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Introduction

Our primary concern has been with the radiation problems associated with the contemplated 200-GeV strong-focusing proton synchrotron. We have been involved in various experiments at the existing proton synchrotrons in the 30-GeV range at Brookhaven and CERN, since these can be considered as models for the higher energy machine.

There are several distinct problems that are associated with radiation that is generated through the cascade process after the primary beam is lost. The magnitude and distribution of this primary beam loss is therefore an input to each of the radiation problems listed below in Table I.

Table I. Radiation Problems

Problem	Running	Shut Down
1. Strongly interacting particles (S.I.P.) penetrating shield	XX	
2. Leakage through ducts and labyrinths	XX	
3. Muons penetrating shield	XX	
4. Skyshine	XX	
5. Radiation damage and heating	XX	
6. Radioactive air, water and dust	XX	XX
7. Induced activity in accelerator		XX
8. Induced activity in tunnel walls		XX

* Work done under the auspices of the U. S. Atomic Energy Commission.

Problems 1-4 relate to the radiation levels in buildings on site and to the off site general population. Problems 5-8 influence the maintainance of the accelerator, and it is in this maintenance that the operators and other radiation workers get the bulk of their radiation exposures.

In 1965-1966 it was agreed by those involved in shielding calculations at CERN, the Lawrence Radiation Laboratory, and the Rutherford High Energy Laboratory that a need existed for a large-scale shielding experiment at the CERN-PS in which the radiation field in the earth shield and the primary beam loss distribution would be measured simultaneously. The specific accelerator projects for which these new data were desired are: the U. S. 200-GeV proton synchrotron, the improved CERN-PS, the CERN intersecting storage rings, and the European 300-GeV proton synchrotron.

The above three laboratories** collaborated in a series of shielding experiments at the CERN-PS from September 28 to November 28, 1966. We had exclusive use of the accelerator for eight 12-hour periods.

1966 Shielding Experiment at the CERN-PS

The use of activation detectors enabled us to determine the radiation field at hundreds of locations inside the machine tunnel and within the earth shield. The response of these detectors is well understood, and spectral information is obtainable. We were able to cover a dynamic range of flux from < 1 to $> 10^8$ neutrons cm^{-2} sec^{-1}. Several counting facilities, with a correspondingly large staff, were required to count the many samples within the times dictated by the induced activities and associated decay lives.

The geometry of the experiment can be seen in Figs. 1-3. Some preliminary data have been presented(1) and a formal report is in preparation.

Beam Loss Distribution

In Fig. 4 is shown the beam loss distribution as measured by aluminum activation detectors placed on the vacuum tank. There is considerable variation in this loss in the quiet region upstream of the target as well as subsequent minima downstream of the target.

** LRL: 200 GeV - W. Gilbert, D. Keefe
Health Physics - J. McCaslin, W. Patterson, A. Smith, L. Stephens

CERN: ISR Division - R. Fortune
Health Physics - K. Goebel

RHEL: K. Shaw, G. Stevenson, R. Thomas

These minima are associated with the gaps between magnets. The pattern is surprisingly well approximated by a constant term plus an exponential that decreases with distance downstream of the target. All the target associated term is accounted for in some half betatron wavelength downstream of the target and some 70 to 80% of the total beam loss is found under this peak.

In addition to a thin foil target, a cleanup collimator, or clipper, was used at a point several betatron wavelengths around the machine. Hereward, Ranft, and Richter (2) have calculated what might be the effects of such a clipper. Figures 5 and 6 show new Monte-Carlo calculations by Ranft(3) as to what the beam loss distribution might be expected to be for the machine operating conditions for our experiment, together with the experimental data. The agreement is fairly good and once again one can see the influence of the magnet-gap geometry in the experimental data. Ranft discusses how these calculations could be carried out for the 200 to 300 GeV accelerators once the various lattice and aperture parameters have been decided upon. For the CERN-PS, the clipper did not clean up the beam and reduce the random losses around the quiet sections as much as the calculations predicted. The reason for this is not clear.

