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Radiation Environment and Induced Activity Near the RHIC Internal Beam Dump

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I. Introduction

The purpose of this note is to document calculations of the radiation environment and induced radioactivity near the internal beam dump. Estimates for these quantities are required for evaluation of potential radiation damage effects on electronics or other equipment near the dump and for determining hazards in this region to personnel during periods when the collider is not running. Estimates of the radiation environment in "quiet" areas of the collider have been previously reported.[1]

II. The Dump Geometry

Figs. 1,2, and 3 are sketches of the dump as now envisaged. Conceptually, the purpose of the dump "core" is to absorb the beam energy while the steel surrounding the core (for $Z < 2.8$m as shown) serves to attenuate the radiation field to an acceptably low level. The marble ($CaCO_3$) side walls and roof are present to reduce the induced radioactivity exterior to the dump. When compared to steel (approximated as Fe), marble has relatively few long-lived spallation products.[2]

III. Energy Deposition Calculations

Energy Deposition calculations were made using CASIM.[3] The first regions of interest examined are indicated in Fig. 4 which shows an outline of the dump cross section (Fig. 1) superimposed in a "typical" ring cross section. The lower cable trays shown in this figure are not required in the regions occupied by the dumps[4] (upstream of Q4O at 10 o'clock). For this reason, energy deposition at the position of the upper cable tray, ~ 70 cm. above the dump roof, was calculated. As indicated in Fig. 4, silicon strips (taken as 4 cm. thick) were artificially assumed to exist at this location as well as at the midplane wall of the tunnel, ~ 1.9m from the beam center line. For these locations, CASIM runs could be made using 2-dimensional approximations of the dump geometry obtained by azimuthally symmetrizing the material along the lines shown in Fig. 4. This procedure greatly increases the statistical precision for a given amount of CPU time while sacrificing the ability to obtain energy deposition densities "everywhere". For comparison with the cable tray and wall positions, energy densities were obtained at the outer edges of the marble roof and side wall as indicated in the figure.

CASIM runs were made with 100 GeV/c protons. The results, expressed in rads/p, are shown in Figs. 5 and 6. The statistical error on the points in these figures below 10^{-13} rad/p is ~ 30%. From the "Beam Loss Scenario"[5] the annual beam dumped (at 4 times the

RHIC design intensity) is equivalent to 1.84 x 10^{17} 100 GeV nucleons. At the cable tray position (Fig.5) the maximum dose is therefore 180 krad per year which descreases to 5.5 krad per year at the entrance to Q5.

The second region of interest explored was near the beam pipe at Q4 and Q5. In this (relatively crude) simulation these magnets were treated as simple Fe cylinders whose inner radius is that of the beam pipe (3.45 cm.) and whose outer radius is that of the yoke (13.8 cm.). Both cylinders were divided into 5 radial and 10 longitudinal regions for the purpose of binning energy deposition and the "beam pipe" is defined as the innermost radial region ($\Delta r \sim 2$ cm.). The azimuthal symmetry is broken by both the incident beam source and the magnetic field[6] in the quadrupoles. The asymmetry is estimated by keeping track of the energy deposition in four azimuthal regions (left, right, up, down) in the entire cylinder and assuming that this average asymmetry applies to all regions.

Energy deposition density averaged over azimuth in the "beam pipe" region is shown in Fig. 7. The error bars shown here result from the rms of three CASIM runs with different random number seeds; in cases where the rms exceeds the average, a downward directed arrow is shown. It should be clear that this geometry suffers from poor statistical precision, especially in the Q5 region, where energy deposition is very low due to the shielding effects of Q4. In both Q4 and Q5, approximately 60% of the energy was in the "right" (side opposite the incident beam) quarter of the azimuth which means the values in Fig. 7 should be multiplied by ~ 2.5 for an object on the beam midplane. Applying this factor combined with the annual beam dumped as above results in:

Dose at Q4 entrance $\sim 8 \times 10^{-13} \times 2.5 \times 1.84 \times 10^{17} = 370$ krad per year

Dose at Q5 entrance $\sim 6 \times 10^{-14} \times 2.5 \times 1.84 \times 10^{17} = 28$ krad per year.

It should be clear that the error on the Q5 estimate is very large.

IV. Estimates of Induced Activity

The method employed for estimating induced activity combines results from CASIM star density calculations with calculations made by Barbier.[2] Barbier gives the induced activity at some point P to be:

$$Ac(P) = D \bullet \phi \bullet W$$

where D is the "danger parameter" tabulated by Barbier for spallation reactions in various materials and for various irradiation energies, ϕ is the neutron flux causing the activity, and W is the fractional solid angle defined at P from a uniformly radioactive body of infinite thickness.

