

Lawrence Berkeley National Laboratory

Recent Work

Title

SHIELDING MEASUREMENT AT THE CERN 25 GEV PROTON SYNCHROTRON

Permalink

<https://escholarship.org/uc/item/0hd4r4g0>

Author

Gilbert, W.S.

Publication Date

1969-10-20

For 2nd Intern. Conf. on Accelerator Dosimetry
and Experience, Stanford, California, November 5-7,
1969

UCRL-19367
Preprint

cy.L

SHIELDING MEASUREMENT AT THE CERN 25 GeV PROTON SYNCHROTRON

W.S. Gilbert

NOV 25 1969
LIBRARY AND
DOCUMENTS SECTION

October 20, 1969

AEC Contract No. W-7405-eng-48

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545*

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

UCRL-19367

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

SHIELDING MEASUREMENT AT THE CERN 25 GEV PROTON SYNCHROTRON

W. S. Gilbert

Lawrence Radiation Laboratory
University of California
Berkeley, California

October 20, 1969

Introduction

In late 1966, a series of eight shielding experiments was carried out on the CERN proton synchrotron (CPS). This was a joint program of CERN, the Rutherford High Energy Laboratory, and the Lawrence Radiation Laboratory — Berkeley. The complete details are available in a final report, UCRL-17941.¹ This report is available, for those who have not already received a copy, from Wade Patterson of LRL. Many copies have already been distributed, and this talk is an outline of the work and the report.

Experimental Procedure1. Method of Generation of Neutron Flux

Two momenta of the primary circulating protons were used in these experiments, 14.6 and 26.4 GeV/c. The circulating internal beam was allowed to interact in a multiple-traversal thin target, which yields the maximum percentage of target interaction. In addition, a clipper to clean up the halo of the beam was placed far from the target; concentrating the loss in the regions of the target and of the clipper should result in a minimum fraction of the beam's being lost randomly around the accelerator.

2. Geometry of Flux Measurement

Figures 1, 2, and 3 show a cross section of the tunnel and shield, a plan view, and an elevation view of the general geometry of the accelerator and the placement of the detector holes. Figure 4 is a detail of the vertical-hole sample holder. In these various sample positions were placed various detectors, the vast majority of which were activation detectors. The use of activation detectors enables one to simultaneously irradiate hundreds of samples in different locations and to count them after the end of the run. All together 15 different detectors, activation detectors, and various counters and chambers are listed in the report. The most important detectors--the

ones most often used--were aluminum and carbon threshold activation detectors. Aluminum responds to neutrons above 6 MeV and carbon to those above 20 MeV. The various activation detectors were placed inside the tunnel, along the vacuum chamber, and in the earth shield, and we could therefore obtain three-dimensional flux data around the target and clipper regions of the CPS.

In addition, by the use of detectors with different energy thresholds, neutron spectra could be determined.

Experimental Results

1. Pattern of Loss Around the Ring

a. Ring top

The ionization caused by the leakage flux through the earth shield above the beam orbit was measured with an integrating ion chamber. The distribution of this radiation is shown in Fig. 5. One can see that the loss is maximum above and slightly downstream from the target and beam clipper, and is much lower above the other positions of the accelerator.

b. Beam vacuum chamber

Aluminum activation detectors were placed on the vacuum chamber at each of the 100 magnets around the accelerator. The induced activity is proportional to the neutron flux above the 6-MeV threshold, and there are reasons to believe that this flux is proportional to the loss rate of the primary multi-GeV protons. Figure 6 is a typical spatial distribution of this induced aluminum activity. An analysis of this loss around the machine enables one to calculate what the source strength, or the emitted flux, is. Figure 7 gives more detail in the region of the target; here aluminum detectors with finer spacing were used. One can see the influence of the individual magnets. Generally, one finds that although the losses in the strongly interacting target and clipper regions are much larger than the random loss far from them, still 10-25% of all the beam that is lost is lost more than $\frac{1}{2}$ betatron wavelength from these two regions, and only some 75-90% of the losses are concentrated there.

2. Angular Distribution of Flux from Target

A variety of detectors with different thresholds was used very near the target (radii of 25 and 100 cm) to determine the angular distribution of emitted radiation. (This is written up in detail in the report.)

3. Attenuation of Flux in the Shield

The same general picture of attenuation of neutron flux in the shield was found irrespective of the detector used. Qualitatively, one found that the loss fell off with distance from the target along the direction of the beam orbit, and also fell off rapidly, approximately exponentially, with increasing

transverse thickness into the shield. The analysis of these data appears in the next section.

4. Neutron Spectra

The neutron spectra displayed in Fig. 8 are derived from the measured activities of detectors with various neutron thresholds.

Theoretical Model -- Fitting of Data

1. Moyer Model

The model we used in attempting to fit the experimental data is an extension of the Moyer model, which is a phenomenological theory that physically concentrates on the penetrating or high-energy part of the neutron spectrum. The low-energy part of the neutron spectrum that actually contributes the majority of the dose delivered is assumed to be locally generated near the point of detection. Because of the shorter attenuation length of this low-energy component, virtually none of it comes from the accelerator itself. The procedure, therefore, is to identify a source strength and a characteristic angular distribution, follow the penetrating component with a proper attenuation length, and assume that for this penetrating component a geometrical attenuation based on the inverse square of the distance from the source point to the field point applies. One then integrates over all possible source elements at a given field point; this should give the observed flux.

Our experiment enabled us to check whether an expression of the type in Eq. (1) can successfully explain our measurements. Figure 9 shows an elevation of the CPS tunnel. In our experiment we obtained values of $\Phi(E > E_0)$ with several threshold detectors, threshold E_0 , over a matrix of points within the shielding and inside the accelerator tunnel. Thus the practical problem is to seek a solution of Eq. (1) from the given measured values of $\Phi(E > E_0)$ in terms of parameters of the quantities within the integral,

$$\Phi_p(E > E_0) = \int S(Z) \cdot \Theta(\theta) \cdot B(X) \cdot e^{-X} d\Omega dZ. \quad (1)$$

Here $S(Z)$ is the number of protons interacting in a line element dZ at a distance Z from the target, $\Theta(\theta)$ is the angular distribution, $B(X)$ is the buildup factor appropriate to the proton primary energy and threshold detector, and $X = \ell_{Fe}/\lambda_{Fe} + \ell_E/\lambda_E$, where ℓ_{Fe} and ℓ_E are respectively the path lengths through the iron and earth at angle θ , and λ_{Fe} and λ_E are the attenuation lengths in the iron and earth.

2. Variation-of-Parameters Program, FLUXFT

FLUXFT is a CDC 6600 program constructed to aid in the determination of a suitable analytic description of radiation flux measurements taken at the CERN proton synchrotron. Basically we desire to construct and evaluate a

function

$$\Phi(p, a) = \int_{-\infty}^{+\infty} f(p, a, z) dz, \quad (2)$$

where p is the point (z_p, y_p) and $[a]$ is a parameter vector $a_1 \cdots a_n$ such that the quantity

$$V(a) = \sum_{i=1}^S \left[\frac{\Phi(p_i, a) - \Phi(p_i)}{\Phi(p_i)} \right]^2 \quad (3)$$

is minimized. The values $\Phi(p_i)$ are the measured fluxes, and S is the number of data points.