Fitting of Experimental Data

A model based on the modified Moyer method has been programmed for the CDC-6600 to yield a best fit to the experimental data.(4) In a given exposure, for a given type detector, there may be from 10 to 80 data points at different locations. At each of these locations a flux is calculated, these fluxes are integrals of the following type.

$$\text{Calculated flux} \equiv \Phi_i = c\int_{-\infty}^{+\infty} \frac{S(Z)\Theta(\theta)}{r^2}\, e^{-\ell_{Fe}/\lambda_{Fe}}\, e^{-\ell_E/\lambda_E}\, dZ$$

$$\text{Experimental flux} \equiv \phi_i$$

$$\text{Variance} = \sum_i \left(\frac{\Phi_i - \phi_i}{\phi_i}\right)^2$$

This is minimized by changing the variables below.

$$S(Z) = 1 + a_1\, e^{-a_3(Z - Z_{target})}$$

$$\Theta(\theta) = a_2\, e^{-a_4\theta}$$

In the range of $90^\circ \pm 30^\circ$, this is similar to measured data from C^{11} and Bi fission detectors.

r = distance from elemental source to field point

$\lambda_{Fe}, \lambda_{Earth}$, C = other adjustable constants

The fit, as shown in Fig. 7, agrees with the experimental data to within about 20%, over 5 orders of magnitude in flux. The $\lambda_{Earth} = 117 g\ cm^{-2}$ for this particular set of experimental data.

Shield Estimates for 200 to 300 GeV and Improved CERN-PS Accelerators

Using the assumed circulating proton beams, loss distributions, and allowable surface radiation levels of the original design reports(1) and the constants for the FLUX program derived from an analysis of the CERN shielding data, Table II represents an interim estimate of the required shielding above the magnets, if one assumes that the 200 and 300 GeV accelerator magnets are the same thickness and geometry as the CERN-PS magnets. The FLUX program allows one to insert the actual magnet configuration and one can do so at a later time.

Table II. Shielding required above main ring, in g cm^{-2}

Accelerators		Quiet region	Target or septa region
Present PS 25 GeV	*2×10^{11} p sec^{-1}	790	1300
Improved PS 25 GeV	*1×10^{12} p sec^{-1}	970	1480
Improved PS 25 GeV	*1×10^{13} p sec^{-1}	1220	1740
Proposed 200 GeV U.S.		1000	1700
Proposed 300 GeV Europe		1180	1800

* These currents represent the total beam lost in the accelerator, not necessarily the total circulating beam.

References

1. R. D. Fortune, W. S. Gilbert and R. H. Thomas, Shielding Experiment at the CERN-PS - CERN/LRL/RHEL Collaboration 1966, UCID-10199, April 28, 1967.

2. H. G. Hereward, J. Ranft and W. Richter, Efficiency of Multi-Traversal Targets, CERN 65-1, January 6, 1965.

3. J. Ranft, Monte-Carlo Calculation of Particle Loss Distributions Along the Vacuum Chamber of the CPS Near Internal Targets and of the Transverse Attenuation of Strongly Interacting Particle Fluxes in the P.S. Magnet Units and Earth Shield, MPS/Int. MV/EP 67-5 JR/id, June 20, 1967.

4. E. R. Close, FLUXFT - A CDC 6600 Code For Fitting Radiation Data Associated with the CERN-PS, UCID-3061, July 6, 1967.

Figure Captions

Fig. 1. CERN Shielding Experiment - Plan View.

Fig. 2. CERN Shielding Experiment - Cross-Section View.

Fig. 3. CERN Shielding Experiment - Elevation View Geometry for FLUX Program.

Fig. 4. Beam Loss Distribution - Experimental Data - Analytic Fit.

Fig. 5. Beam Loss Distribution Target - Ranft Monte-Carlo Calculations - Experimental Data.

Fig. 6. Beam Loss Distribution Clipper - Ranft Monte-Carlo Calculations - Experimental Data.

Fig. 7. Orbit Hole Aluminum Detector Data - FLUX Program Fit.

