Fermi National Accelerator Laboratory

FN-414
1100.050
(Submitted to Nucl. Instrum. Methods)

ABSORBED DOSE MEASUREMENTS AT AN 800 GeV PROTON ACCELERATOR; COMPARISON WITH MONTE-CARLO CALCULATIONS

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January 1985

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

ABSTRACT

Shielding design at high energy proton accelerators is often done using Monte-Carlo computer simulations. This report compares such predictions with measurements made at proton energies up to 800 GeV. Agreement of the measurements with the calculations is quite good (within 20 per cent) at small radial distances from the beam axis ($R<0.5$ m) while even for a thick soil shield ($R\approx5$m) the agreement is acceptable for radiation protection purposes (typically within a factor of two). The scaling with energy of these calculations is found to be in good agreement with a recently published analysis based on the Moyer shielding model. These results are an indication that present techniques of shielding calculations can be extended to those required for higher energy proton accelerators.

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1. Introduction

In recent years, shielding design at high energy proton accelerators has conventionally been done using Monte-Carlo computer techniques to simulate the development of the hadronic cascade. The standard program used at Fermilab is CASIM, developed by A. Van Ginneken.[1,2] The predictive power of this program has been experimentally checked for proton energies up to 400 GeV both for targets of relatively small dimensions (using the techniques of foil activation and target heating[3,4]), and for shields of a variety of sizes including very large ones (using measurements of absorbed dose[5]). In all cases the agreement of calculations made using CASIM with the measurements at small shield or target thicknesses is quite good, typically within 20 per cent, while for the thicker shields acceptable agreement within factors of two or three is obtained at locations of peak radiation intensity.

Thomas and Thomas[6] have incorporated thick shield results reported in Ref. 5 in a reanalysis of the parameters of the empirical Moyer model of shielding most recently given a detailed exposition by Stevenson, et. al.[7]. This reanalysis included shielding data for incident proton energies, E, spanning the range from 7.4 to 350 GeV. Among the results reported by these authors is that the dose equivalent external to a reasonably thick lateral shield, H, scales with incident proton energy as:

$$H \propto E^{0.8 \pm 0.1} \qquad (1)$$

(errors are 95% confidence limits)

These authors also give a constant of proportionality appropriate for tunnel geometries containing "magnet-like" objects and a factor which represents the attenuation of the radiation by the shield and the radial dependence; given that an equilibrium spectrum has been achieved. The Moyer model is useful for both point and line source geometries and has been used by Thomas and McCaslin[8] and Cossairt and Elwyn[9] to make predictions of the shielding requirements for the 20 TeV Superconducting Super Collider presently being given serious consideration. Clearly the design of this very large accelerator will require credible hadron shielding calculations to adequately protect personnel and the public at minimum cost.

The present paper reports on absorbed dose measurements made during the initial operation of the Fermilab Tevatron at 800 GeV in 1984. This new data, taken at a proton energy of more than twice that used in the measurements of Ref. 5, provides a checkpoint on the predictive power of the program CASIM. Calculations verified by measurement are, then, used to check Eq. (1).

2. Experimental and Calculational Technique

This work is in the spirit of an extension of the 1982 work reported in Ref. 5. Available test cases for study were limited by severe shortages of beam time which could be diverted from the high energy physics program during the initial operation of the Fermilab Tevatron at 800 GeV. The absorbed dose measurements were performed in conjunction with the ongoing needs of the operational health physics monitoring program. The cases reported here had readily verifiable geometry and well-understood beam intensities and beam loss mechanisms. Targetry was limited to direct beam dumping; cases of distributed ("scraping") losses of beam were neglected because of uncertainities in reproducibility due to extreme sensitivity to the exact details of beam direction, spot size, and profile.

The Monte-Carlo calculations using the code CASIM were done by modifying a FORTRAN subroutine to describe the geometry under study. Incident beams were represented as having two-dimensional Gaussian profiles with widths chosen to match data recorded by beam profile instrumentation during the absorbed dose measurements. The code includes a standard momentum cutoff of 0.3 GeV/c, below which no particles are followed. Concrete used at Fermilab has a density of 2.4 g/cm^3, while the local soil is known to have a rather high value of 2.25 g/cm^3. These are used in the calculations along with the standard values for other materials.

Absorbed dose was measured with a commercially available tissue-equivalent proportional chamber also used for some of the 1982 measurements[10]. The succeeding sections of this paper will describe the results for the individual cases selected.

