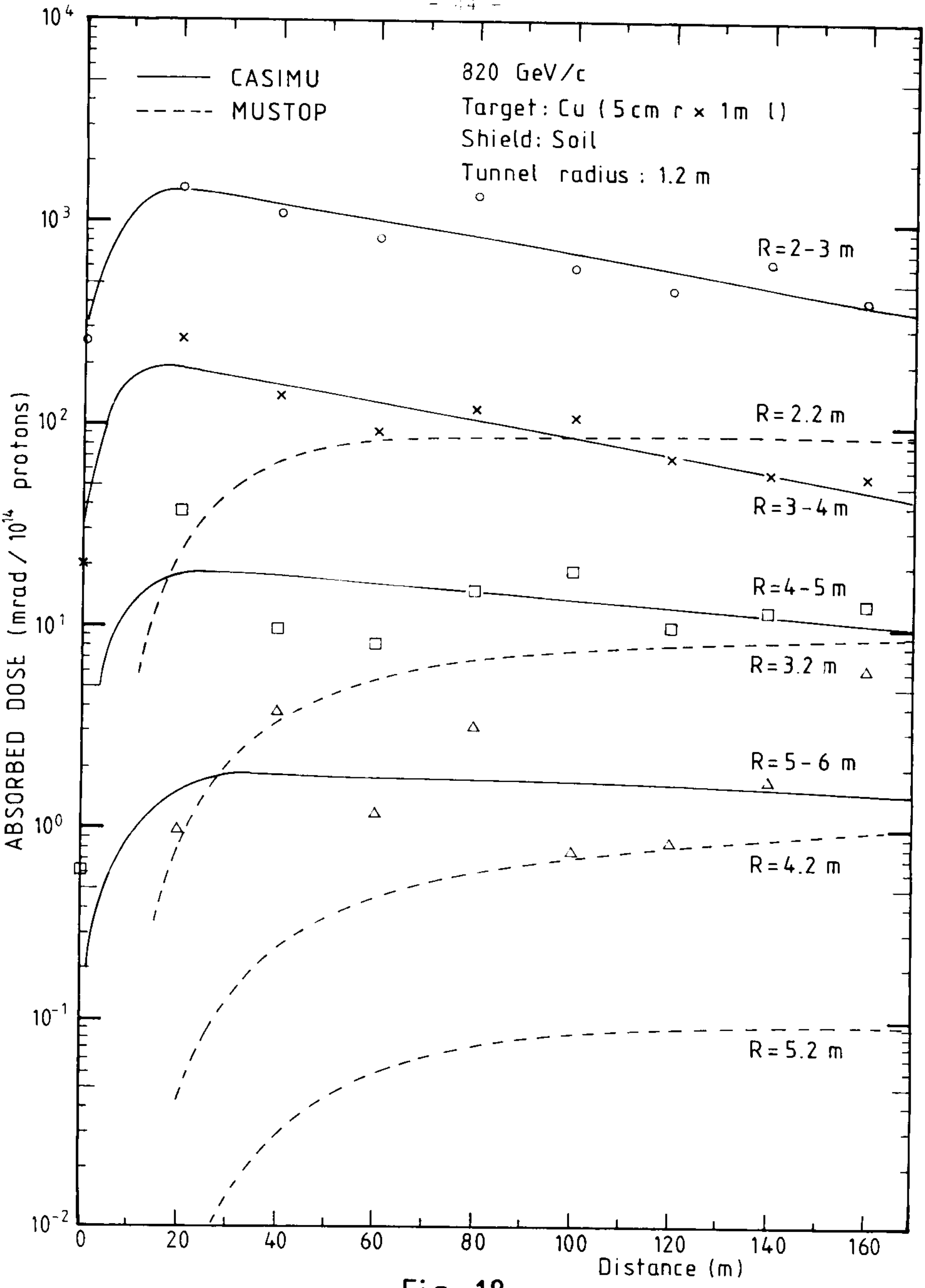

CASIMU
MUSTOP
820 GeV/c
Target: Cu (5 cm r × 1m l)
Shield: Soil
Tunnel radius: 1.2 m
R = 2-3 m
R = 2.2 m
R = 3-4 m
R = 4-5 m
R = 3.2 m
R = 5-6 m
R = 4.2 m
R = 5.2 m
ABSORBED DOSE (mrad / 10^14 protons)
Distance (m)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120
140
160