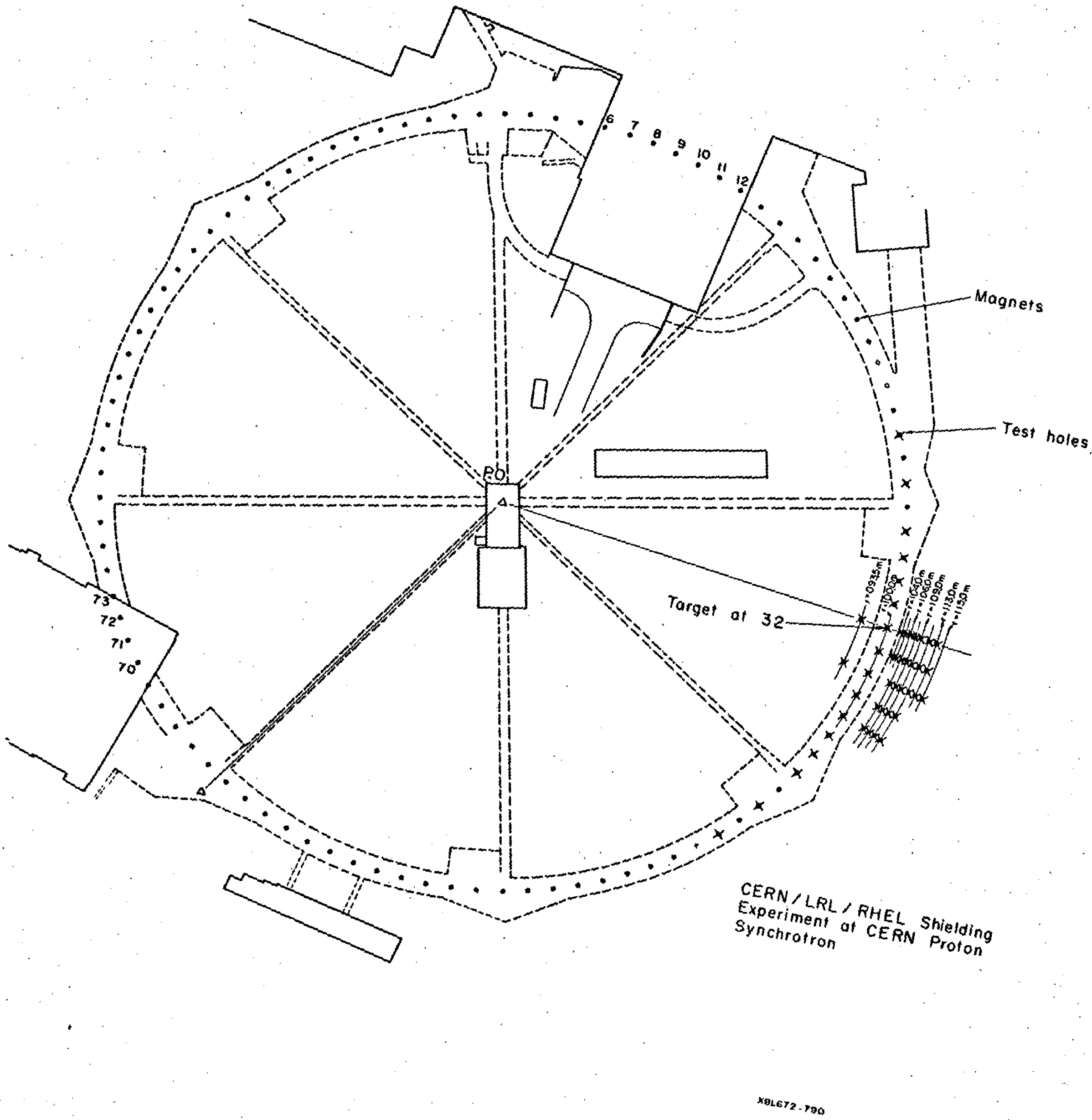
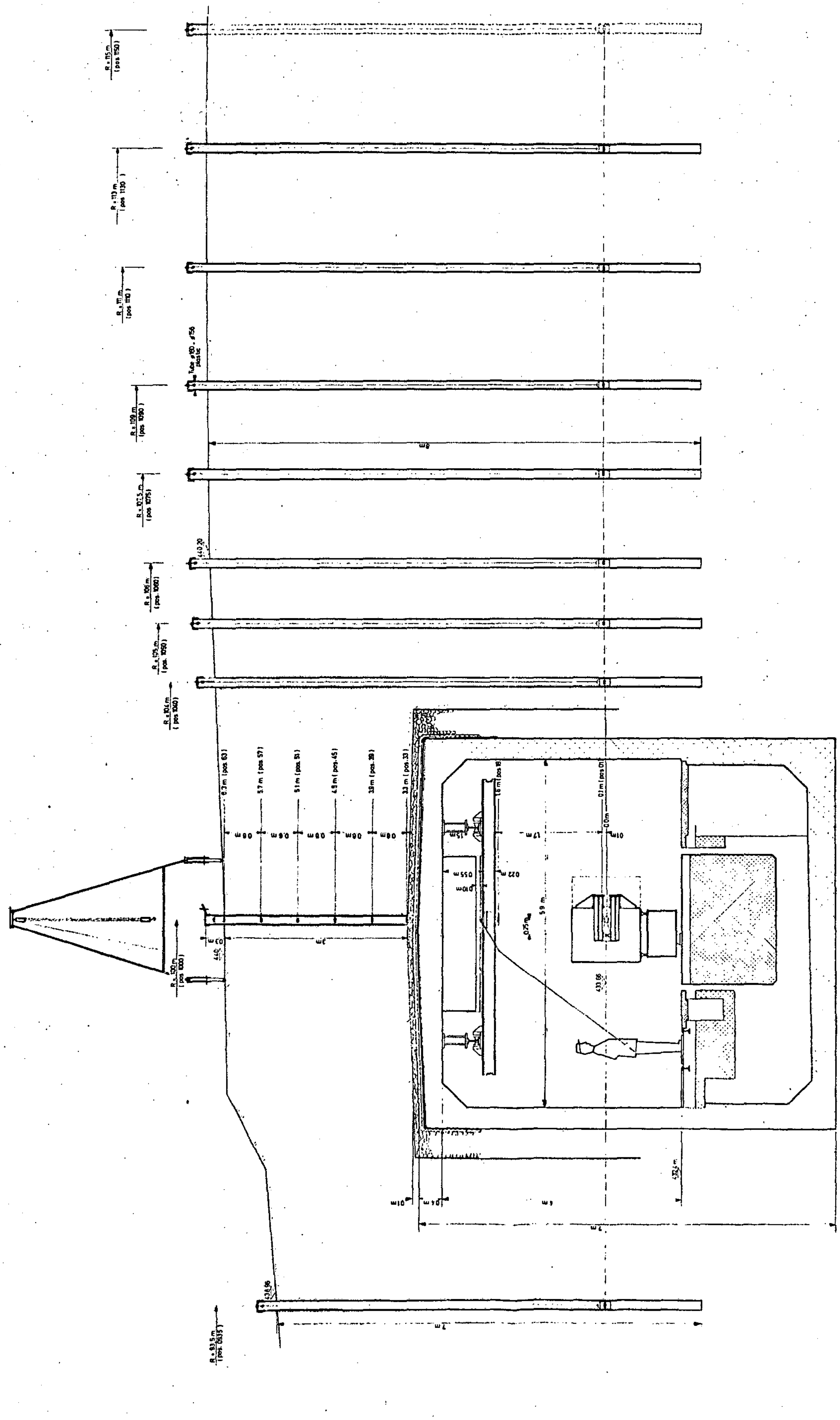