3. Case A

For this test the geometry is shown in Fig. 1. A beam of 800 GeV protons was incident perpendicularly on the iron block in a Gaussian profile approximately 2 mm in standard deviation, in both transverse coordinates. Approximately 42,000 protons were received on this target in a 20 second beam burst every minute as measured a short distance upstream of the iron block by a pair of scintillation counters in coincidence. The absorbed dose rates were measured at beam height in contact with the iron at several values of the longitudinal coordinate Z defined in the figure. A single measurement was also taken at the downstream end of the iron block. Beam profile monitors and geometrical measurements indicate that the beam hit the "lifting eye" as shown.

The Monte-Carlo calculations with CASIM were performed at four different bombarding energies; 200, 400, 600, and 800 GeV. Conversion factors taken from Ref. 2 were used to change the primary output of the program of stars cm^{-3} (nuclear interactions cm^{-3} above the momentum cutoff of the program) to absorbed dose. In this paper, absorbed dose will be expressed in grays (one gray = one joule/kg = 100 rads). In this case a value of 1.3×10^{-8} Gy-cm^3/star was used along the sides of the iron block while Fig. VI.4 of Ref. 2 led the authors to use 4.0×10^{-8} Gy-cm^3/star for comparison with the measurement at the end of the iron block on the beam axis. The justification of these conversion factors is discussed in detail in Ref. 2, and are accurate to within 20 per cent for the cases studied here. The results of the measurements and three of the Monte-Carlo calculations are shown in Fig. 2 (the 600 GeV calculation is similar in general appearance). Error bars on the data points are estimates of reproducibility based upon the data taken over several different beam spills at each location. At Z = 4.66 m, the error bar in radial coordinate R indicates the finite diameter of the proportional chamber used, and is of course representative of the "averaging volume". The width of the bands represent the statistical errors of the Monte-Carlo calculation (one standard deviation). Each calculation represents about 1.5 hours of CPU time on the Fermilab central computer facility (CYBER-175 System). If one models the geometry with the beam incident on the iron block without inclusion of the "lifting eye", the calculated absorbed doses are reduced somewhat (<20 per cent) for Z < 2 meters, compared to the results indicated here.

Agreement between the 800 GeV data and the corresponding Monte-Carlo calculation is quite good, well within the errors, though it is unfortunate that a datum does not exist at the peak of the cascade. Along with the results of the 800 GeV measurement, the conclusions of Refs. 3, 4, and 5 indicate that CASIM predicts the properties of hadronic cascades quite well for similar size targets at incident hadrons energies between 200 and 800 GeV.

While a thick lateral shield is not involved here, it is instructive to test the energy dependence of the maximum value of the CASIM calculations along the side of the iron block for the four incident proton energies considered here, ignoring any spectral changes (expected to be small) over this domain of bombarding energy. To do this, a statistically weighted average of the peak absorbed dose in the calculation was taken over a domain in Z of 0.5 m at the surface of the iron block. Regression analysis was then applied to the log-log transformation of these values and the energy variable. The results are listed in Table 1. Good agreement with the power law parameter of Thomas and Thomas[6] is obtained. Thus, if the cascade developed in this block were the source of radiation penetrating a thick soil shield, the energy dependence would be that expected from the Moyer model, given this experimental verification of CASIM.

4. Case B

Figures 3 and 4 describe a rather complicated beam dumping scenario. The proton beam was incident perpendicularly on the upstream face of the iron beam stop in a Gaussian beam spot of standard deviation approximately one mm (both planes). A secondary emission monitor (SEM), thought to be calibrated to ± 10 per cent monitored the beam intensity of about 2×10^{11} protons per spill. Absorbed dose measurements were done with beam from the Tevatron at 800 GeV (one 10 sec. spill every minute) in 1984 and at 400 GeV (one 1 sec. spill every 10 sec.) from the Fermilab Main Ring in 1980 directly over the beam centerline along the Z coordinate.

In the Monte-Carlo simulation, the Cartesian coordinates were defined as shown in Fig. 3 and 4. Components within a radius $R < 0.5$ m of the beam centerline were modeled exactly while structures at $R > 0.5$ m were modeled in cylindrical symmetry setting the material boundaries to match those encountered along the perpendicular to the top surface of the shield (where the measurements were made). This was done both for simplicity and to minimize the statistical errors in the Monte-Carlo by increasing the solid angle sampled. Calculations were also done at 200 and 600 GeV.