The problem, as considered here, is a two-dimensional one. That is, we assume that the circular machine in the region of interest is suitably represented by a straight line. With this assumption, the problem can be defined by using a two-dimensional coordinate system in which z represents the linear distance along the beam line, and y the vertical height above the beam-line center. The origin is assumed to be to the left of minus infinity [this is physically meaningful, since $f(p, a, z)$ approaches 0 quickly] and all magnets and data points are assumed to be to the right of the origin. That is, we assume that $z > 0$ is true and that the integral converges in this region. The problem is defined by specifying all magnet edges, the magnet height, the earth-shielding height, the heights of the layers with different densities in the earth shielding, the measured flux $\Phi(z_p, y_p)$ over the set of data points, and suitable starting values of the parameter vector components a_i . Standard library integration and minimization routines are used in the program to evaluate the integral and obtain the value of the parameter vector $[a]$ that minimizes the quantity $V(a)$. The program has been constructed as a set of subroutines and function subroutines to allow the analytic form of $f(p, a, z)$ to be easily changed.

The FLUXFT program has been in routine use on the LRL Berkeley CDC-6600 for over a year. In addition, it has been used on the IBM-360 at the Rutherford High Energy Laboratory. The problem parameters and optional functional forms are enumerated below:

a. Source distribution function, $S(Z)$

It is possible to input, in addition to the analytic expression for $S(Z)$, below, a tabular set of source values which are linearly interpolated by a program subroutine:

- (i) $S(Z) = 1 + a_1 \exp(-a_3 Z),$ (4)
- (ii) Tabular set of source values $S_i(Z)$.

b. Angular distribution function, $\Theta(\theta)$

The angular distribution of emitted neutrons is assumed to be the same for every source element, $S(Z)$. Two options are available:

- (i) $\Theta(\theta) = (1 + a_2 \theta)^{-a_4},$ (5)

$$(ii) \quad \Theta(\theta) = a_2 e^{-a_4 \theta} \quad (6)$$

c. Attenuation lengths, $a_5 = \lambda_{Fe}$, $a_6 = \lambda_E$

The neutron transmission in iron is $e^{-\ell_{Fe}/a_5}$ in units of meters of Fe, and in earth it is

$$e^{-\ell_E/a_6},$$

in units of $g\text{-cm}^{-2}$. In the general case, one allows both a_5 and a_6 to be free parameters. However, it is plausible that

$$\frac{\lambda_{Fe}}{\lambda_E} = \left(\frac{A_{Fe}}{A_E} \right)^{1/3}, \quad (7)$$

so that

$$\lambda_{Fe} \approx 1.26 \lambda_E. \quad (8)$$

d. Buildup factor, $B(x)$

The buildup factor may be written as a polynomial in x , the number of neutron attenuation mean free path traversed:

$$x = \ell_{Fe}/a_5 \text{ or } x = \ell_{Fe}/a_5 + \ell_E/a_6.$$

We have limited this polynomial to a quadratic expression

$$B(x) = 1 + a_7 x + a_8 x^2. \quad (9)$$

e. Total independent parameters

Equation (1) for the calculated neutron flux above a given threshold E_0 can be written

$$\begin{aligned} & \Phi(z_i, y_i, a) \\ &= a_9 \int_{-\infty}^{+\infty} \frac{(1 + a_1 e^{-a_3 z}) a_2 e^{-a_4 \theta} e^{-\ell_{Fe}/a_5} e^{-\ell_E/a_6} (1 + a_7 x + a_8 x^2) dz}{(z - z_i)^2 + y_i^2} \end{aligned} \quad (10)$$

If a_2 is a fixed parameter, a_9 is a normalizing factor and is not an independent, or free, parameter. Usually a_2 is taken outside the integral and $(a_2 \cdot a_9)$ is a composite normalizing factor. Therefore with the simpler exponential version of the angular distribution, the maximum number of free,

or computer-adjustable, parameters is seven ($a_1, a_3, a_4, a_5, a_6, a_7, a_8$).

Simplification to only four free parameters is possible if the buildup factor is assumed constant and a_5 is set proportional to a_6 or set equal to a constant (a_1, a_3, a_4, a_6). Thus, by the use of a physically plausible model, it should be possible to reduce to as few as four the parameters necessary to describe experimental data involving 20 to 100 separate measurements. Two of these parameters, a_1 and a_3 , refer to the distribution of primary beam loss and are therefore part of the accelerator beam-dynamics problem. The other two parameters, a_4 and a_6 , refer to the equivalent angular distribution of those neutrons that dominate the shielding problem and the attenuation of these neutrons, and are therefore fundamentally related to the physical cross sections involved and not to the details of the accelerator in question. How well the data are fitted by the method discussed above and the values of the parameters to use for various accelerators are discussed in the following section 3.

f. Minimization of quantity $V(a)$

Define

$$V_i(a) = \left[\frac{\phi(p_i, a) - \phi(p_i)}{\phi(p_i)} \right]^2, \quad V(a) = \sum_1 V_i(a). \quad (11)$$

The computer program FLUXFT minimizes the quantity $V(a)$ through a variation of the parameter vector $[a]$ ($a_1, \dots, a_8$ for those components of $[a]$ that are allowed to be free variables). The quantity $V(a)$ has sometimes been referred to as the problem variance, which is an extremely loose use of the term. Since no statistical conclusions are drawn from the final numerical values of $V(a)$, the exact nomenclature is not important. Inspection of Eq. (11) shows that we are summing the squares of the relative errors for each measured flux, and giving each point an equal weighting factor. In certain counting experiments one gives higher weight to points measured with better statistical precision, and in certain types of error analysis one gives greater weight to points with the smaller relative or absolute errors; our giving all points equal weight calls for an explanation.

The dynamic range of neutron flux that exists around the CPS and that we measured is nine orders of magnitude. Within the earth shield, the fluxes vary by five orders of magnitude. Weighting on the basis of absolute error would make the low flux points dominate, which is unphysical since the total volume of the shield contains detector points. The counting statistics for all detectors are less than 5%, with most within less than 1%, which is negligible compared with the differences between measured and calculated fluxes.

Two classes of systematic errors arise in using the model discussed above: one involves the departures of the actual accelerator and detector geometry from the model assumed for the calculations, the other involves not taking into account the spatial fluctuations in the primary beam loss. We feel that differences of 30% between calculated and measured fluxes are quite reasonable in view of these sources of systematic error, and that, since agreement is found over five orders of magnitude, the use of a more detailed computational model is not justified.

An extremely large $V(a)$ means that there are gross differences between the calculated and measured fluxes, due either to initially poor choices for

the free parameters (a variables) or to incorrect input data. A correctly input problem will typically have $V(a) \approx 0.25$ per point. The minimizing routine will then vary the parameter vector a until the $V(a)$ reaches a minimum, typically $V(a) \approx 0.05$ per point. The end-point parameter vector $[a]$ does not depend on the starting vector $[a]$. As discussed above, systematic errors could easily explain errors of 20 to 30% per point between measured and calculated fluxes. For this reason the smallest $V(a)$ we expect is about 0.05 per point. Smaller $V(a)$'s are taken to be fortuitous rather than necessarily representing a better fit.