6 7 8 9 10 11 12
Magnets
Test holes
P0
Target at 32
73
72
71
70
CERN/LRL/RHEL Shielding
Experiment at CERN Proton
Synchrotron
XBL672-790

Fig. 1



XBL672-791

Fig. 2

CERN Shielding Experiment- Elevation

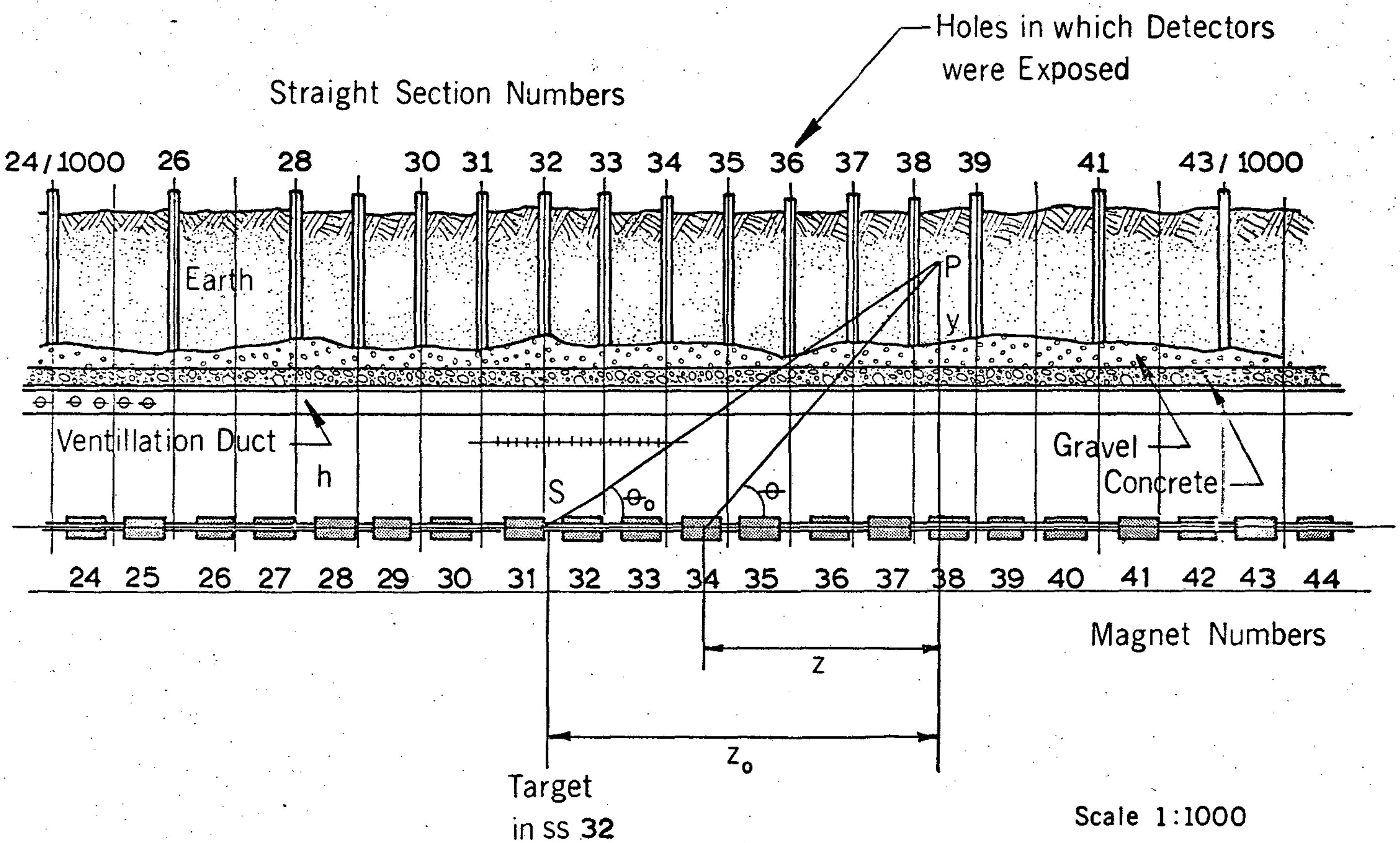
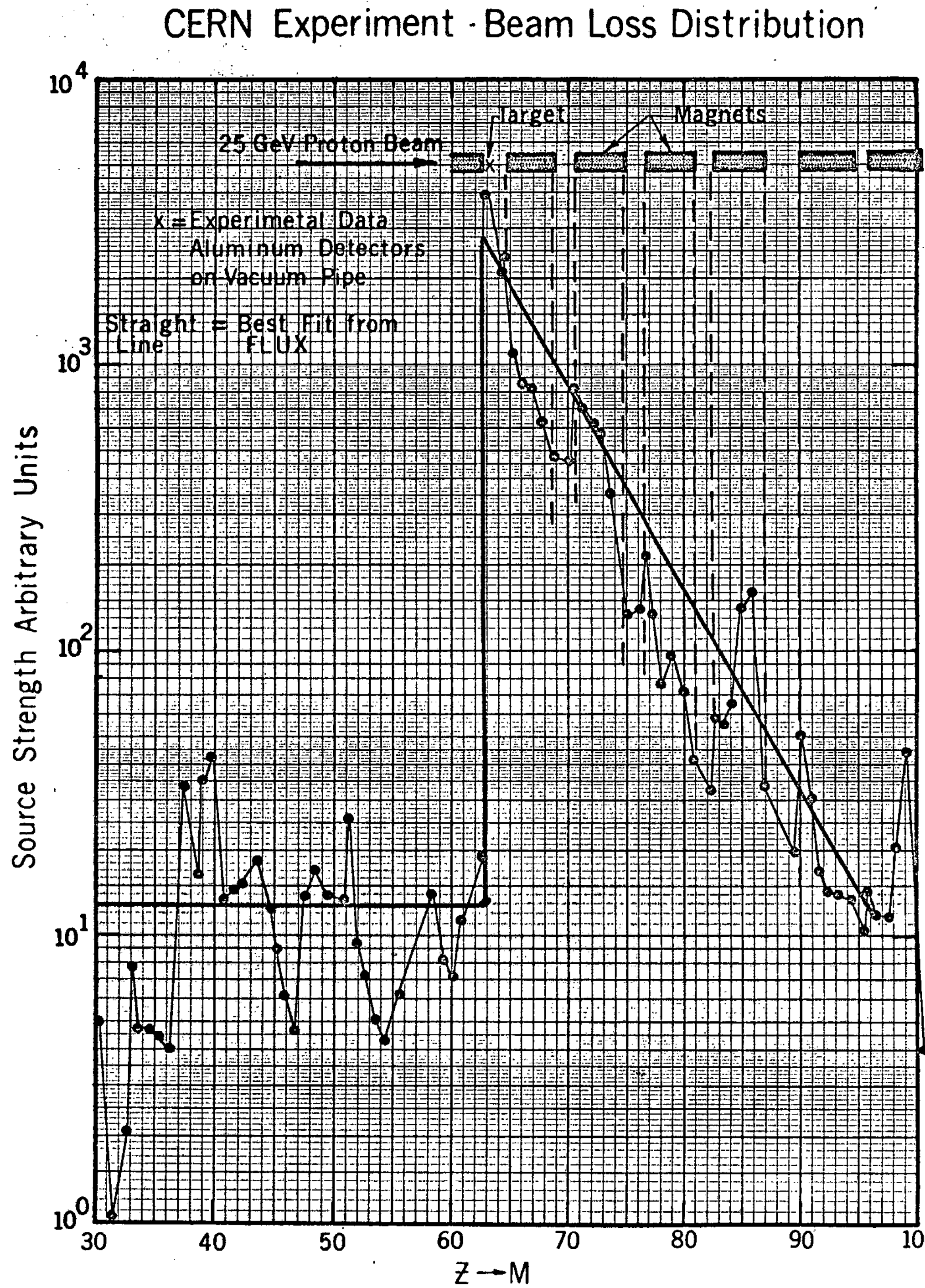