Fig. 18

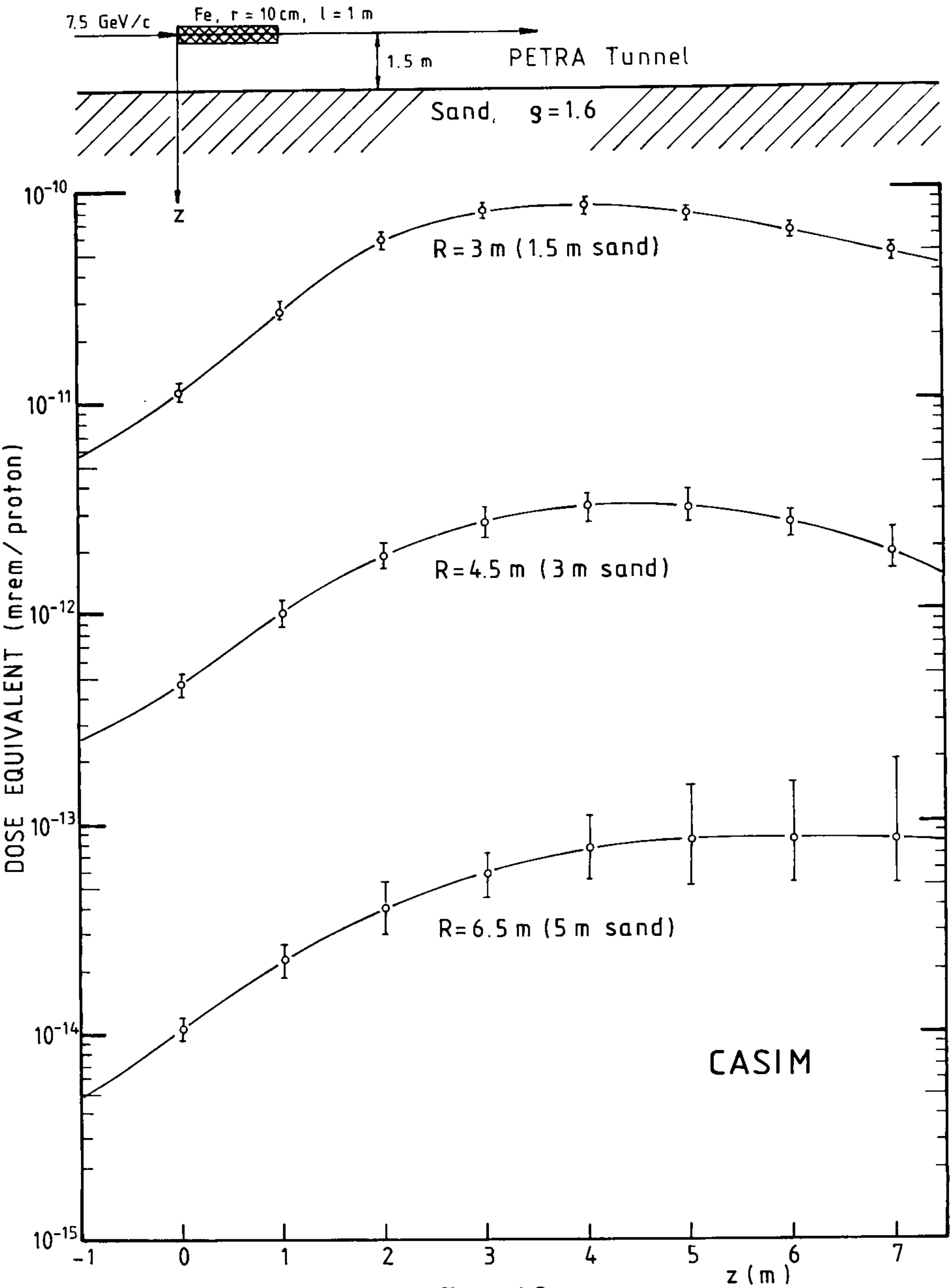

7.5 GeV/c
Fe, r = 10 cm, l = 1 m
1.5 m
PETRA Tunnel
Sand, ϱ = 1.6
z
R = 3 m (1.5 m sand)
R = 4.5 m (3 m sand)
R = 6.5 m (5 m sand)
CASIM
DOSE EQUIVALENT (mrem/proton)
z (m)
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
-1
0
1
2
3
4
5
6
7

Fig. 19

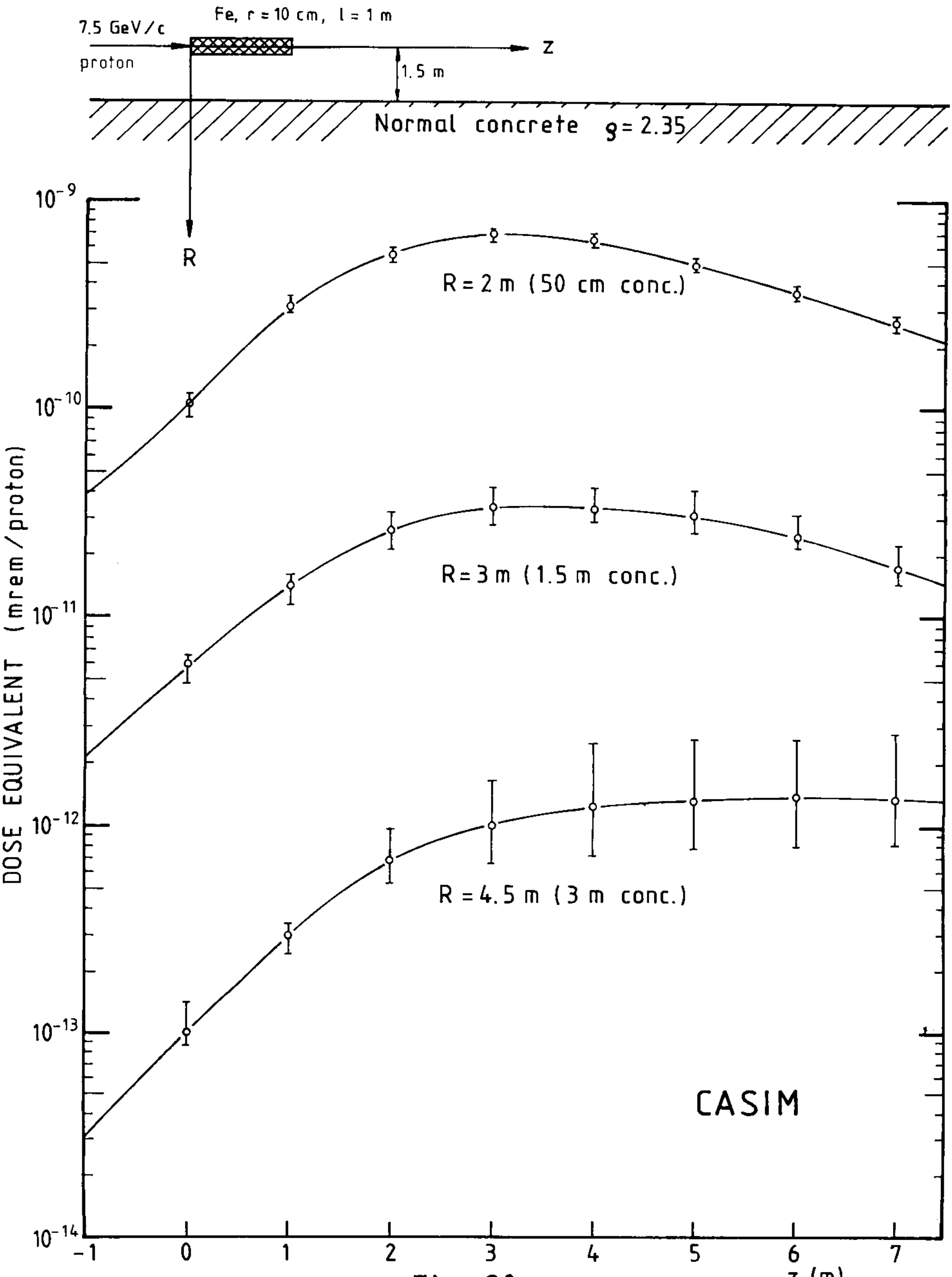

7.5 GeV/c
proton
Fe, r = 10 cm, l = 1 m
z
1.5 m
Normal concrete ϱ = 2.35
R
DOSE EQUIVALENT (mrem/proton)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
R = 2 m (50 cm conc.)
R = 3 m (1.5 m conc.)
R = 4.5 m (3 m conc.)
CASIM
-1
0
1
2
3
4
5
6
7
z (m)