The results of the measurements and calculations are shown in Fig. 5. The error bars on the data correspond, again, to estimates based upon the reproducibility of the data during different beam spills. Measurements were also made above the dump with the beam stop removed and the protons transported through the beam channel. A uniform background of about 10^{-20} Gy/proton was found in this region. Checks with a scintillation telescope indicate the radiation to be charged particles in sychronization with the accelerator cycle, i.e., muons arising from beam losses upstream. This background absorbed dose has been subtracted from the data shown in Fig. 5. Statistical errors (one standard deviation) in the Monte-Carlo results are indicated by the shaded areas in the histograms, each bin of which represents an average over a 0.96 m domain in Z along the line where the measurements were done. The raw output of CASIM (stars cm^{-3}/incident proton) has been converted to absorbed dose using a conversion factor (Ref. 2) of 1.5 x 10^{-8} Gy-cm^3/star for the portions above concrete and 1.6 x 10^{-8} Gy-cm^3/star above the soil (correcting for the material density). Fig. 5 also displays the 200 GeV calculation; the 600 GeV calculation is not shown, but has a similar shape.

The general shape of the data is reproduced well by the calculations, which underestimate the magnitudes by typically a factor of two. The agreement with the data is thus similar to that reported in Ref. 5 for shields of comparable thickness; the present shield is 1246 g/cm^2 for Z <3.3m and 1080 g/cm^2 for Z>5m. A somewhat anomalous result is the agreement of the data taken at the two energies. It is felt that the apparent improvement in agreement between measurement and calculation at 800 GeV over that at 400 GeV reflects a unexplained change in the beam intensity normalization in the intervening four year period and would not be seen if measurements at the two energies could be made, for example, on the same day. During the interval between the two measurements, extensive changes were made to the beamline immediately upstream of the beam stop.

Again, for this case it is interesting to check the energy dependence of the Monte-Carlo predictions at the outer boundary of this thick shield. Table 2 contains the results which, of course, have larger uncertainties than those of Case A due to the greater statistical errors at the larger radii involved for a finite amount of computer time. One still finds that results to be consistent with the relationship of Eq. (1).

5. Conclusion

It is concluded that the Monte-Carlo code CASIM, properly applied, is able to predict absorbed doses outside of both thick and thin shields for 800 GeV protons to the same accuracy as previously found for $E \lesssim 400$ GeV, even for the rather complicated geometry of Case B. Also, the energy dependence of the intensity of the radiation at a given location in the cascade appears to be consistent with that previously determined by others for $E < 400$ GeV. It thus seems reasonable to extend present techniques to hadronic cascade calculations at still higher energies. Such predictions may be very important for the shielding design of larger accelerators.

We wish to thank Thornton Murphy and Jon Hawkins for their help in scheduling the beam time for these measurements and the technicians who collected the data. We appreciate the careful reading of the manuscript by Alex Elwyn and acknowledge his helpful comments.

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8. R. H. Thomas and J. B. McCaslin, "General Shielding for the 20 TeV Hadron Collider Facility: Hadron Considerations", Lawrence Berkeley Laboratory, University of California, Berkeley, CA, Note HS-14 (unpublished).

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Table 1

Case A: Log-Log Regression Analysis of CASIM Results

E, Energy (GeV)	D, Peak Absorbed Dose (Gy/incident proton)
200	$(2.50 \pm 0.16) \times 10^{-13}$
400	$(4.47 \pm 0.27) \times 10^{-13}$
600	$(6.42 \pm 0.38) \times 10^{-13}$
800	$(7.87 \pm 0.48) \times 10^{-13}$

Result of Analysis:

$$D = [(3.00 \pm 0.50) \times 10^{-15}]\, E^{0.84 \pm 0.02}$$

(All errors are 95 per cent confidence limits)

Table 2

Case B: Log-Log Regression Analysis of CASIM Results

E, Energy (GeV)	D, Peak Absorbed Dose (Gy/Incident Proton)
200	$(0.58 \pm 0.10) \times 10^{-18}$
400	$(0.90 \pm 0.28) \times 10^{-18}$
600	$(1.02 \pm 0.24) \times 10^{-18}$
800	$(1.39 \pm 0.25) \times 10^{-18}$

Result of analysis:

$$D = [(2.25 \pm 1.16) \times 10^{-20}]\, E^{0.61 \pm 0.08}$$

(All errors are 95 per cent confidence limits)

List of Figure Captions

1. Plan and elevation views of the geometry studied as Case A.

2. Measurements at 800 GeV (data points) and Monte-Carlo calculations at three incident proton energies (bands) of absorbed dose plotted as a function of Z along the outer surface of the iron block shown in Fig. 1 The inset shows the measurements and calculations at 800 GeV as a function of radius R at Z = 4.7 meters.