3. Results and Best Fits

In each of our eight accelerator runs, several sets of data were obtained simultaneously, a given set corresponding to one type of detector in one class of location, viz., aluminum detectors in orbit hole locations. The entire experimental program used several thousand data points. Data sets used in FLUXFT computer analyses ranged from 8 to 72 points. The larger the number of input data points, the longer the machine running time, and generally, the more constrained the fitting parameters. As explained above, the FLUXFT program has a total of eight parameters (a's) that describe the physics involved, and one can choose how many of these parameters the program can vary to obtain the best fit to the data. Not only can one specify how many adjustable parameters there will be, but also in what groups and order these variations will be made. For a medium-size problem, say 40 locations or data points, the running time on the CDC-6600 can range from less than a minute if one fixes all the parameters and has the program evaluate only the various integrals, to some 20 minutes if one allows all eight parameters to be free or adjustable. Over 500 computer runs were made in the course of analyzing the data, the conclusions of which are summarized in the following discussions.

In run 11, the primary proton momentum is 26.4 GeV/c. Aluminum detector data from orbit-hole locations (52 fluxes) were input to the FLUXFT program with the following results:

a. Agreement between calculated and measured fluxes

$$\begin{aligned} \text{We have } V(a) &= 1.47 \text{ or } \frac{V(a)}{52} = \overline{V_i(a)} \\ &= \left[\frac{\phi(p_i, a) - \phi(p_i)}{\phi(p_i)} \right]^2 = 0.029/\text{point}. \end{aligned}$$

Therefore the average difference between the calculated and measured neutron flux $= 0.17 = (0.029)^{1/2}$, over a flux range of 10^5 . The largest difference is 33%.

The mean free path in earth, which is tightly constrained in the fitting process, is $117 \pm 2 \text{ g cm}^{-2}$.

4. Summary

The major features of the radiation field around the CERN proton synchrotron are described well by our physical model that incorporates the shielding

physics implicit in the Moyer model. The entire problem is separable in two parts: one involves the accelerator beam dynamics through the loss pattern of the primary protons; the other involves particle physics through secondary particle production in terms of both neutron energy and angular production as well as attenuation of these neutrons. In summary, the results of our study are as follows:

- (i) Beam-loss distribution is discussed in Chapter V of the original report (Ref. 1). The general features can be explained through calculations of the type made by Ranft. Presumably such calculations can be made on machines still in the design stage, and even more detailed theory is required to explain more detailed beam-loss features.
- (ii) The angular distribution of emitted neutrons is discussed in Chapter VI of Ref. 1, primarily from the standpoint of measurements made near the target. Theoretical aspects of this problem, based on a model by Ranft, are discussed in Chapter X.
- (iii) The removal cross section, a factor which enters through the neutron-attenuation mean free path in earth, is well determined, and is constant for different detectors, different primary proton momenta, and different thicknesses of shield.
- (iv) The neutron energy spectrum for transverse shielding reaches an effective equilibrium after only a few mean free paths. Hence the dose equivalent for unit fluence is constant throughout most of the shield volume, so long as the shield material is of uniform chemical composition.

Extrapolation of Shielding to Higher-Intensity and Higher-Energy Accelerators

On the basis of this model, and the physical constants that have been derived, we think that one can extrapolate this method to higher-energy machines and higher-intensity accelerators than exist at present.

1. An Improved Higher-Intensity CPS

Figure 10 shows the dose versus shielding thickness in the target region and in the quiet region for the CPS. On the basis of this curve, which through the FLUXFT program can be extended to greater thickness when the proton intensity is increased, one can calculate for present high energy accelerators what shielding thicknesses are required at any given intensity. The loss mechanisms and the generation of secondaries as a function of primary proton energy clearly do not require any extrapolations, since they are based on the present dynamics of the machine.

2. 200- and 300-GeV Accelerators

The general problem here is to make assumptions as to the initial generation of penetrating particles from a higher energy proton than is currently available. Quite a bit of theory is necessary to do this. The theoretical

treatment generally yields the conclusion that the same number of penetrating particles per GeV will exist from approximately 15 to 1000 GeV. The various material constants are assumed to be the same for the attenuation of these penetrating particles, since they are mostly in the range of 100 to just a few hundred MeV. The 200-GeV (Ref. 2) and 300-GeV (Ref. 3) predictions couple loss assumptions, desired flux levels, and material constants from this general work, and the conclusions are presented in the following tables.

Table I. 200-GeV (US) shield thicknesses.

Calculation	Target region	Quiet region near buildings	Quiet region, general area
This report	1855 g-cm ⁻²	1320 g-cm ⁻²	1160 g-cm ⁻²
200-GeV design study	2345 g-cm ⁻²	1515 g-cm ⁻²	1240 g-cm ⁻²
^t _{FLUXFT} / ^t _{design study}	0.79	0.87	0.94

Table II. 300-GeV (European) shield thicknesses.

Calculation	Target region	Quiet region
This report	1900	1285
300-GeV design study	1940	1480
^t _{FLUXFT} / ^t _{design study}	0.98	0.87

REFERENCES

1. William S. Gilbert, Denis Keefe, Joseph B. McCaslin, H. Wade Patterson, Alan R. Smith, Lloyd D. Stephens, Kenneth B. Shaw, Graham R. Stevenson, Ralph H. Thomas, Ronald D. Fortune and Klaus Geobel; 1966 CERN-LRL-RHEL Shielding Experiment at the CERN Proton Synchrotron, UCRL-17941, Sept. 1968.
2. 200-BeV Accelerator Design Study, UCRL-16000 (2 vols.), June 1965.
3. Report on the Design Study of a 300-GeV Proton Synchrotron by the CERN Study Group on New Accelerators, CERN/563 (2 vols.), Nov. 1964.

FIGURE CAPTIONS

1. Cross section of tunnel and shield in target region.
2. Plan view of tunnel and shield in target region.
3. Elevation of tunnel and shield in target region.
4. Detail of vertical hole detector holder.
5. Ring top ionization -- spatial distribution.
6. Aluminum cavity on vacuum chamber -- spatial distribution.
7. Aluminum activity -- target region.
8. Neutron spectra.
9. Elevation of target region -- geometry used in Moyer model.
10. Dose vs shield thickness, CPS.