Fig. 20

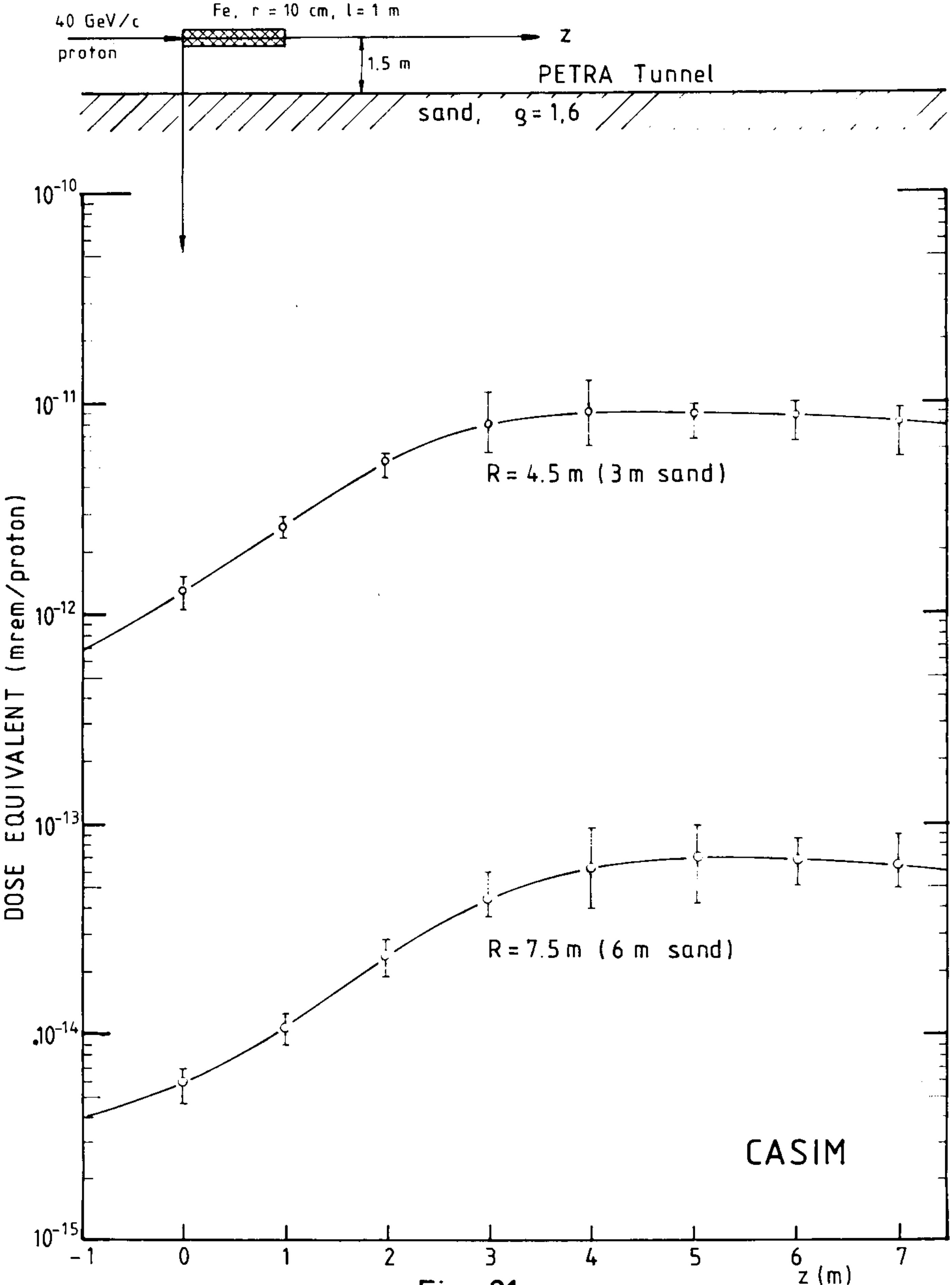

40 GeV/c
proton
Fe, r = 10 cm, l = 1 m
z
1.5 m
PETRA Tunnel
sand, ϱ = 1,6
DOSE EQUIVALENT (mrem/proton)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
R = 4.5 m (3 m sand)
R = 7.5 m (6 m sand)
CASIM
-1
0
1
2
3
4
5
6
7
z (m)