3. Plan view of the geometry studied as Case B. Note that the horizontal scale differs from the longitudinal scale.

4. Elevation view of the geometry studied as Case B. The vertical and longitudinal scales are equal in this view.

5. Measurements at 400 and 800 GeV (data points) and Monte-Carlo calculations at three incident proton energies (histograms) of absorbed dose plotted as a function of Z along the surface of the earth and concrete above the beam stop indicated in Fig. 4.

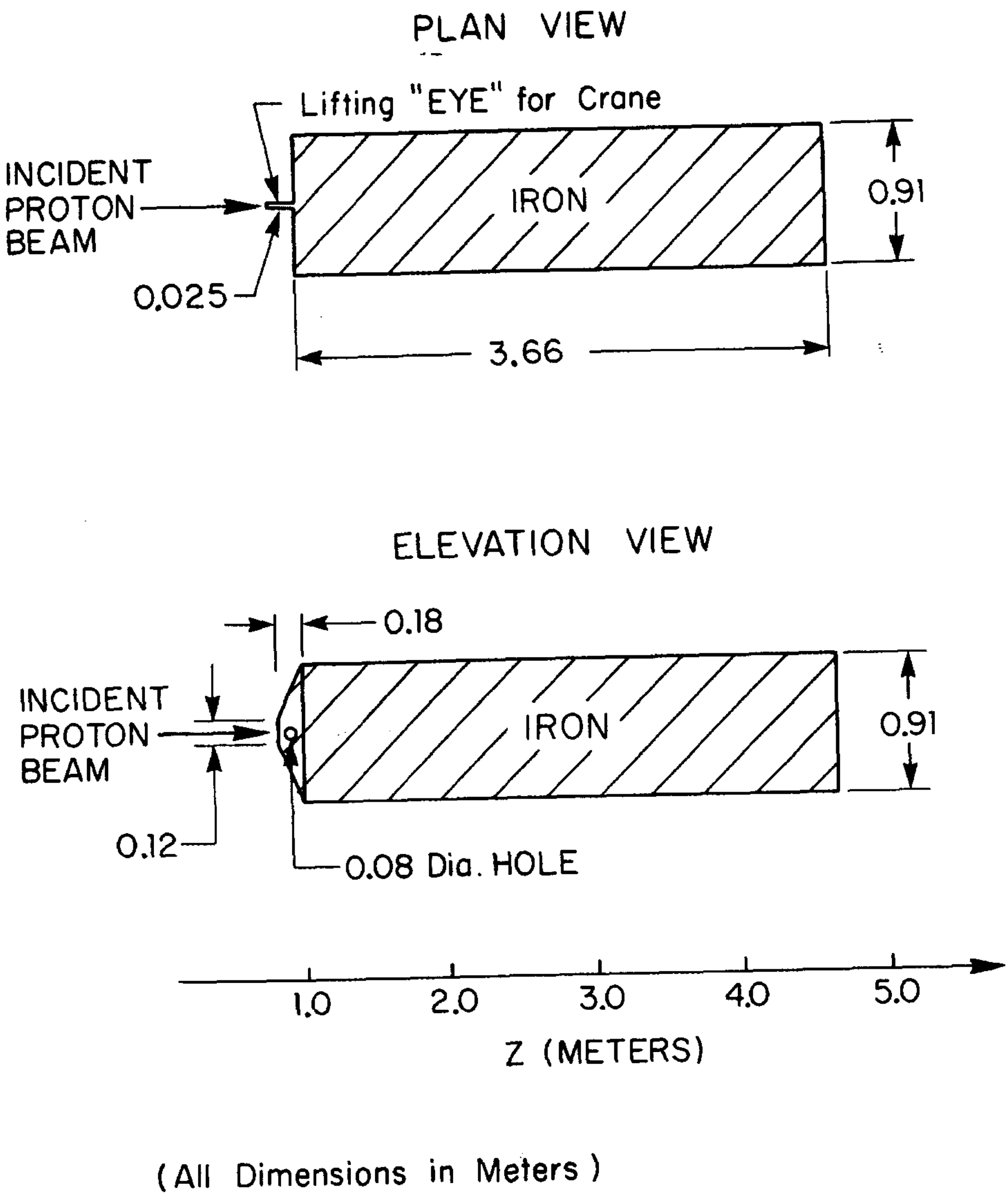

PLAN VIEW
Lifting "EYE" for Crane
INCIDENT PROTON BEAM
IRON
0.91
0.025
3.66
ELEVATION VIEW
0.18
INCIDENT PROTON BEAM
IRON
0.91
0.12
0.08 Dia. HOLE
1.0
2.0
3.0
4.0
5.0
Z (METERS)
(All Dimensions in Meters)