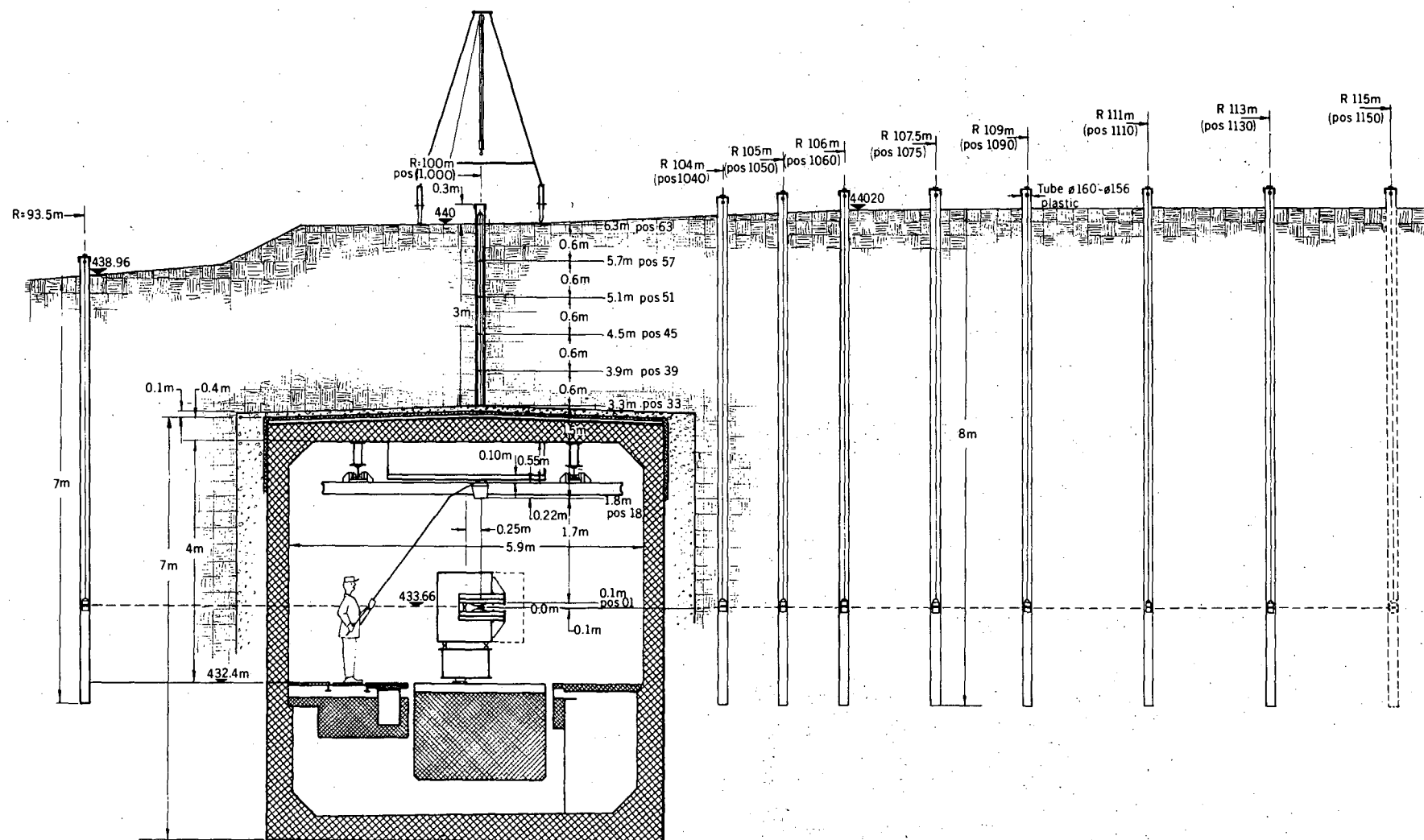


Fig. 1