Fig. 21

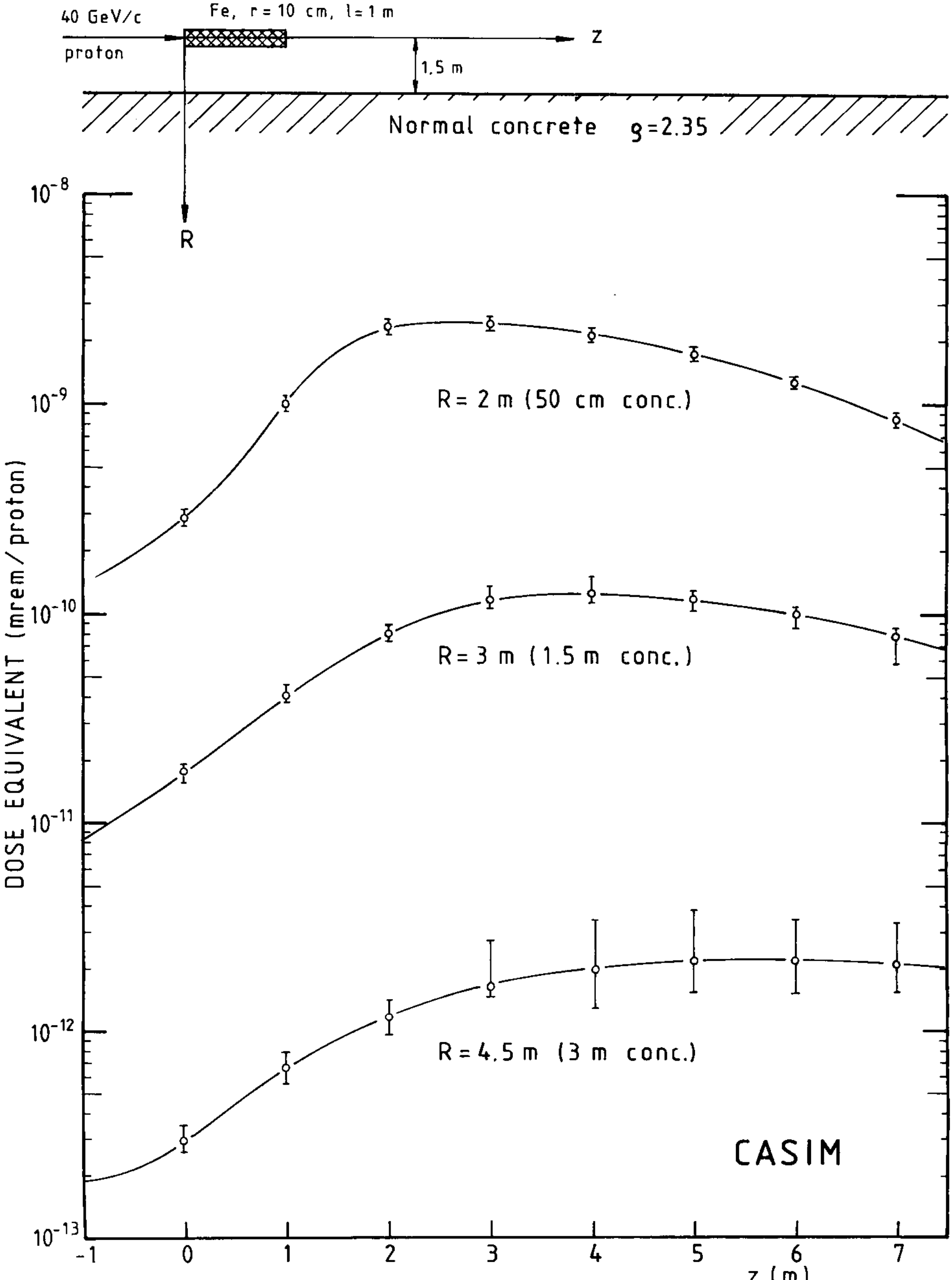

40 GeV/c
proton
Fe, r = 10 cm, l = 1 m
z
1.5 m
Normal concrete ρ = 2.35
R
DOSE EQUIVALENT (mrem/proton)
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
R = 2 m (50 cm conc.)
R = 3 m (1.5 m conc.)
R = 4.5 m (3 m conc.)
CASIM
-1
0
1
2
3
4
5
6
7
z (m)

Fig. 22

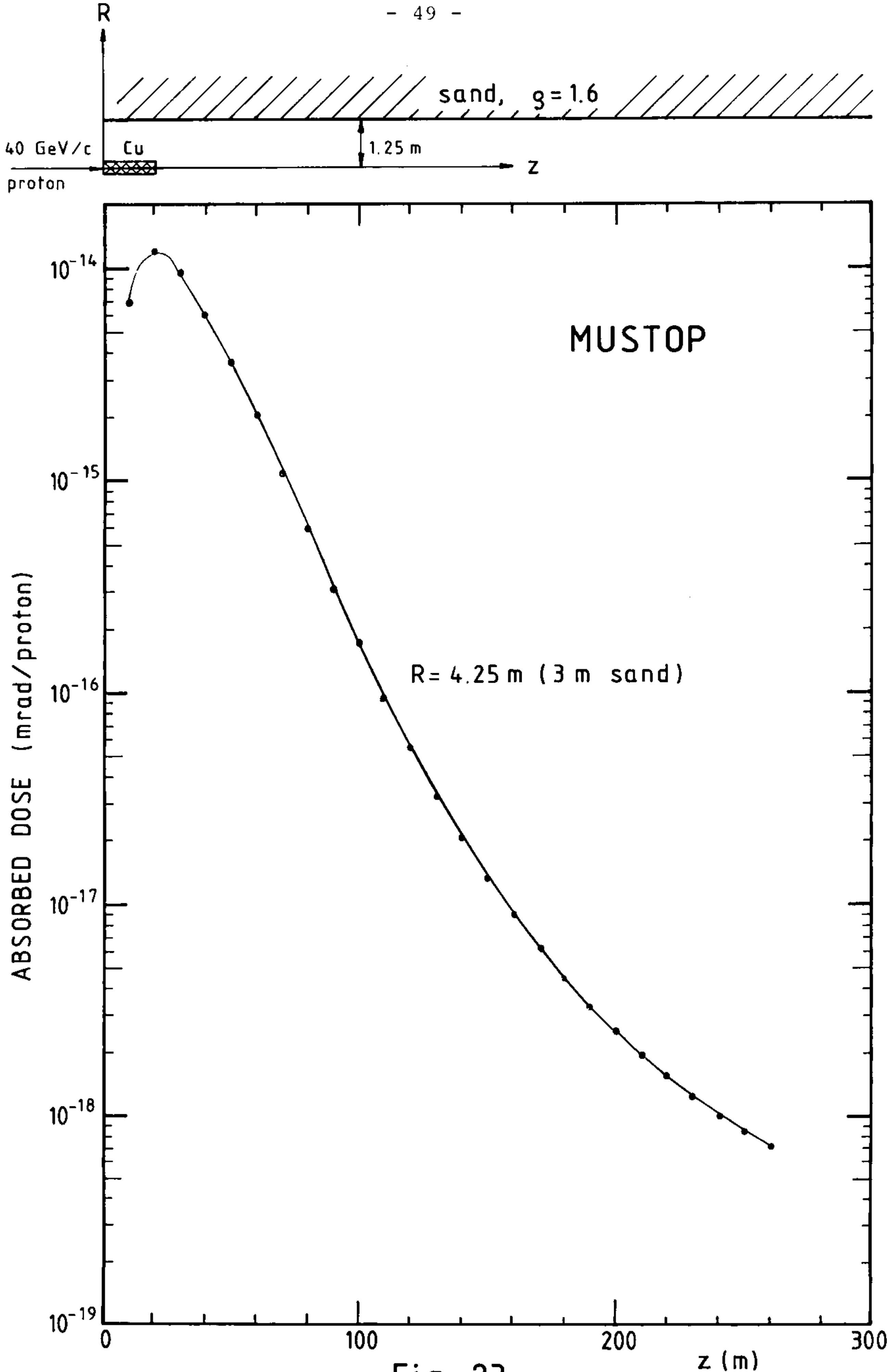
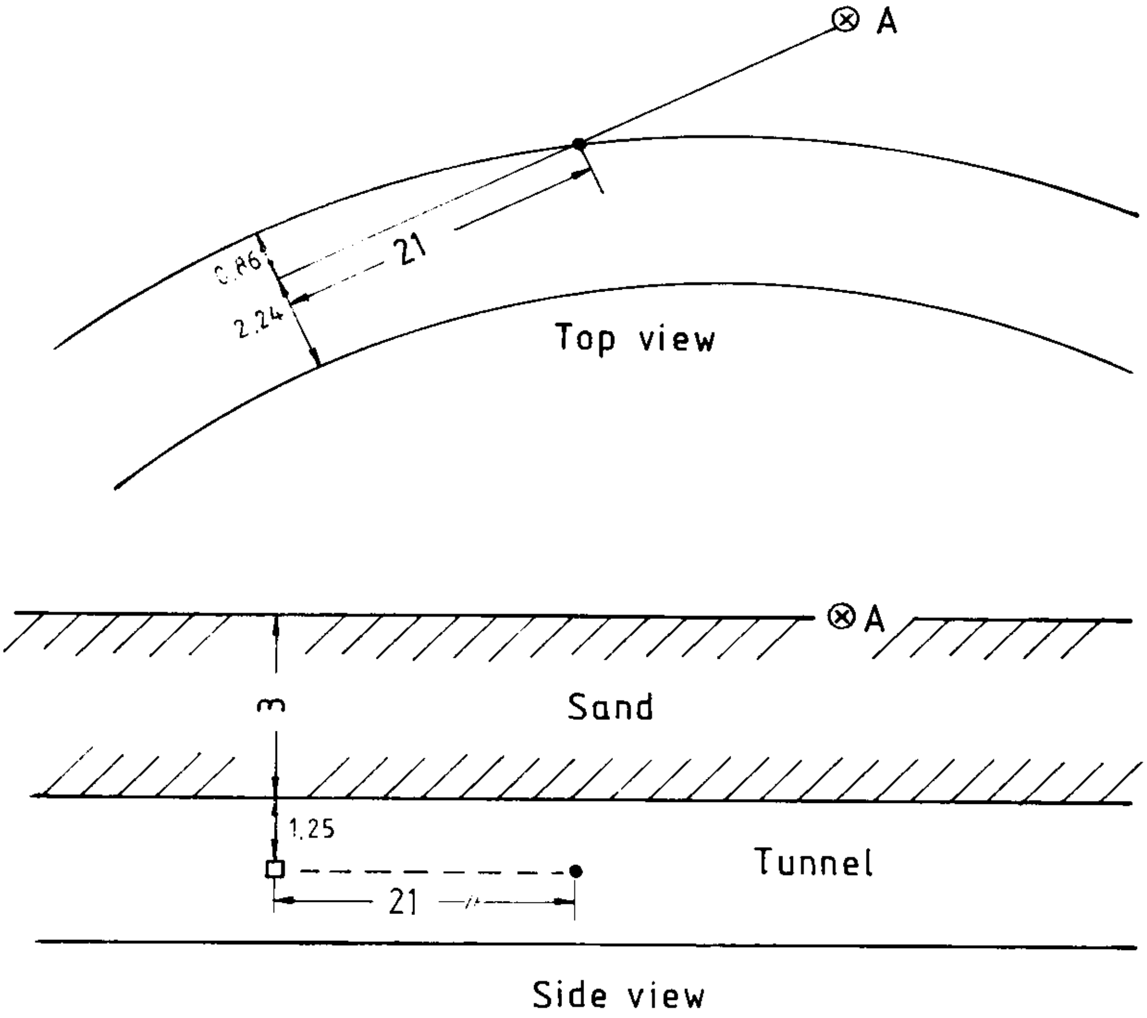