Many approximations must be made since the bodies in question here - the dump itself and the first two magnets, Q4 and Q5, downstream of the dump - are neither infinite nor uniformly irradiated by mono-energetic neutrons. In the approximation that all CASIM hadrons are neutrons, the flux of neutrons above the CASIM threshold of 47 MeV is given by $\phi = I \bullet \lambda \bullet S.D.$ where I is the rate of incidents per second, λ is the (high energy) neutron interaction length in cm. and S.D. is the "star density" calculated by CASIM[3] in stars/cm^3. In the case of marble (steel), we will assume that the relevant star density is that averaged over the outer 10 cm. (3 cm.) of the region in question. This value is appropriate given the assumption that the "typical" photon causing induced activity is 500 keV; such a photon has an absorption length of 12.5 g/cm^2 in both materials.[7]

With these approximations, the activity at point P viewing some surface S becomes:

$$Ac(P) = K \bullet D \bullet I \bullet \lambda \bullet (\int_S S.D.dW)/4\pi$$

where K is an enhancement factor which has two parts. The first corrects the CASIM threshold to an assumed spallation threshold of 10 MeV and amounts to a factor of 2.[8] The second part is a photon build-up factor which is also taken to be a factor of 2.[9] We then have:

$$Ac(P) = D \bullet I \bullet \lambda \bullet (\int_S S.D.dW)/\pi$$

$$(1) \qquad Ac(P) = D \bullet I \bullet \lambda \bullet (\int_S S.D.\{e_r \bullet e_n/r^2\}dA)/\pi$$

where e_r is a unit vector directed from an area dA on the surface S with normal e_n to the point P a distance r from dA.

The combination of CASIM runs and numerical integrations of the expression given above have been performed the geometries described below. From Ref. [5], the highest repetitive beam dumping occurs in either studies or periods of proton, Au running. In either case, approximately 4 times the design Au intensity can be dumped every two hours for extended periods of time. This is equivalent to 4.49 x 10^{13} 100 GeV nucleons in two hours which gives:

$$I = 6.24 \times 10^9 \text{ 100 GeV/c protons per second.}$$

For the danger parameter, we choose the 500 MeV values for 360 days of irradiation given in Ref. [2] which are reproduced in Table I below:

Table I
Danger Parameters for 500 MeV and 360 days irradiation
in units of mrad/hr per neutron/cm^2sec.

Cooling time	Marble	Steel
1 hour	4.6×10^{-6}	5.0×10^{-5}
1 day	1.3×10^{-6}	3.2×10^{-5}
10 days	4.2×10^{-7}	1.8×10^{-5}

The geometry used for the evaluation of eqn (1) is sketched in Fig. 8 which shows three points considered, each one 1 ft. from an irradiated object. The first two points in this figure, P_1 and P_2, view the dump side wall where Z < 2.8m and Z > 2.8m respectively. For both these points, the integral is calculated for both the outer marble surface and the closest steel surface.[9] The actual contribution at these points from the steel is reduced by the shielding represented by the marble. Again assuming the typical photon to be 500 keV obtains a reduction factor of $e^{-t/4.62}$ where t = 15 cm. for P_1 and 10 cm. for P_2. The third point in Fig. 8 is 1 ft. from a crude approximation of the cryostat, namely a cylindrical volume extending from R = 13.8 cm. to R = 39 cm. filled with Fe at 2% of the normal density or 0.15 g/cm^3. In this case the star density used for the cryostat contribution was averaged over the entire cryostat volume and, as in the case of the dump, added to a contribution from the outer 3 cm. of the yoke steel.

The results, which combines star density CASIM calculations in the regions described with the values of I and D given above and a numerical evaluation of eqn. (1) are shown in Table II below.

Table II
Induced Activity in mrem/hr at 1 ft. from Locations Indicated

	Dump (Z < 2.8m)			Dump (Z > 2.8m)			Q4
Cooling time	marble	steel	Total*	marble	steel	Total*	
1 hour	6.0	9.5	6.4	6.6	25.8	9.6	0.9
1 day	1.7	6.1	1.9	1.9	16.5	3.8	0.6
10 days	.55	3.4	.70	.60	9.3	1.7	0.3

* Total = marble + steel•$e^{-t/4.62}$ where t = 15 cm. or 10 cm.

The values shown in Table II are the worst-case values found at 1 ft. distance in the Z (beam direction) ranges indicated; the points shown in Fig. 8 are illustrative. Although not indicated in Table II, the activity at 1 ft. distance from Q5 was also calculated and found to be 20 times lower than the value quoted for Q4.

Also calculated, by the same methodology, was the induced activity at a 1 ft. distance from the bare dump core. This value is of interest because of the possibility of damage to the dump. We assume here that repair would involve first removing the marble roof and outer steel shielding which would be followed by swapping the dump core, together with its vacuum pipe, with a spare core assembly. At 1 ft. from the core and 1 hour cooling time, the induced activity was found to be ~ 300 mrem per hour.

V. Summary

Estimates of both the radiation environment and induced radioactivity at selected locations near the RHIC internal dump have been made. At about 1m lateral distance from the dump, the radiation dose may achieve a maximum value of near 200 krad per year which decreases to ~ 5 krad per year 15m downstream of the dump. At the beam pipe radius, the dose is expected to be in the 200-400 krad per year range at the entrance of Q4O (7m downstream of the dump entrance) which decreases by an order of magnitude or more at the entrance of Q5O.

At a 1 ft. lateral distance and 1 hour cooling time, induced activity is estimated to be quite small, nominally 10 mrem/hr at the dump and 1 mrem/hr at Q4. The induced activity at 1 ft. from a bare dump "core", which might be exposed in the event a swap of core assemblies were required, has been estimated to be 300 mrem/hr.

References/Footnotes

1. A.J. Stevens, "Radiation Levels at Floor Level from Local Beam Loss in RHIC," AD/RHIC/RD-27, 1991.

2. M. Barbier, **Induced Radioactivity**, North-Holland, New York, 1969. Note especially the concept of "Danger Parameters" discussed in Chapter 1 of this reference and tabluated in Appendix B.

3. A. Van Ginneken, "CASIM; Program to Simulate Hadron Cascades in Bulk Matter," Fermilab FN-272 (1975).

4. P.K. Feng, private communication. The lower cable trays shown would likely interfere with space required to assemble and disassemble the dump.