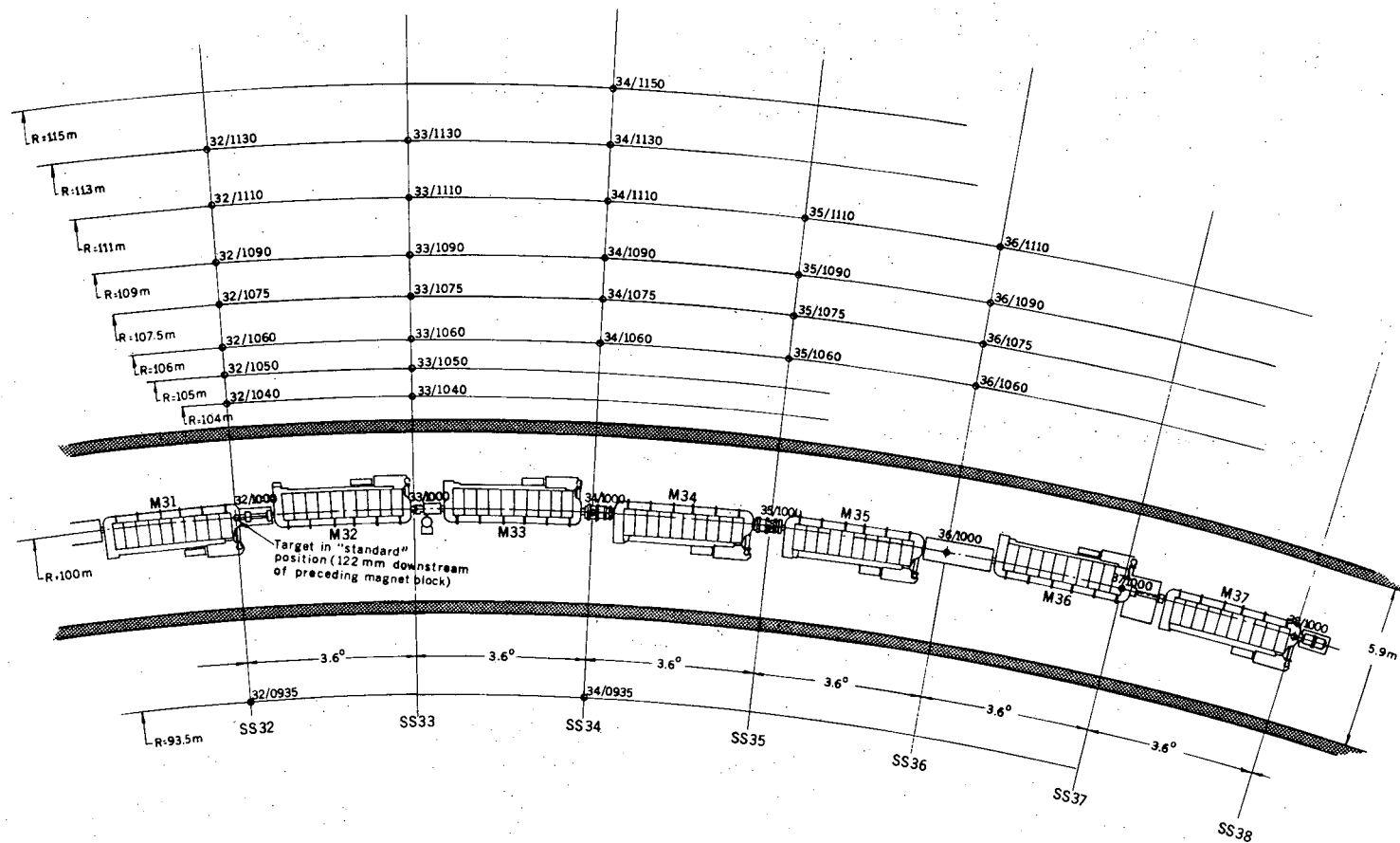
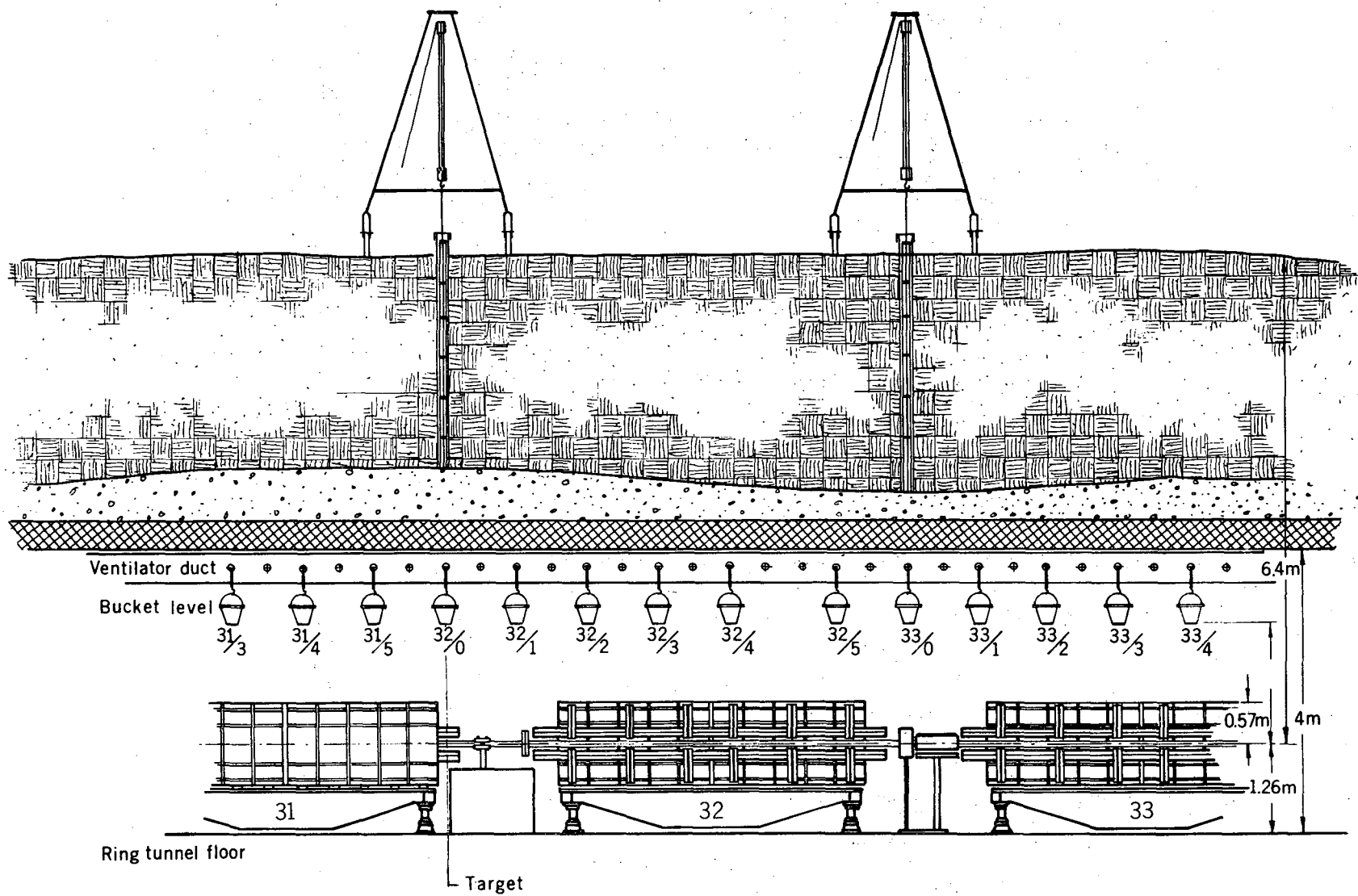