R
sand, ϱ = 1.6
40 GeV/c
proton
Cu
1.25 m
z
MUSTOP
R = 4.25 m (3 m sand)
ABSORBED DOSE (mrad/proton)
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
0
100
200
300
z (m)

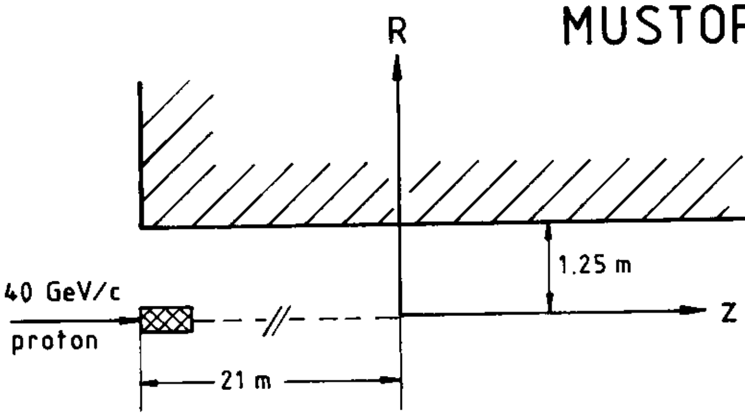
Fig. 23



(Figures in meter)