Fig. 3



XBL6782067

Fig. 4

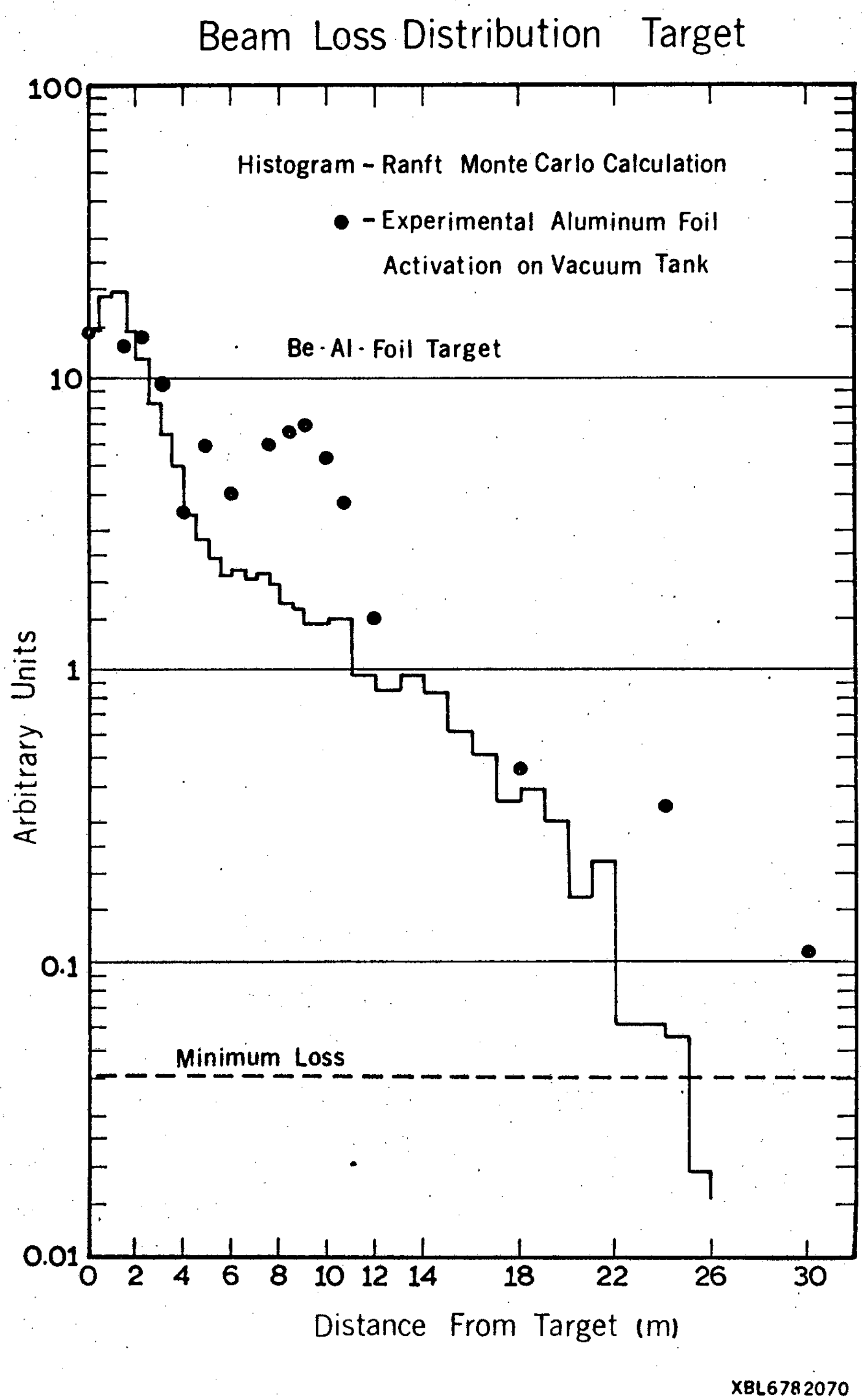

Beam Loss Distribution Target
Histogram - Ranft Monte Carlo Calculation
● - Experimental Aluminum Foil
Activation on Vacuum Tank
Be·Al·Foil Target
Minimum Loss
Arbitrary Units
100
10
1
0.1
0.01
0 2 4 6 8 10 12 14 18 22 26 30
Distance From Target (m)
XBL6782070