5. M. Harrison and A.J. Stevens, "Beam Loss Scenario in RHIC", draft version 8 dated 09/11/92.

6. The (purely quadrupole) magnetic field is simulated within the gap ($r < 3.45$ cm.) but ignored in the Fe cylinder.

7. Barbier, Fig. I.16.

8. A.J. Stevens, "Analysis of Radiation Levels Associated with Operation of the RHIC Transfer Line", Draft RHIC Tech. Note dated 09/28/92. This reference gives the assumed equilibrium spectrum which is used to estimate effects below the threshold. Above 7 MeV, an energy dependence of $E^{-1.4}$ is assumed.

9. The contribution at P_2 shown in Fig. 8 is confined to the wall for $Z > 3$m. The "hole" in the marble wall between $Z = 2.8$m and $Z = 3$m should, in fact, be filled and any contribution from this region has been ignored.

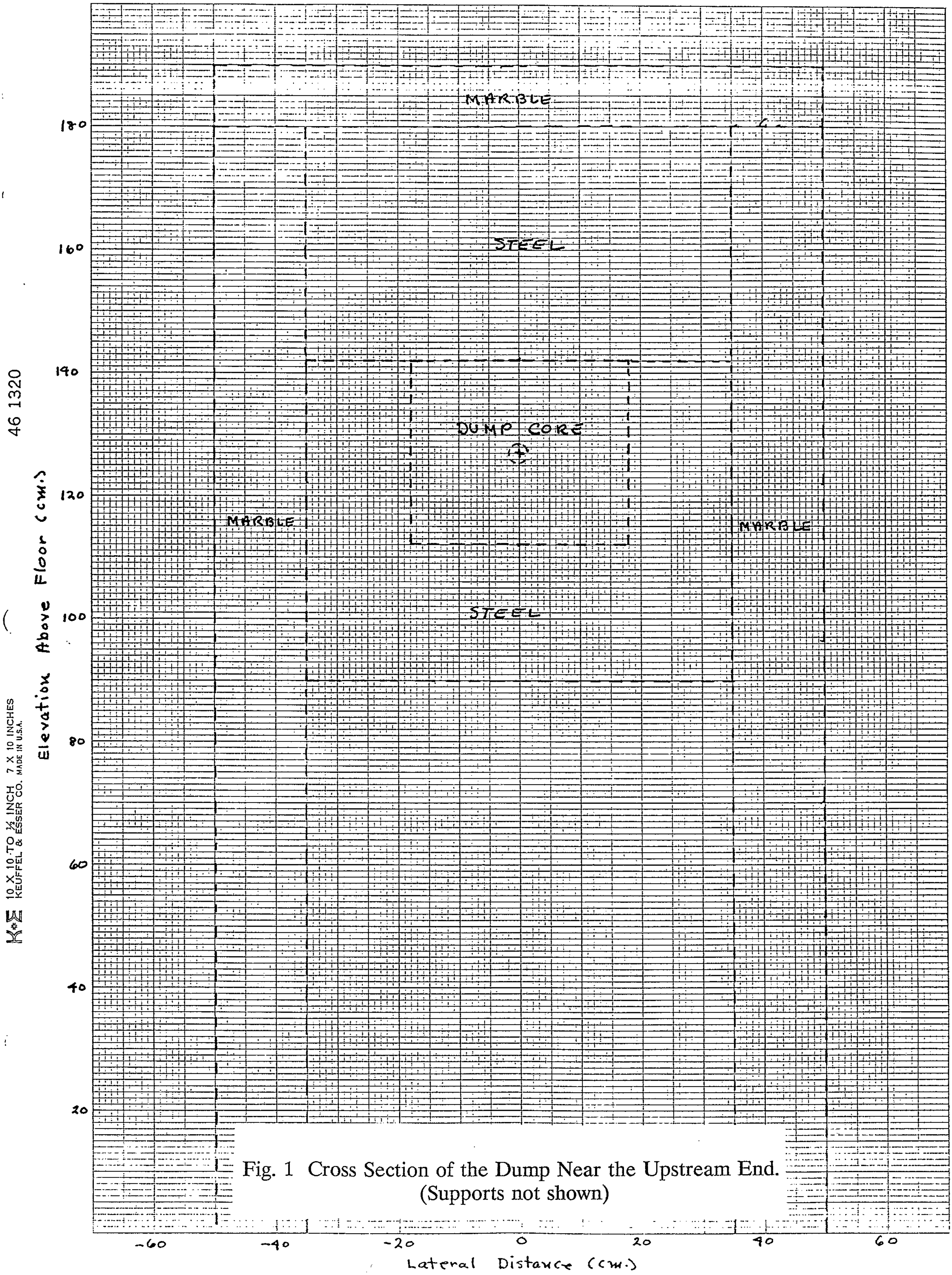

Fig. 1 Cross Section of the Dump Near the Upstream End.
(Supports not shown)