Fig. 24

MUSTOP



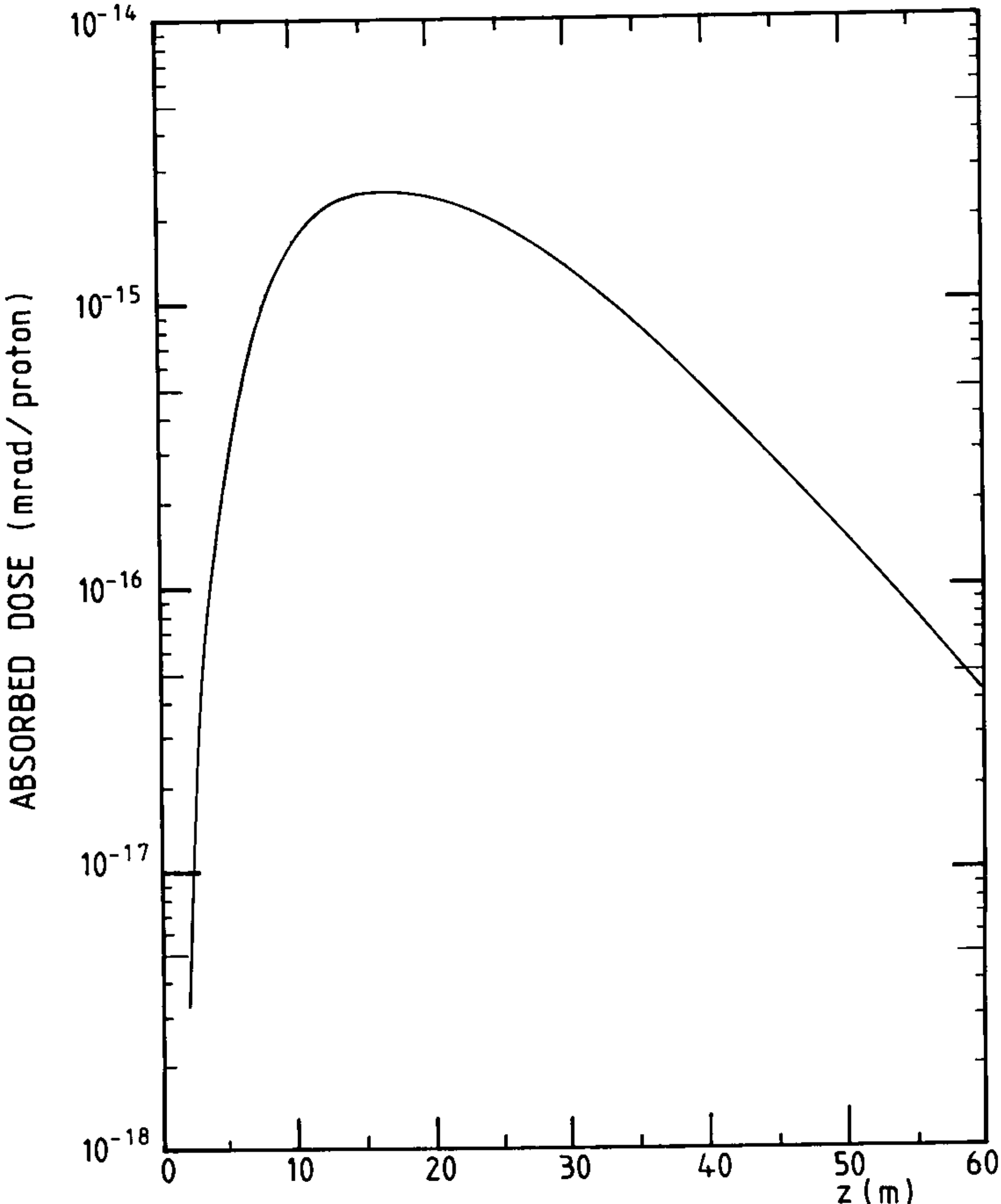
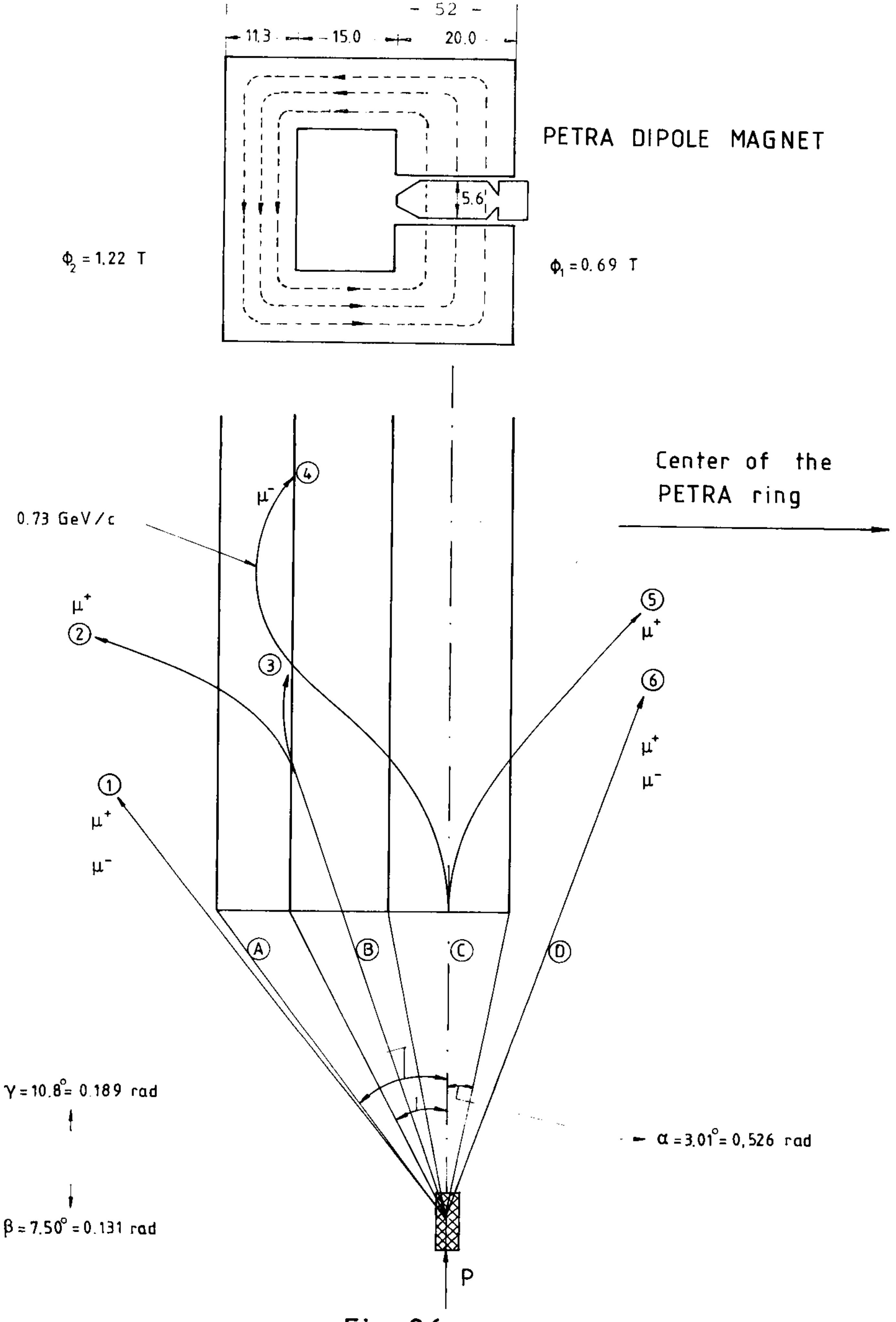