Fig. 2

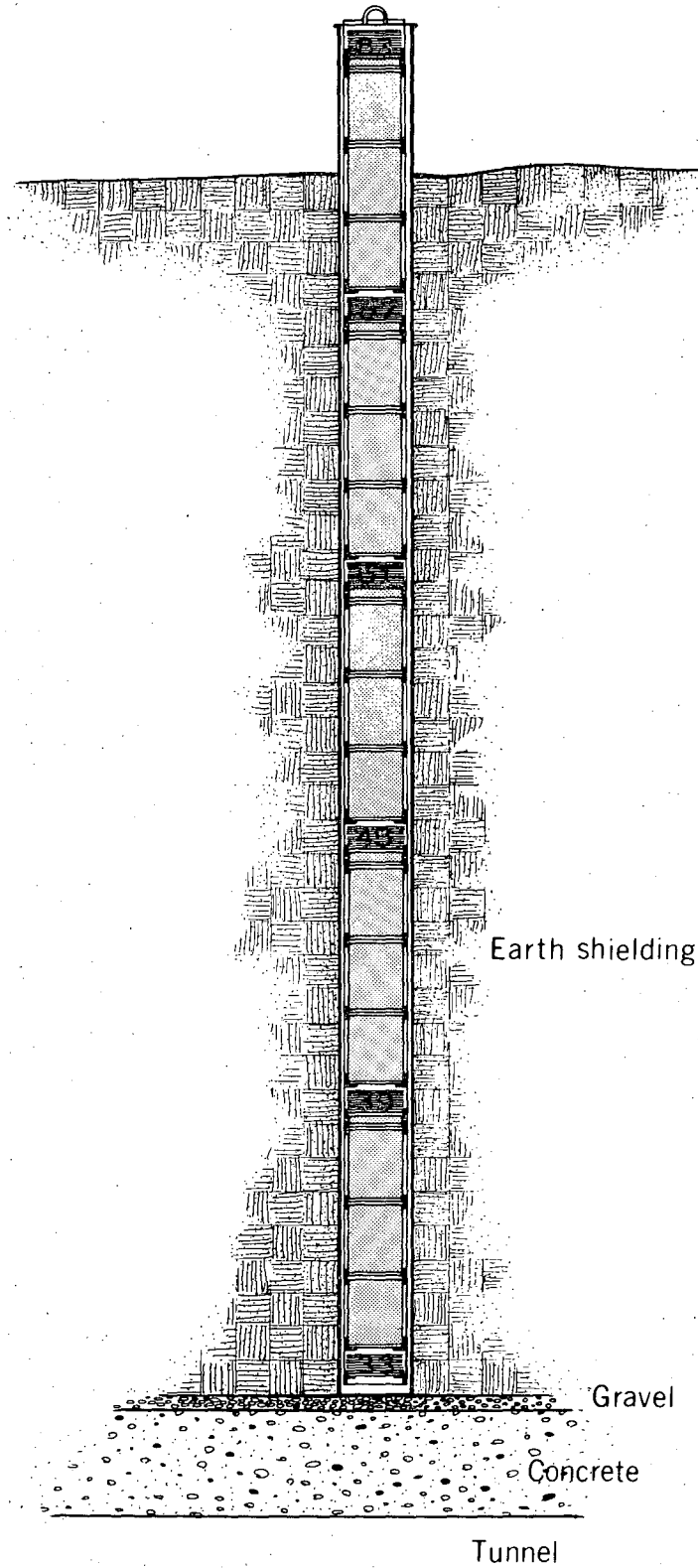
XBL 6712 21:9



-14-

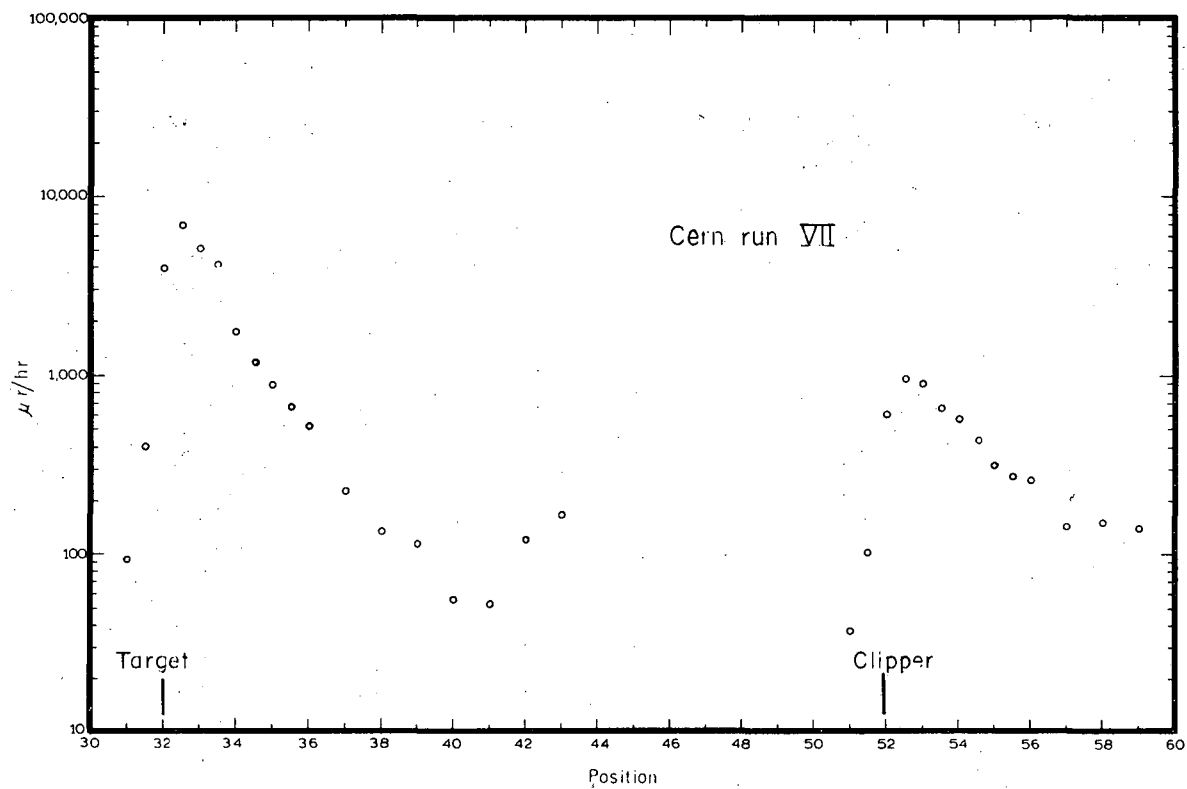
Fig. 3

XBL 6712 2118



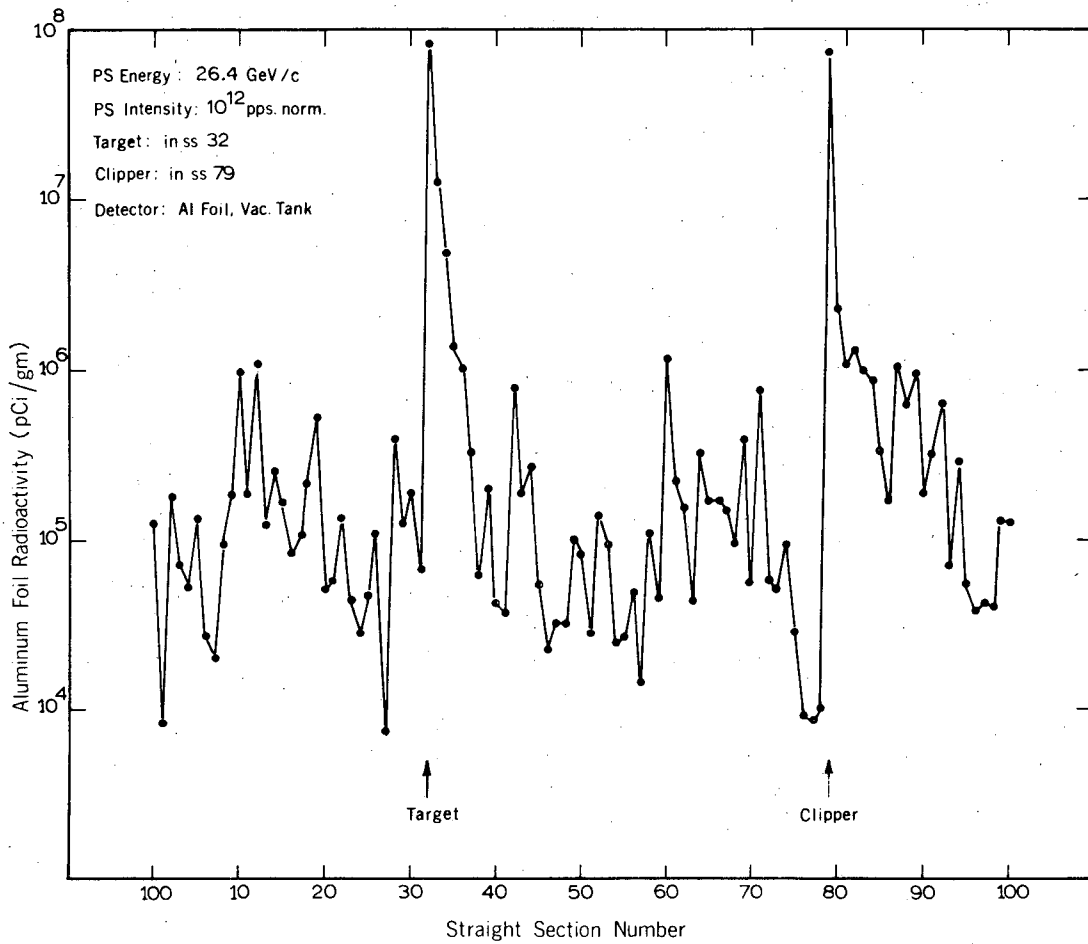
XBL 681 4404

Fig. 4



XBL 684 4826

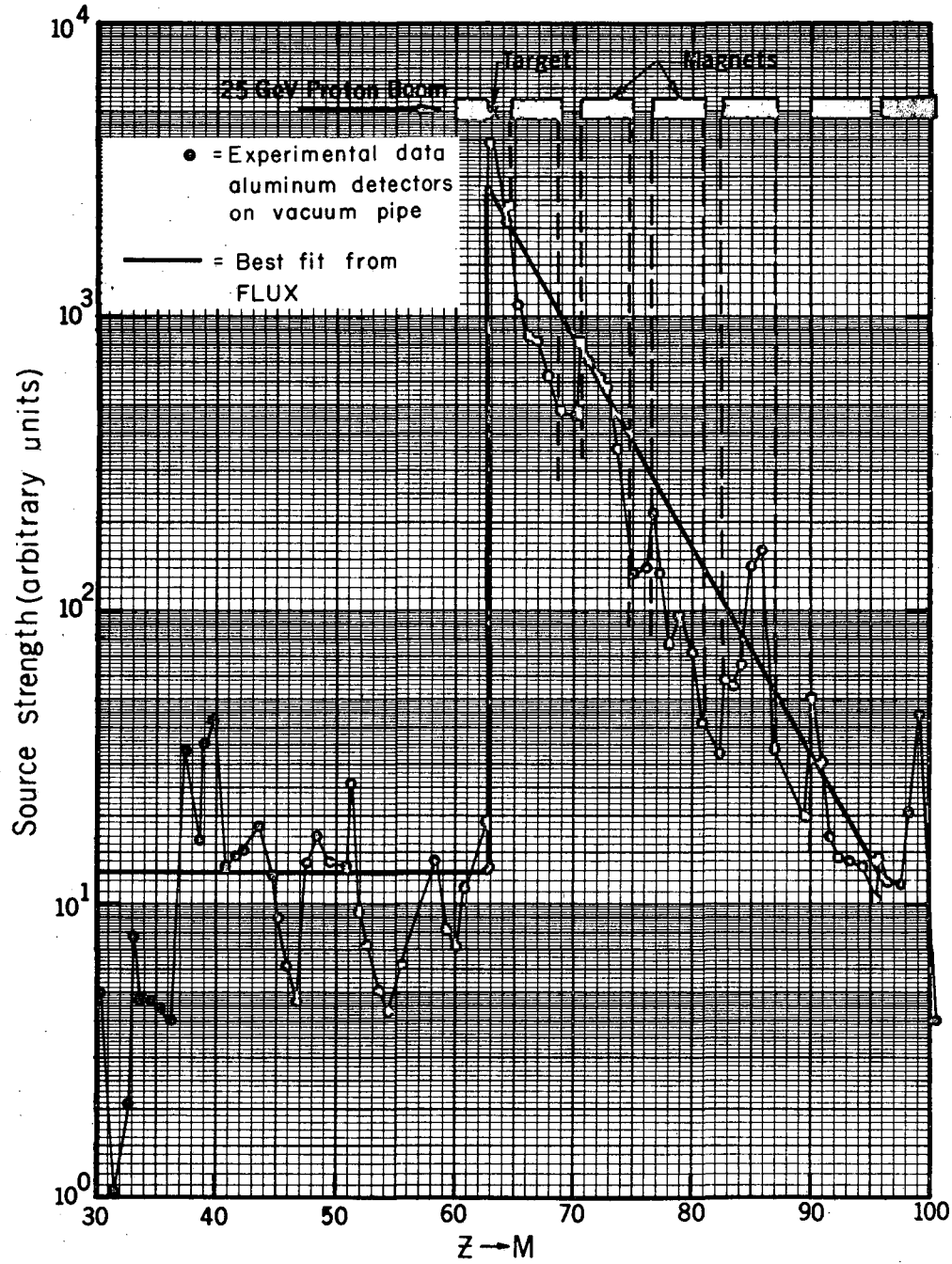