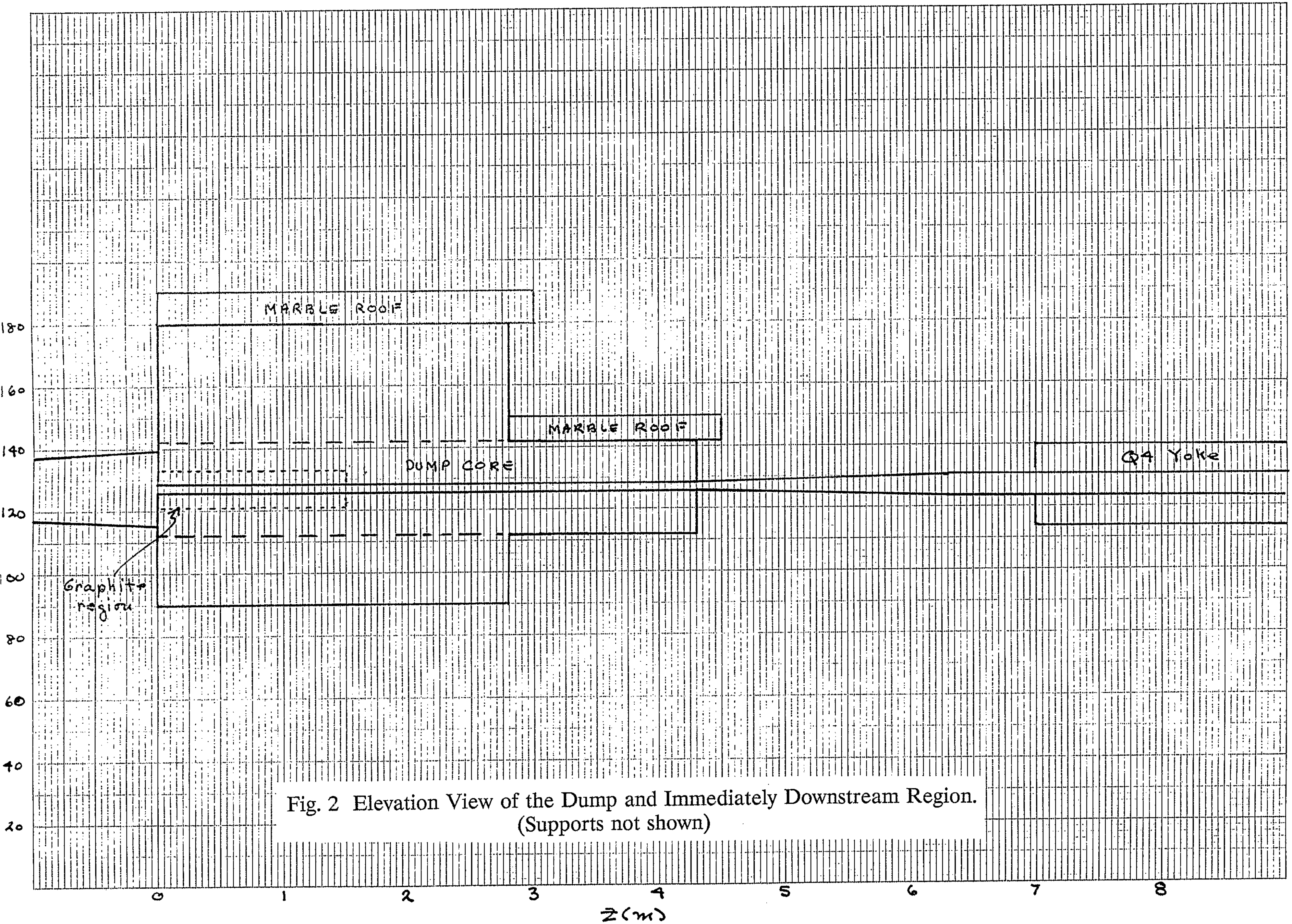

Fig. 2 Elevation View of the Dump and Immediately Downstream Region.
(Supports not shown)