Fig. 25



52
11.3
15.0
20.0
PETRA DIPOLE MAGNET
5.6
Φ2 = 1.22 T
Φ1 = 0.69 T
Center of the PETRA ring
0.73 GeV/c
μ⁻
4
μ⁺
2
3
5
μ⁺
6
μ⁺
μ⁻
1
μ⁺
μ⁻
A
B
C
D
γ = 10.8° = 0.189 rad
α = 3.01° = 0,526 rad
β = 7.50° = 0.131 rad
P

Fig. 26

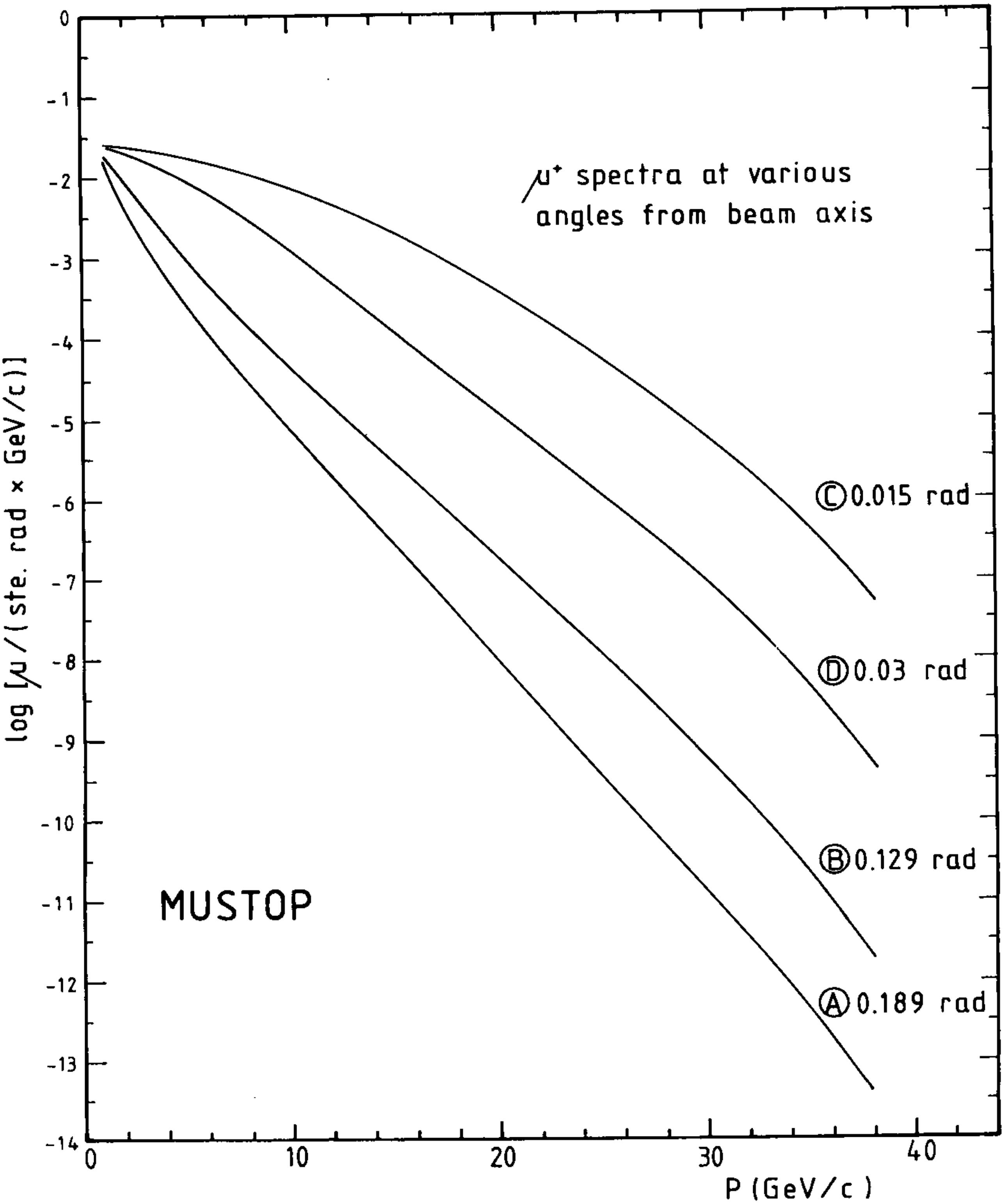

μ⁺ spectra at various angles from beam axis
Ⓒ 0.015 rad
Ⓓ 0.03 rad
Ⓑ 0.129 rad
Ⓐ 0.189 rad
MUSTOP
log [μ / (ste. rad × GeV/c)]
P (GeV/c)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
0
10
20
30
40