Fig. 5



XBL672-2014

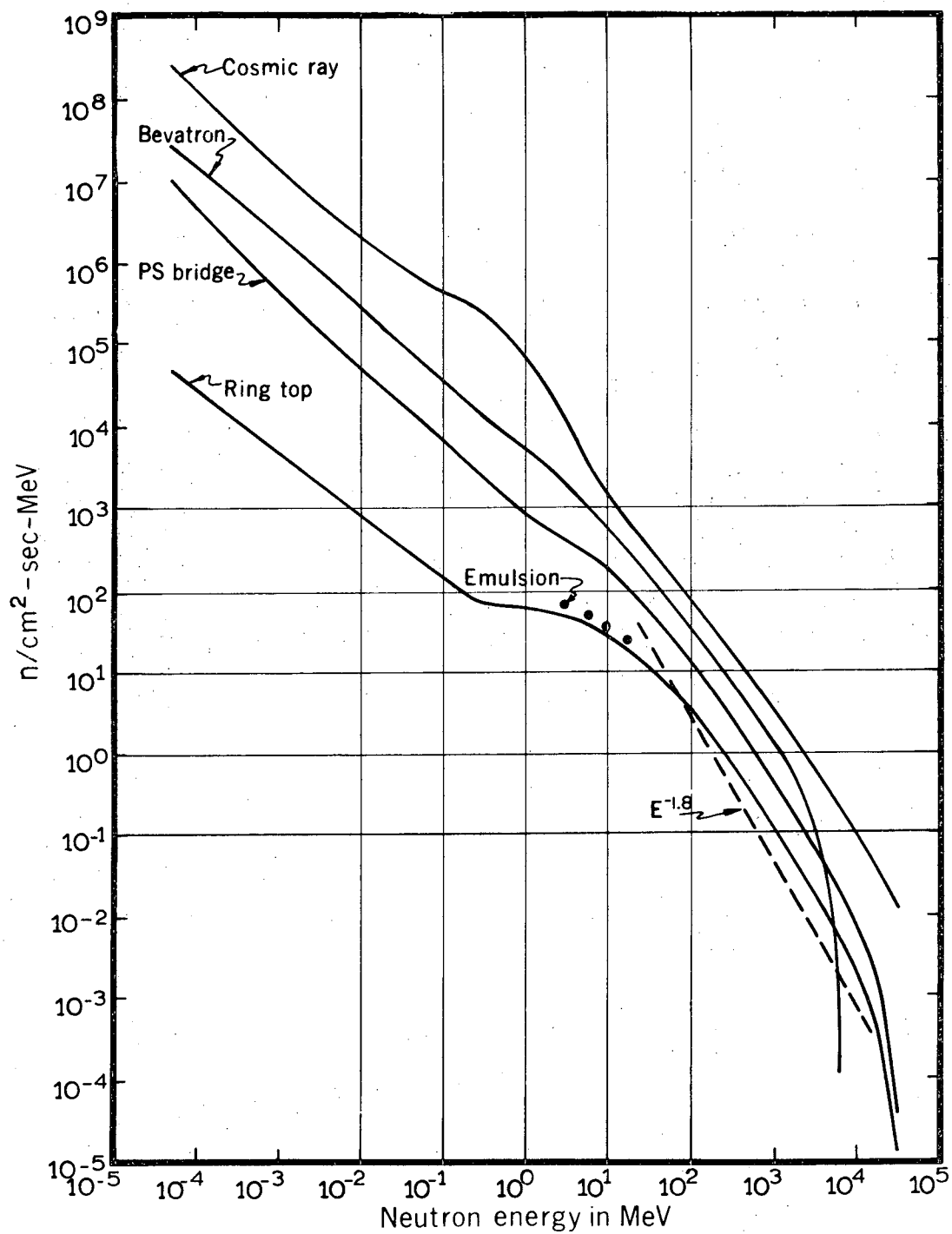
Fig. 6

CERN Experiment - Beam Loss Distribution



XBL6782067

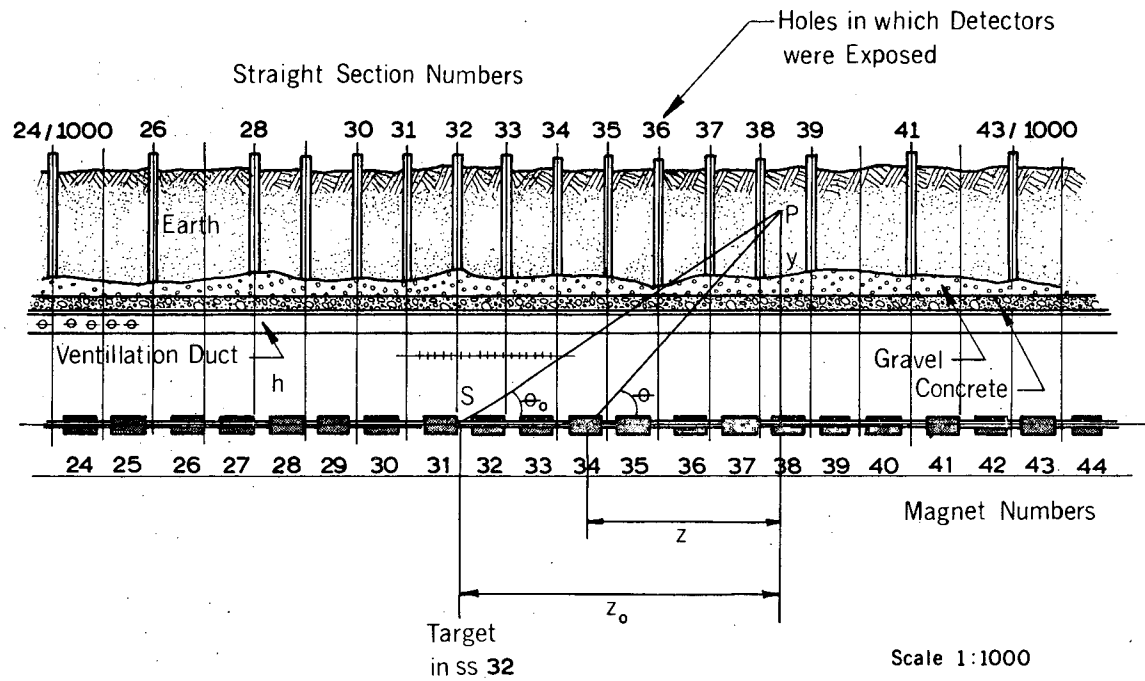
Fig. 7



XBL 682 4493

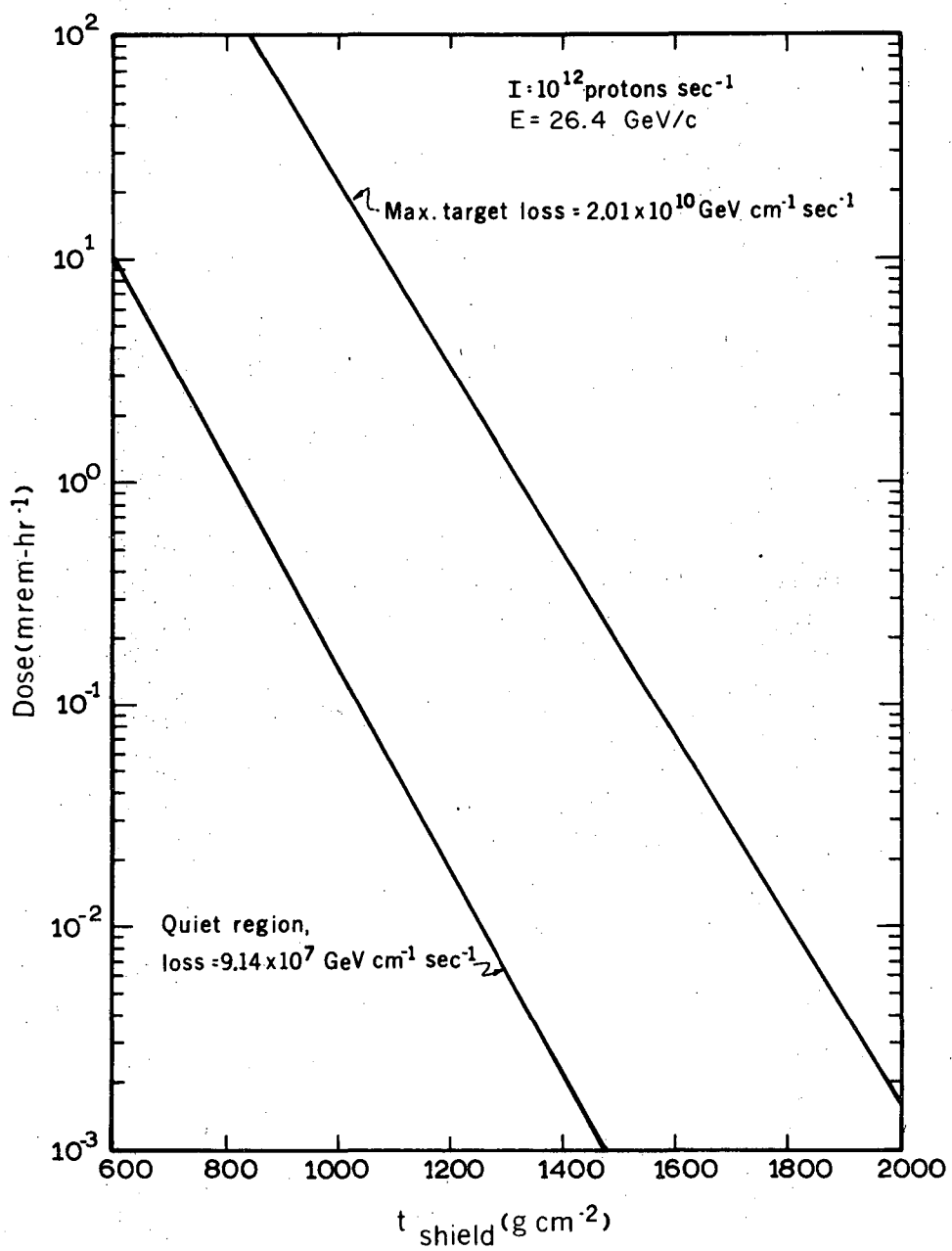
Fig. 8

CERN Shielding Experiment - Elevation



XBL6782071

Fig. 9



XBL 6810 4935

Fig. 10

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or*
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.*

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720