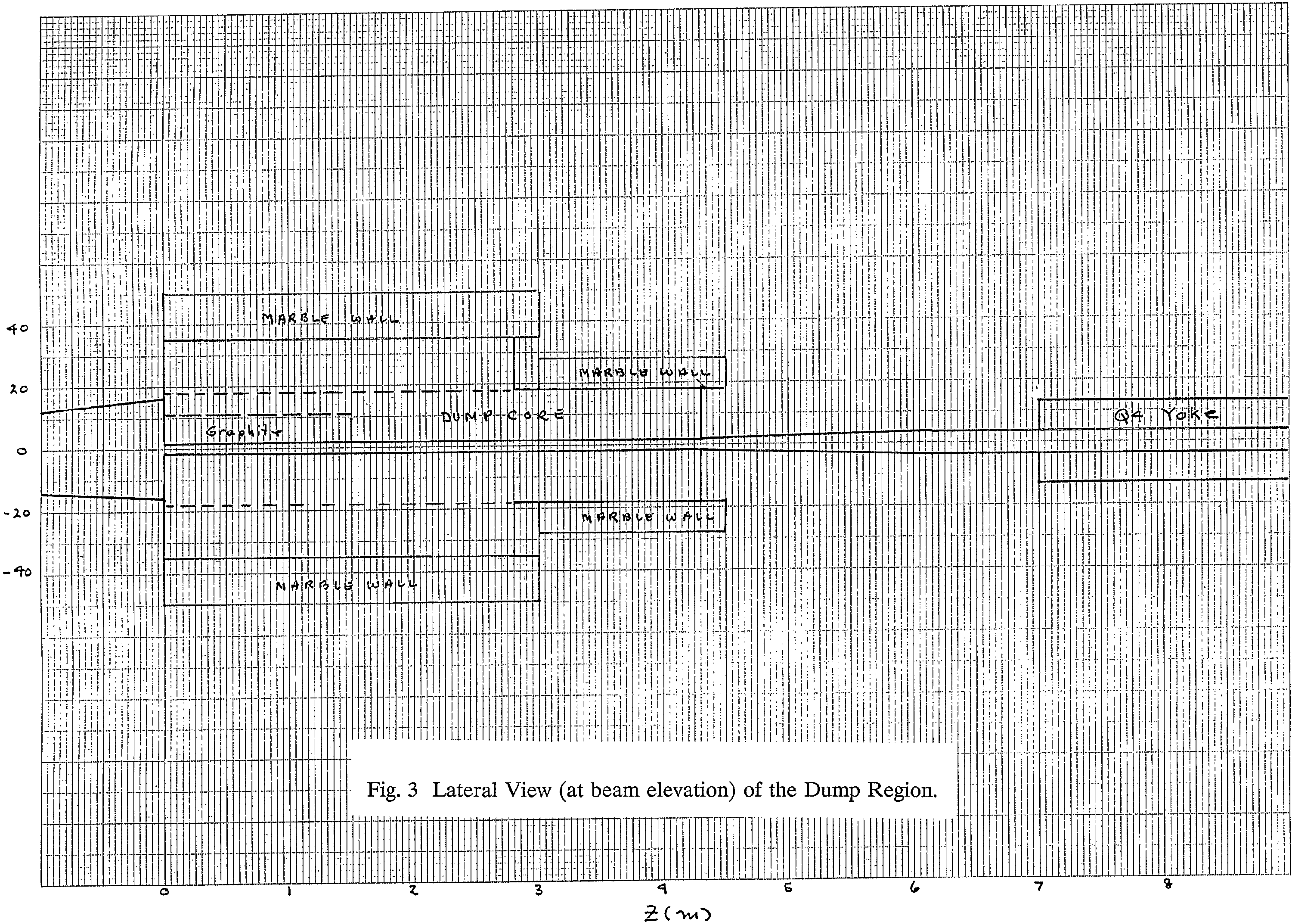

Fig. 3 Lateral View (at beam elevation) of the Dump Region.

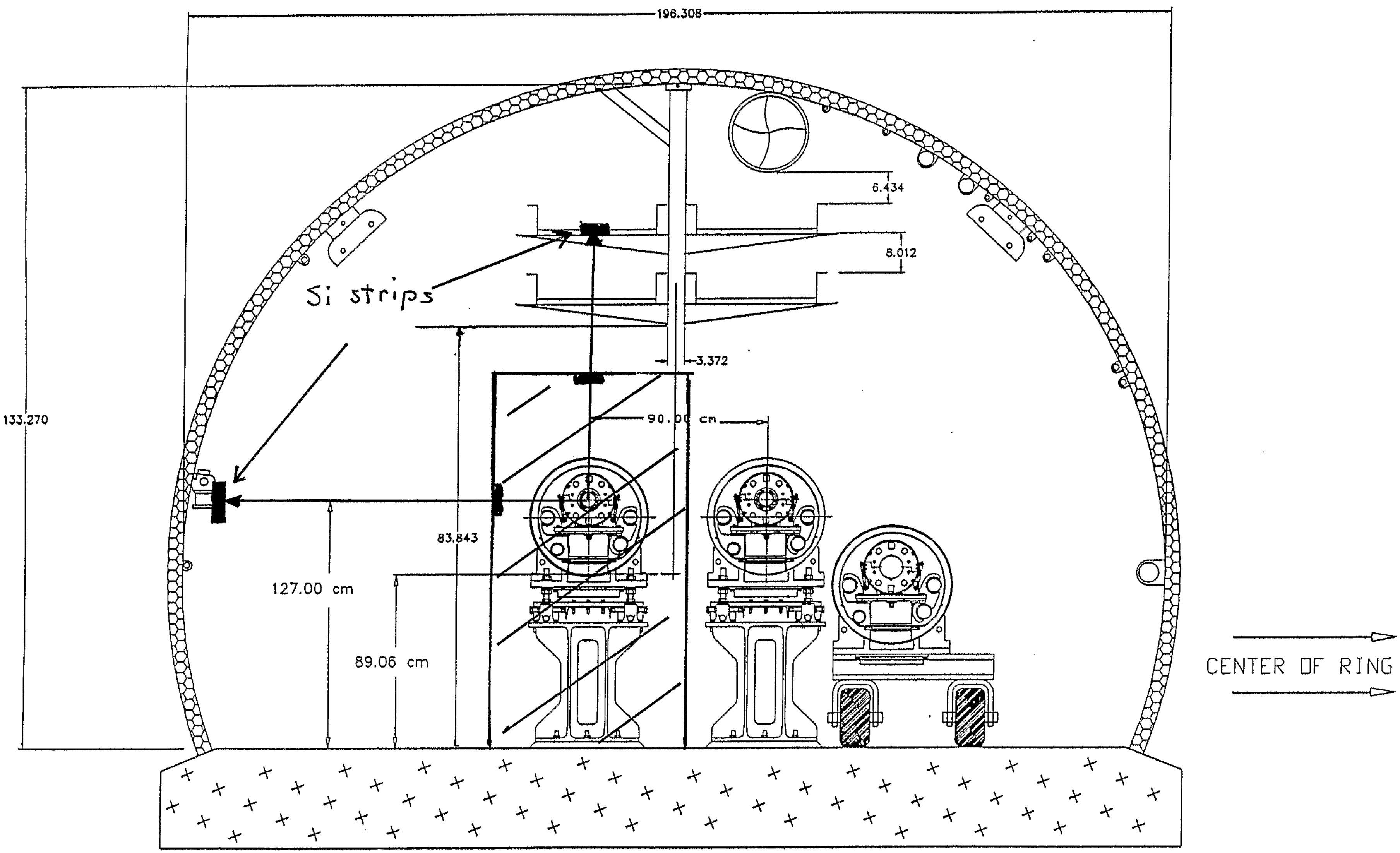

Fig. 4 The Dump Upstream Cross Section as Located in the Tunnel. Energy Deposition is Calculated (vs. Z, the beam direction) in the dark regions shown.