Fig. 5

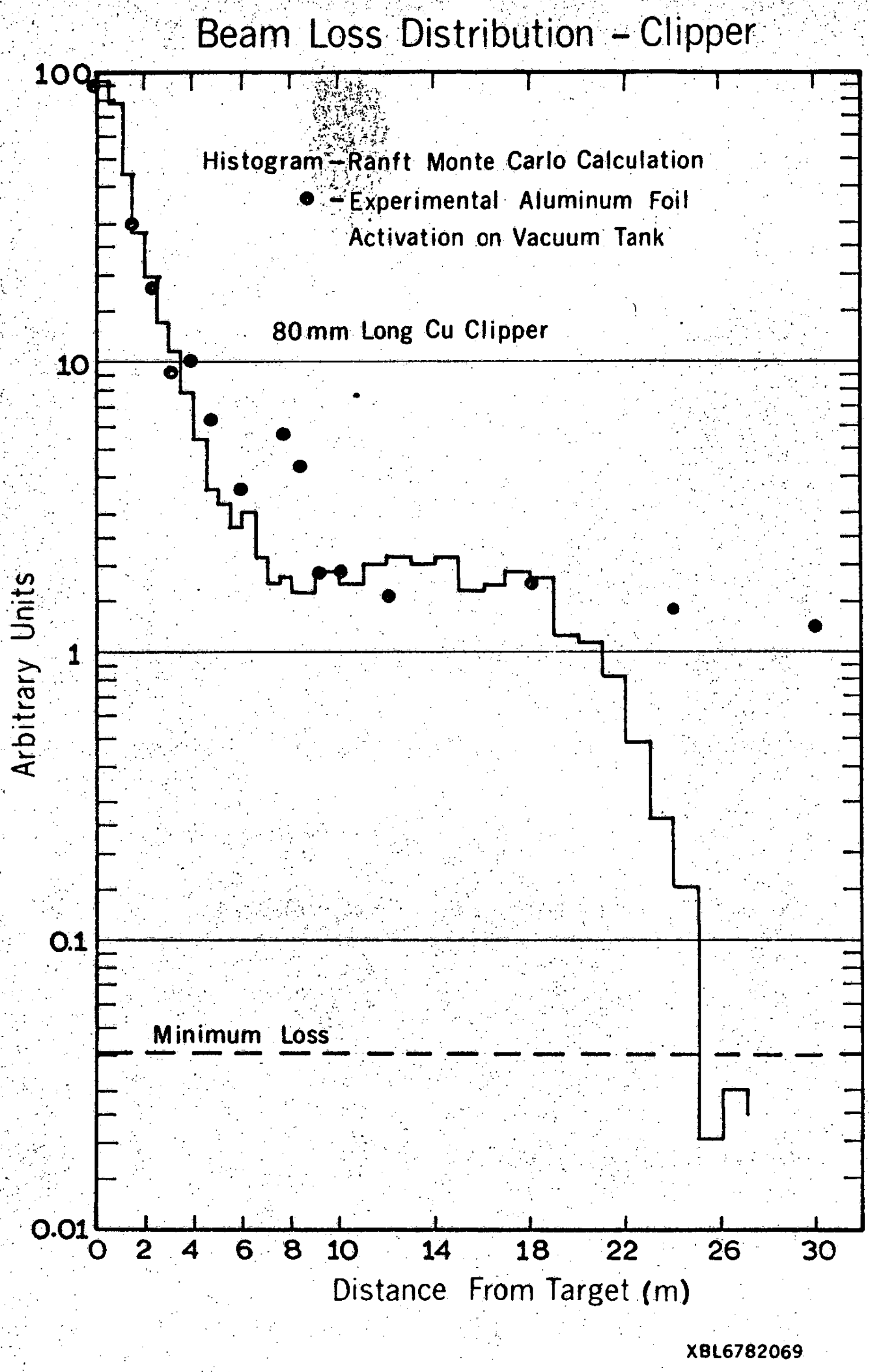

Beam Loss Distribution – Clipper
Histogram – Ranft Monte Carlo Calculation
● – Experimental Aluminum Foil Activation on Vacuum Tank
80 mm Long Cu Clipper
Minimum Loss
Arbitrary Units
100
10
1
0.1
0.01
0
2
4
6
8
10
14
18
22
26
30
Distance From Target (m)
XBL6782069