Figure 1

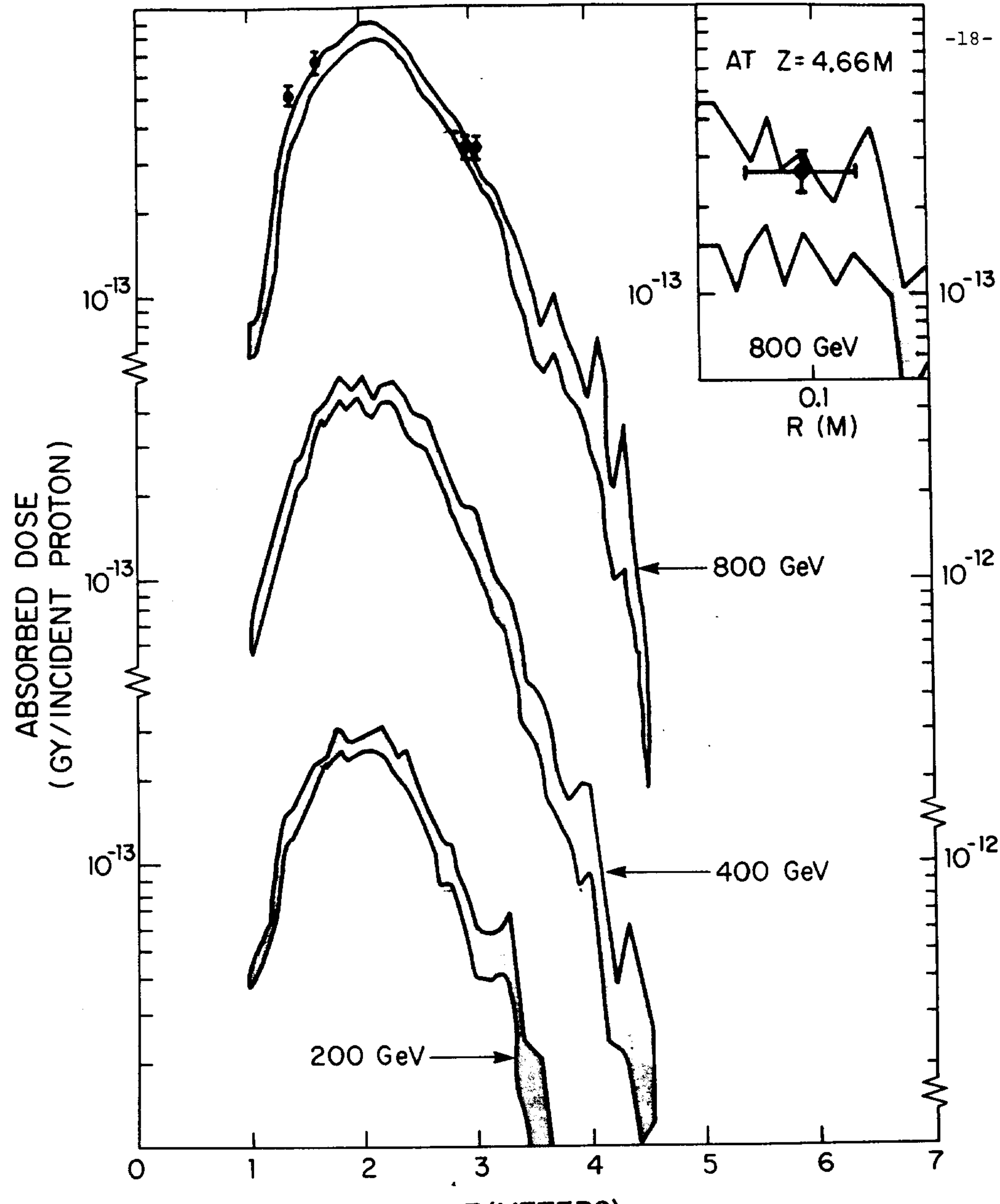

AT Z=4.66M
800 GeV
0.1
R (M)
10^{-13}
10^{-13}
10^{-13}
10^{-13}
10^{-13}
10^{-13}
10^{-12}
10^{-12}
ABSORBED DOSE
(GY/INCIDENT PROTON)
800 GeV
400 GeV
200 GeV
0
1
2
3
4
5
6
7
Z (METERS)