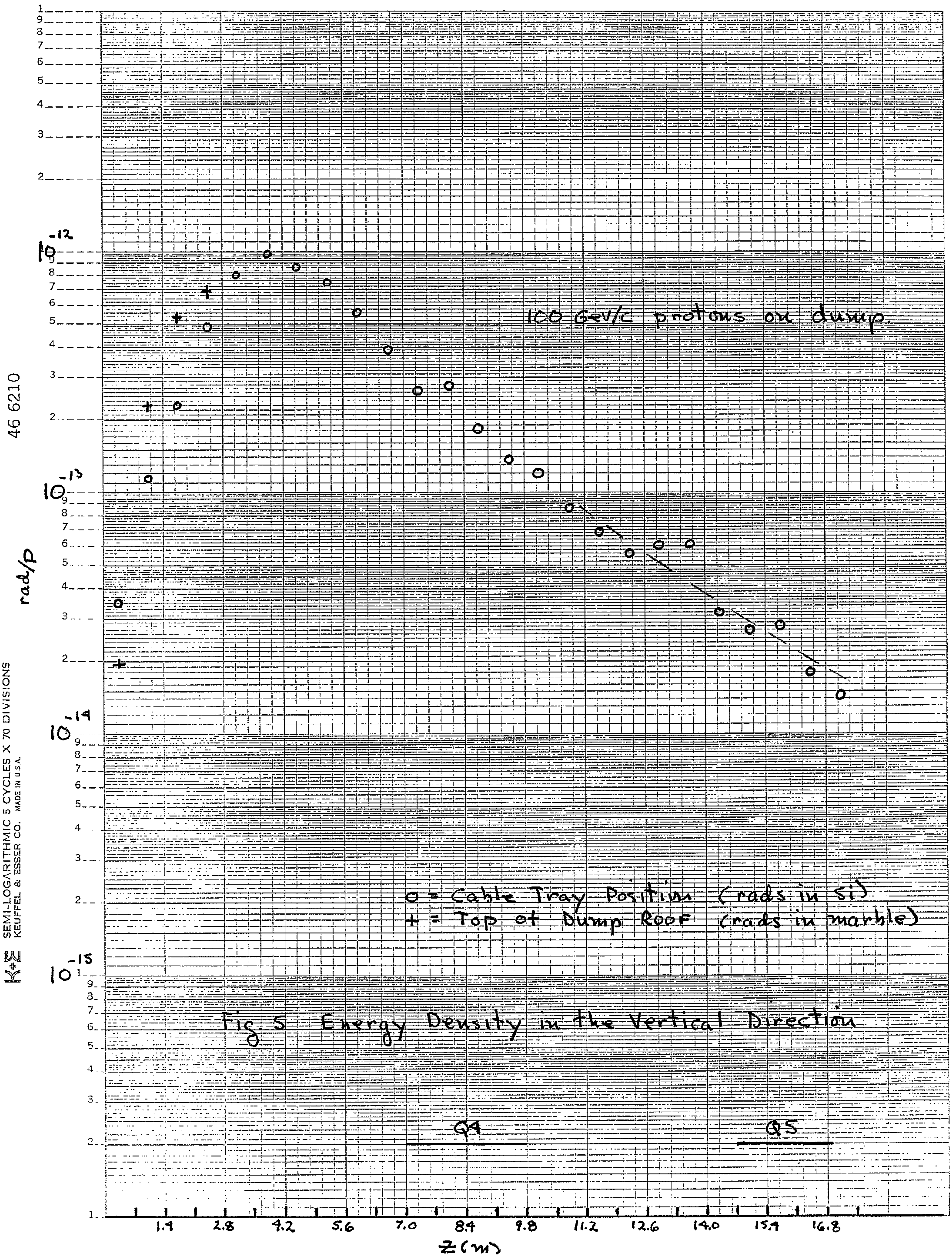

Fig. 5 Energy Density in the Vertical Direction

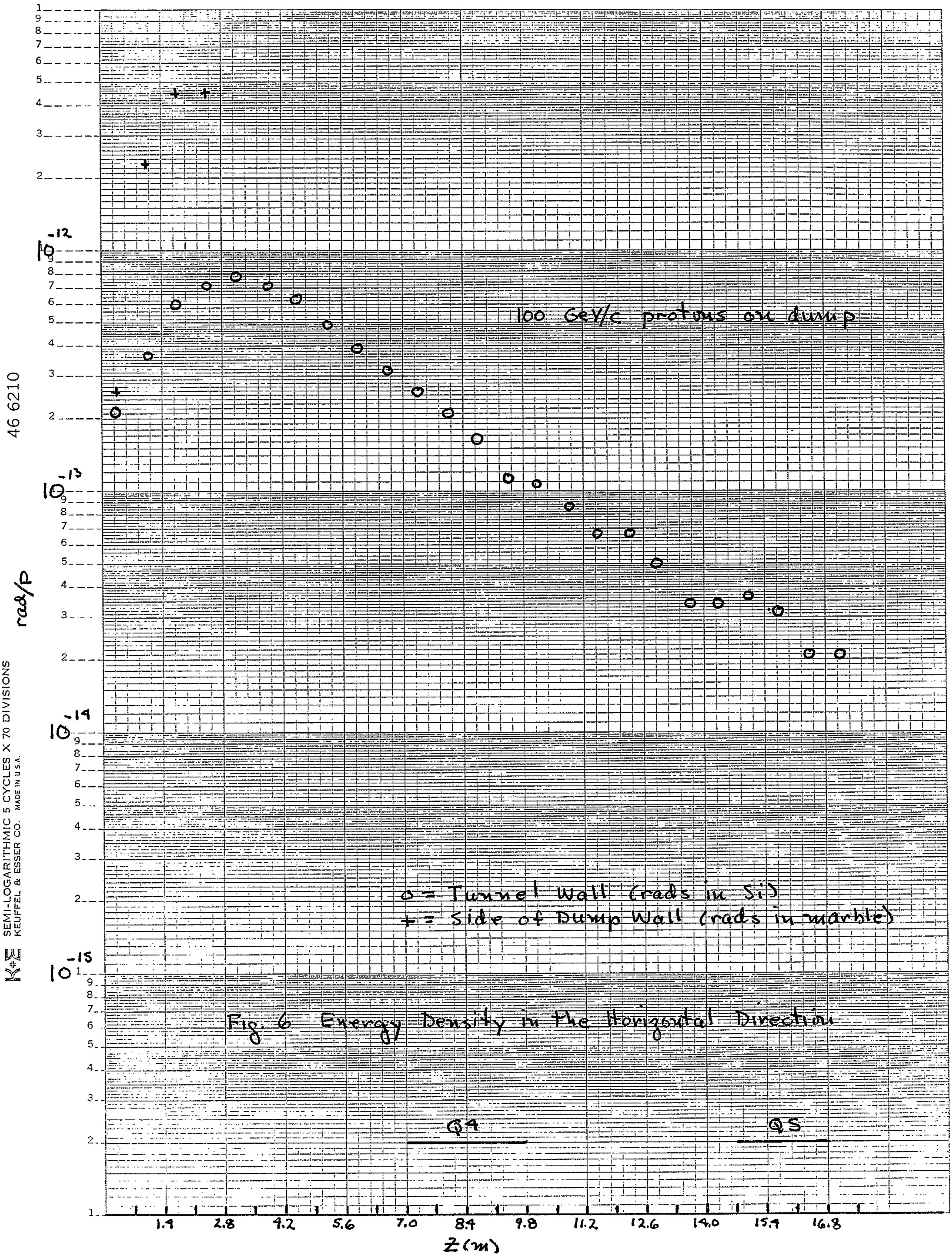