Fig. 6

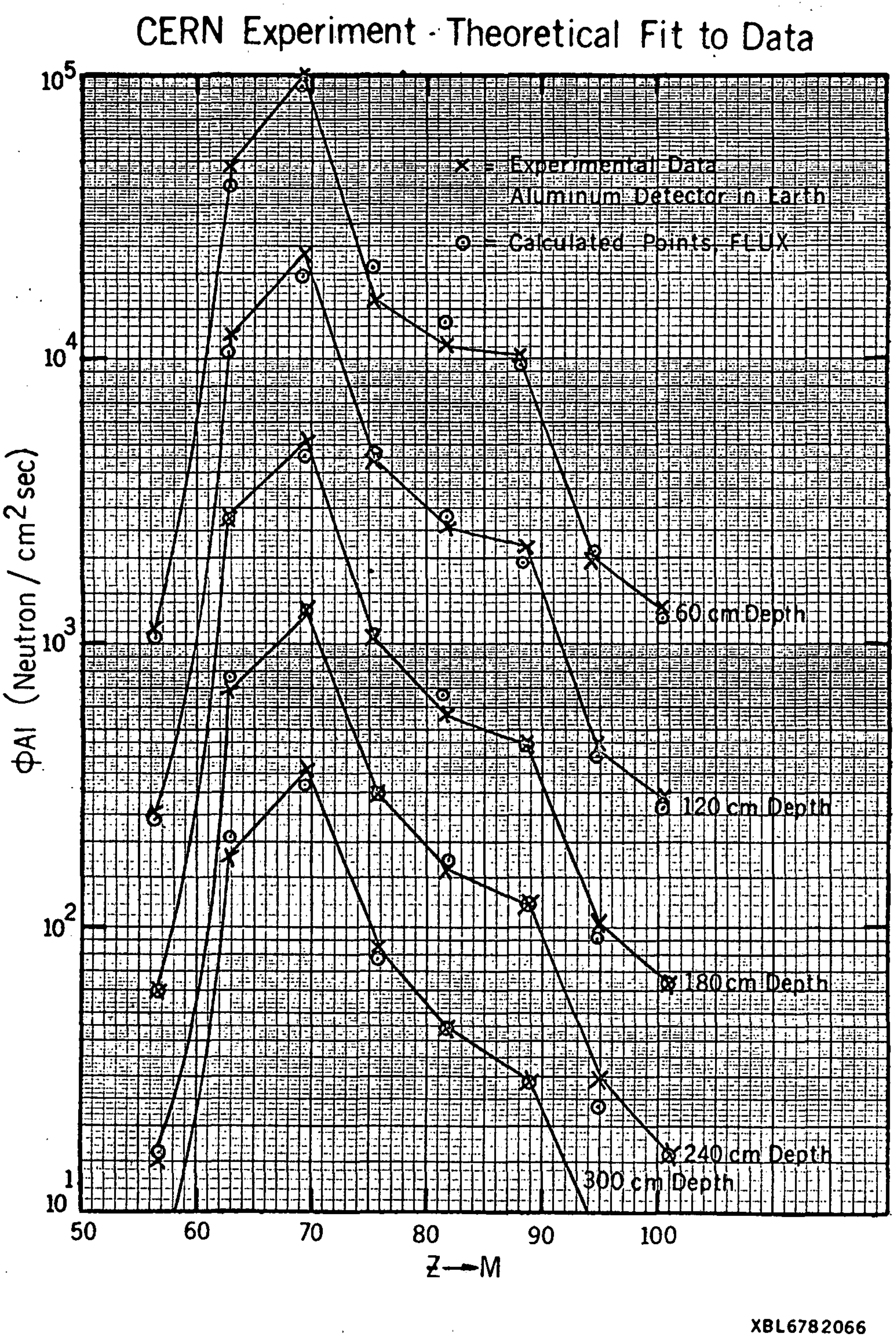

CERN Experiment - Theoretical Fit to Data
× = Experimental Data
Aluminum Detector in Earth
⊙ = Calculated Points, FLUX
60 cm Depth
120 cm Depth
180 cm Depth
240 cm Depth
300 cm Depth
ΦAl (Neutron / cm² sec)
Z ⟶ M
XBL6782066

Fig. 7