Figure 2

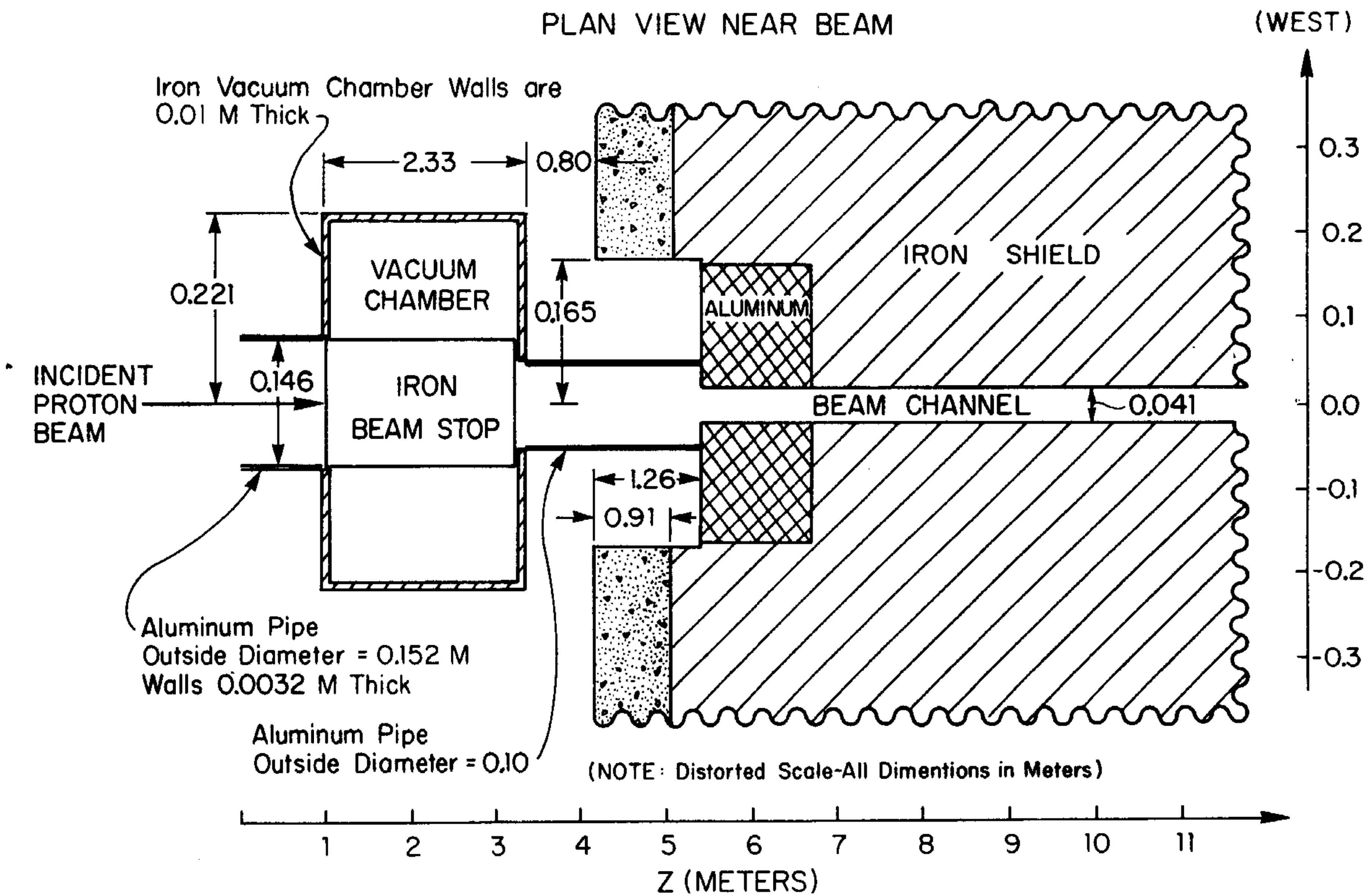

PLAN VIEW NEAR BEAM
(WEST)
Iron Vacuum Chamber Walls are
0.01 M Thick
2.33
0.80
0.221
0.146
0.165
VACUUM
CHAMBER
IRON
BEAM STOP
INCIDENT
PROTON
BEAM
ALUMINUM
IRON SHIELD
BEAM CHANNEL
0.041
1.26
0.91
Aluminum Pipe
Outside Diameter = 0.152 M
Walls 0.0032 M Thick
Aluminum Pipe
Outside Diameter = 0.10
(NOTE: Distorted Scale-All Dimentions in Meters)
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
1
2
3
4
5
6
7
8
9
10
11
Z (METERS)