Fig. 6 Energy Density in the Horizontal Direction

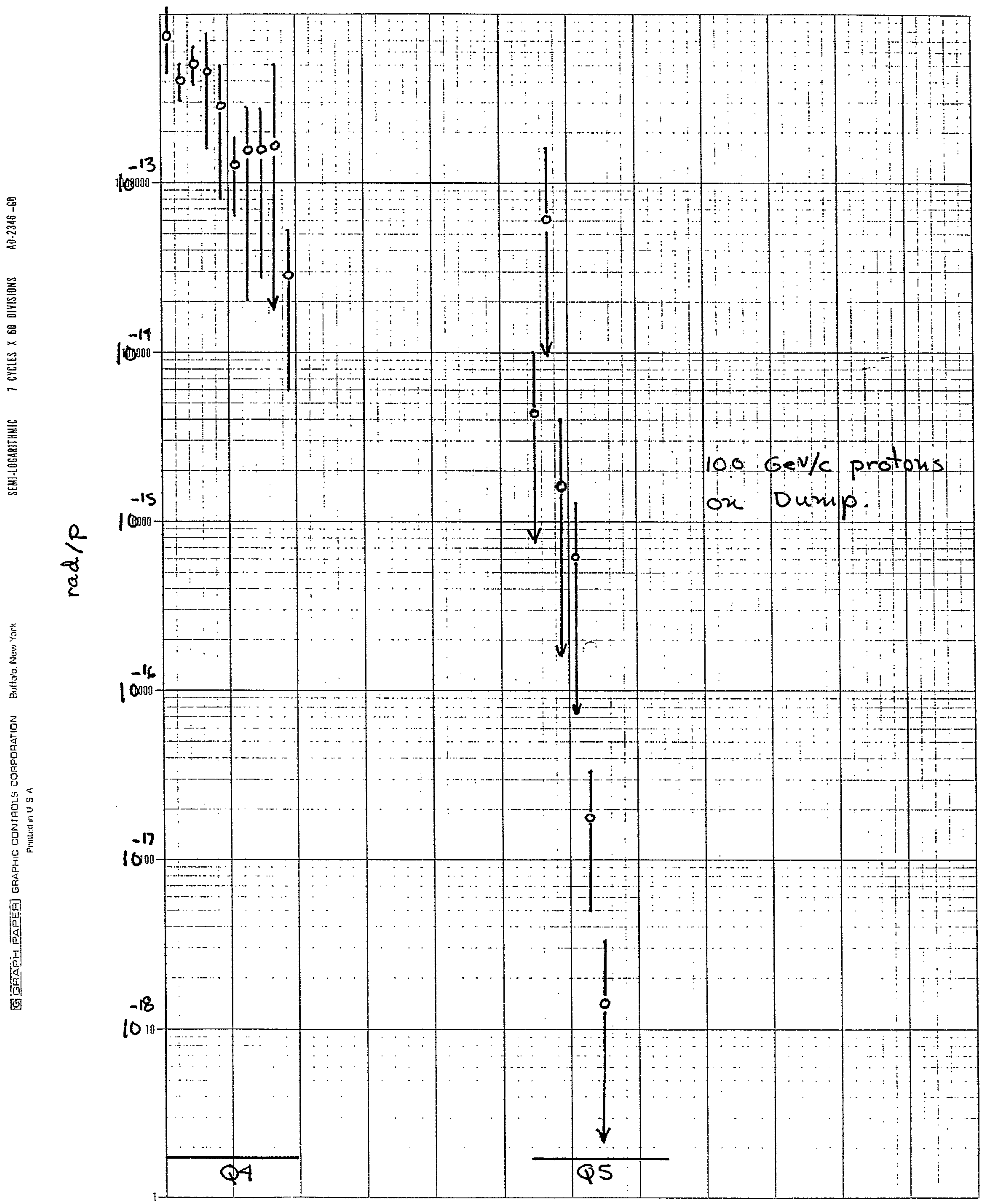

Fig. 7 Azimuthally Averaged Energy Density in the Innermost Radial