Fig. 27

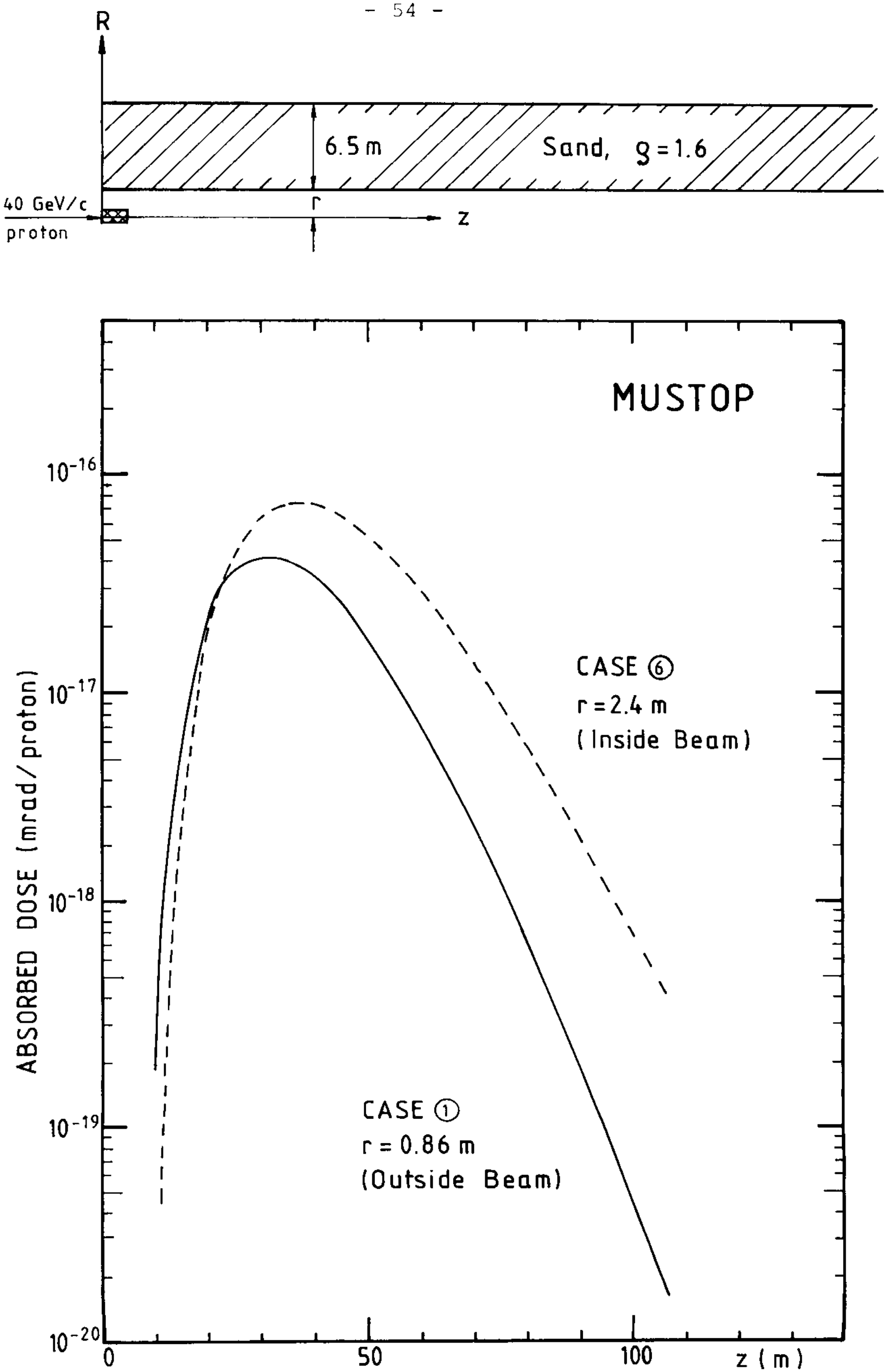

R
6.5 m
Sand, ϱ = 1.6
40 GeV/c
proton
r
z
MUSTOP
CASE ⑥
r = 2.4 m
(Inside Beam)
CASE ①
r = 0.86 m
(Outside Beam)
ABSORBED DOSE (mrad/proton)
10^-16
10^-17
10^-18
10^-19
10^-20
0
50
100
z (m)

Fig. 28

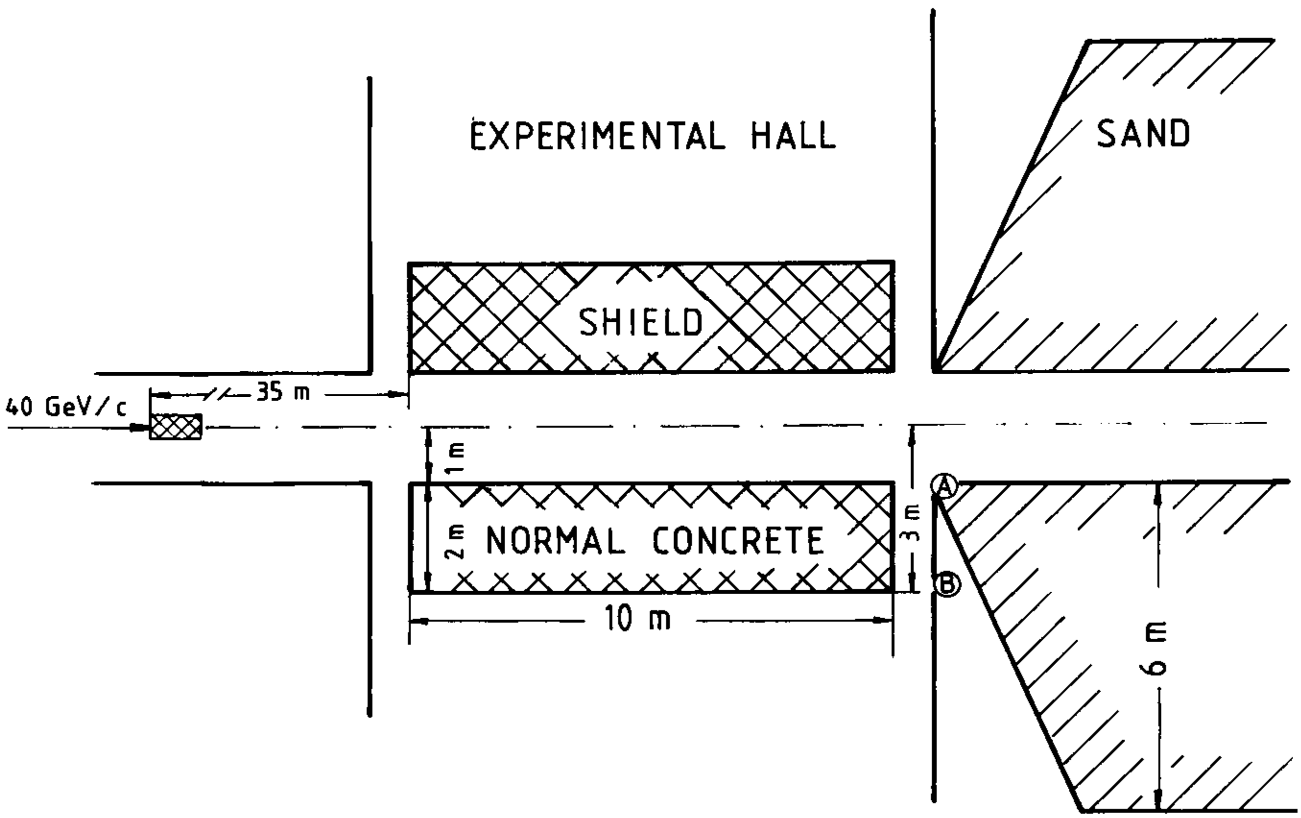

EXPERIMENTAL HALL
SAND
SHIELD
40 GeV/c
35 m
1 m
2 m
NORMAL CONCRETE
3 m
A
B
10 m
6 m

Fig. 29