Figure 3

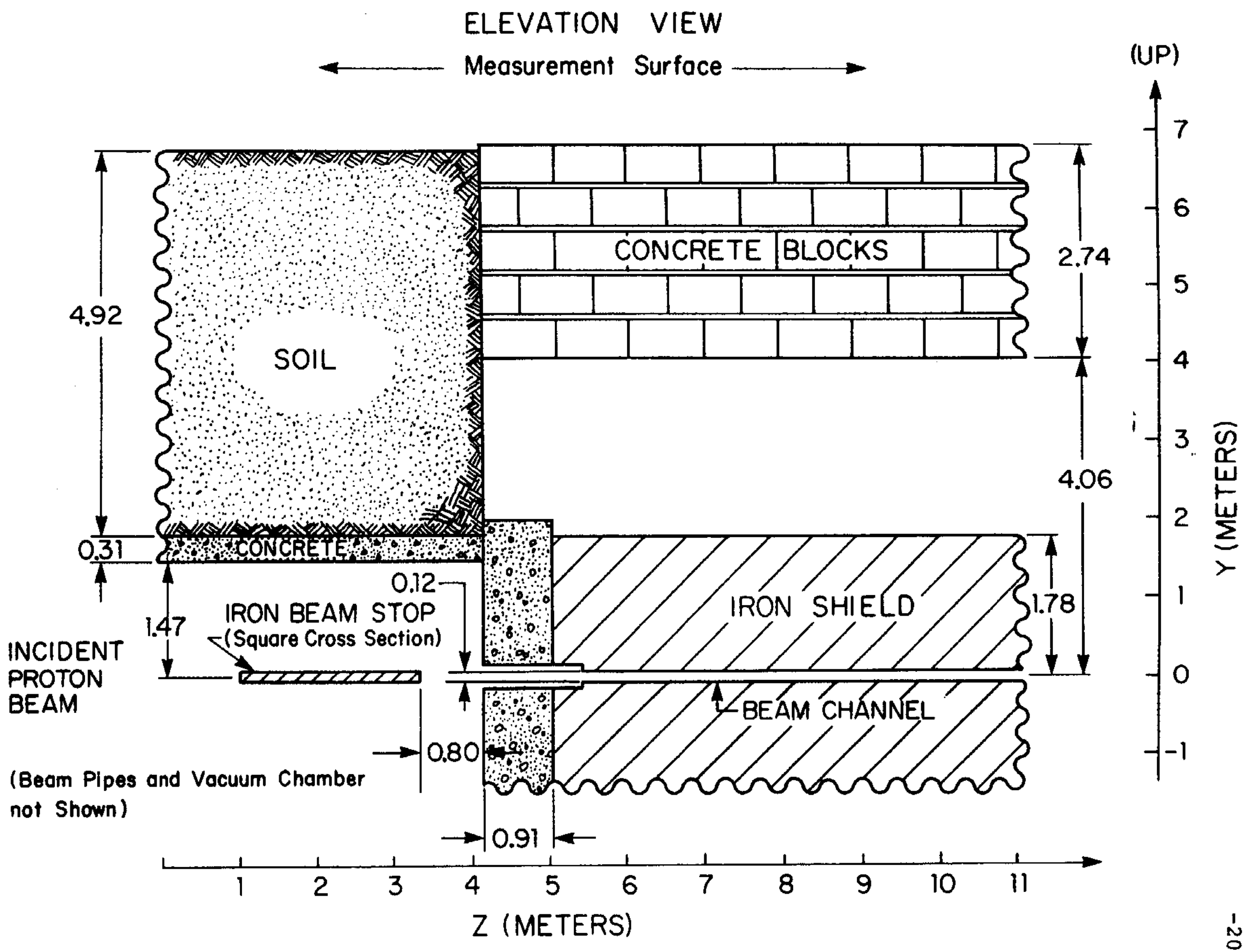
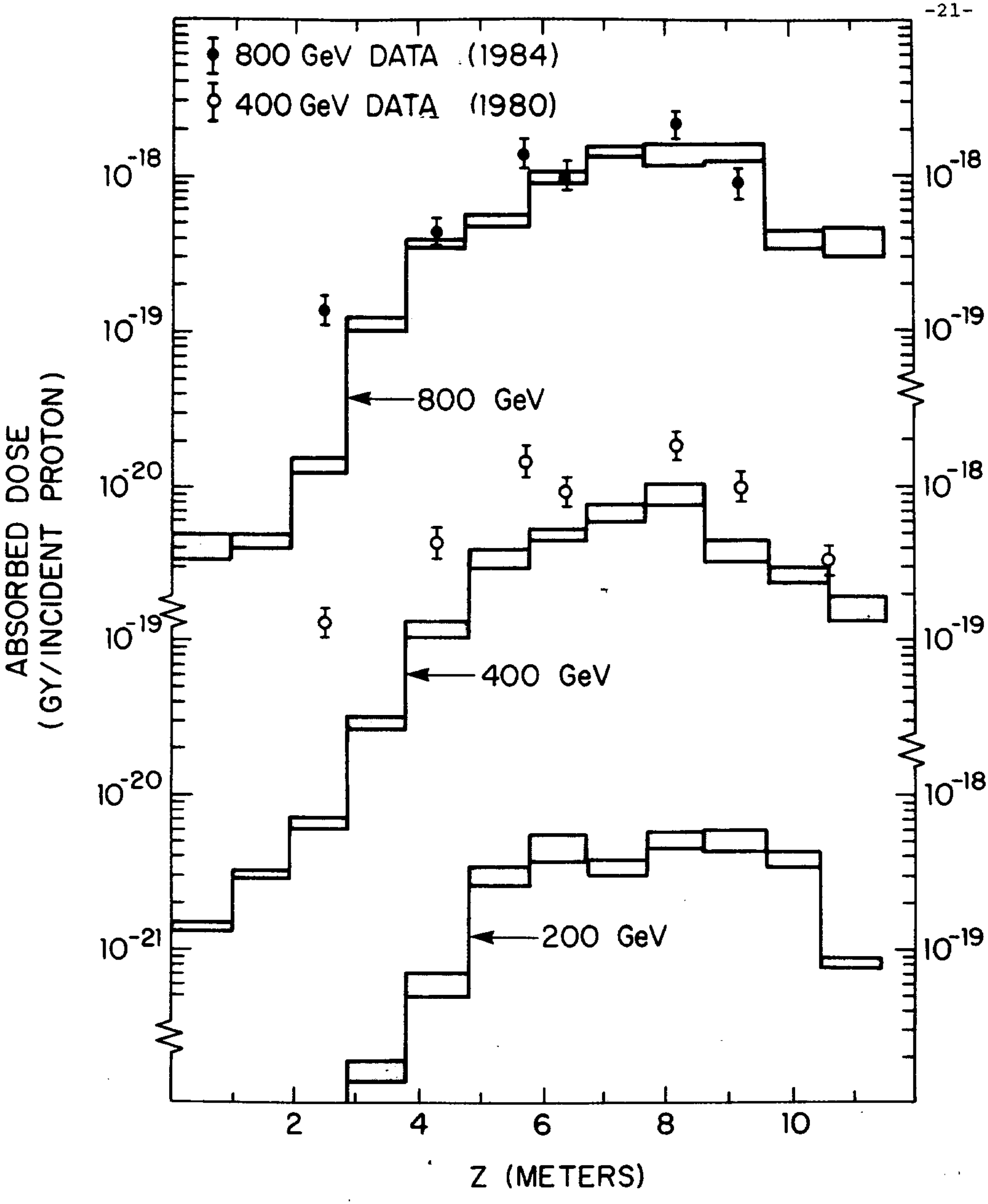

ELEVATION VIEW
Measurement Surface
(UP)
Y (METERS)
Z (METERS)
SOIL
CONCRETE BLOCKS
CONCRETE
IRON SHIELD
BEAM CHANNEL
IRON BEAM STOP
(Square Cross Section)
INCIDENT PROTON BEAM
(Beam Pipes and Vacuum Chamber not Shown)
4.92
0.31
1.47
0.12
0.80
0.91
2.74
4.06
1.78
7
6
5
4
3
2
1
0
-1
1
2
3
4
5
6
7
8
9
10
11

Figure 4



800 GeV DATA (1984)
400 GeV DATA (1980)
800 GeV
400 GeV
200 GeV
ABSORBED DOSE (GY/INCIDENT PROTON)
Z (METERS)

Figure 5