Region vs. Length in Q4 and Q5

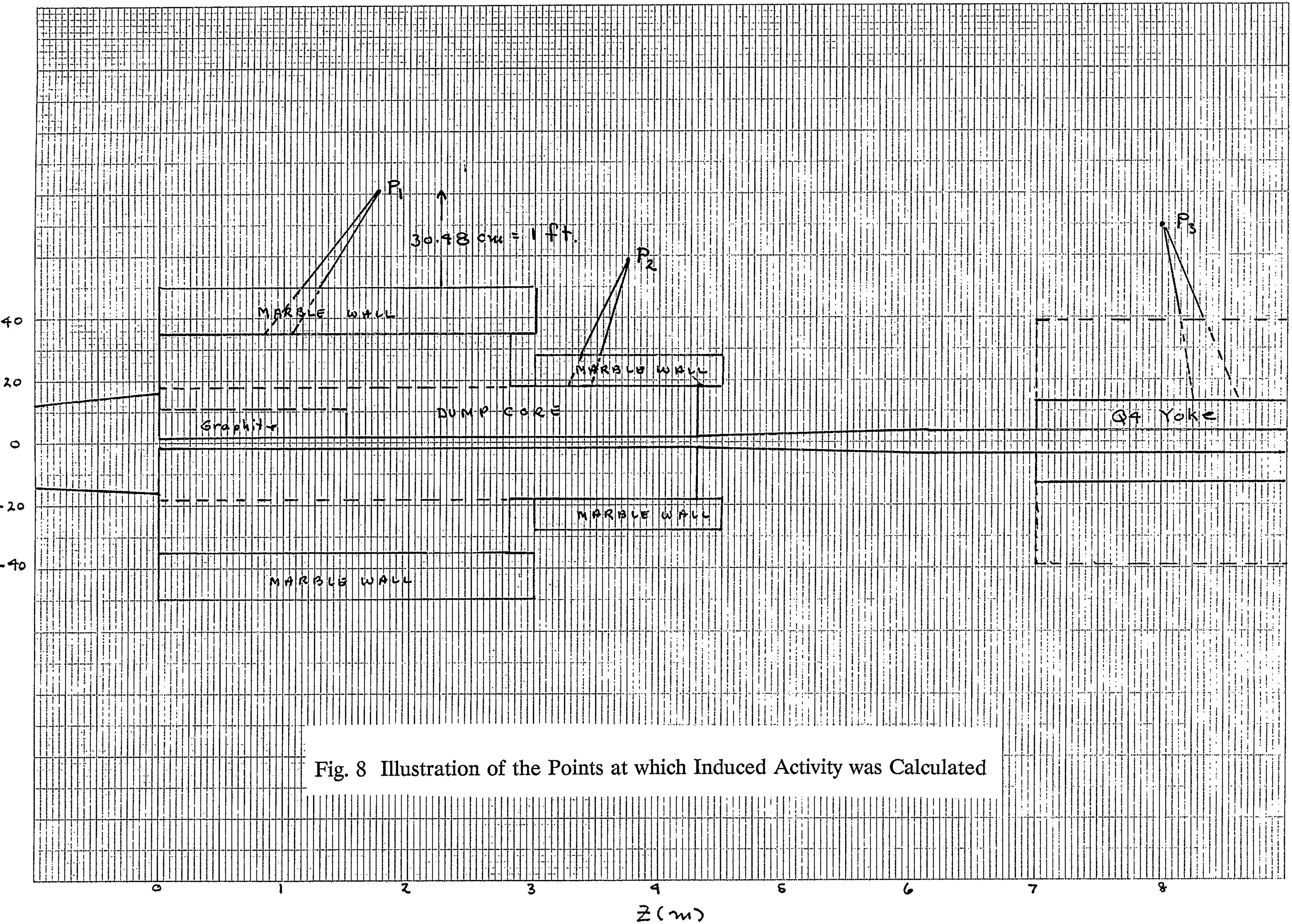

Fig. 8 Illustration of the Points at which Induced Activity was Calculated