Pbar Note : 491

Gamma Ray Activation of the Fermilab Pbar Target

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1 Introduction

A quantitative understanding of the induced radioactivity in the parts of a high energy particle accelerator and particle detectors is one of the topic of interest for a quite long time. Especially certain components like targets, beam dumps, scrapers and kickers could be highly radioactive because of the direct interactions of the beam. Many short and long lived radioactive nuclei may be formed. A theory of induced radioactivity by a continuous beam of high energy particles on a thick target has been developed (Ref. 1). But, the particle beams from a synchrotron are pulsed with pulse separation of the order of several seconds. For example the proton beam used to produce pbars in the Fermilab collider facility is pulsed with total of 1.6μ sec in length and with a separation of about 2.0 sec. So it will be interesting to re-examine the theory of induced radioactivity of a thick target arising from a pulsed beam.

In this report an attempt has been made to make a realistic estimate of residual gamma ray activity of the pbar target which is directly exposed to pulsed 120 GeV proton beams. An expression to be used in any such calculations is given. Derivation of the expression is given in the Appendix A. Finally we make some comments.

2 Calculation of Gamma-ray Activation

When a high energy particle interacts with a nucleus it may be elastically scattered, knockout some nuclei or create some new high energy particles. The energetic secondary particles also induce nuclear reactions. This gives rise to particle showers and electromagnetic showers. Each such nuclear reaction center is called a star. If the resulting nuclei are highly unstable and/or created in their excited states (which is generally true) they will de-excite by boiling off neutrons, gamma rays, beta rays or by emitting internal conversion electrons. Each such process of decay will be characterized by its decay constant. The cross section for formations of any radioactive nucleus could be very small (of the order of mb) at high energies. But in a target of thickness comparable to the interaction length of the incident particle the possibility of forming a radioactive nucleus will be quit large. Previously an energy dependence of the formation cross section for various radioactive nuclei in a copper target has been studied by Hudis et al (Ref. 2) in the energy range of 3 GeV to 30 GeV protons. About 19 radioactive products of copper spallation indicate no energy dependence. Based on similar observations on many target materials the cross-section for formation of any radioactive nucleus produced in the interaction of high energy particle has been paramaterized (Ref. 1). However a precise calculation might need experimental data. Table 1 gives list of different long lived radioactive nuclei (with life-time longer than about 5.0 min) produced by spallation in a copper target. The mass varies from A = 7 to 65 (some of the nuclei with very small production cross sections are not listed here). To estimate the total radiation emitted at the decay of an irradiated sample we have to account for the effect of every individual product.

Total gamma ray radiation dose rate D of a target in (R/hr), which is bombarded by high energy particle beam is given by (see Appendix A),

$$D = -\sum_j \frac{dN_j}{dt_c}$$

$$= N_o A \sum_j p_j \lambda_j \frac{1-e^{-\lambda_j t_I}}{1-e^{-\lambda_j}} e^{-\lambda_j t_c} \sum_k \omega_k(j) E_k(j) \int_V \frac{e^{-\mu_k(j) X(x,y,z)} \rho_s(x,y,z)}{(X+d)^2} d\tau \quad (1)$$

where 'j' indicates a particular radioactive nucleus formed, t_I is the total time that target is being irradiated with the primary beam. N_o is the number of primary beam particles per bunch per second. p_j is the probability with which a nucleus is formed in a nuclear interaction. λ_j is the radioactive decay constant of the nucleus 'j'. t_c is the cooling time. ω_k is the absolute intensity for a gamma ray of type 'k' (because there could be more than one gamma ray coming from a daughter nucleus). $E_\gamma(k)$ is the energy of gamma ray, μ_k is the attenuation coefficient for the gamma ray 'k' in the target material. ρ_s is the star density of nuclear interactions. The integration is taken over the entire target volume. The constant A is given by

A = 1.23E-11 if X and d are in meters

A = 6.0E-10 if X and d are in ft

Because of the spacial dependance of the star density in the target and geometry of the target, it is difficult to evaluate the integral in Eq. 1. However, one can incorporate these aspects into a Monte-Carlo code and estimate the dose rate exactly.

Here we made calculations for pbar target used in the 1988-89 collider run. Predictions have been compared with the available data. In all of the calculations the star density have been generated by Monte-Carlo calculations using MARS10 (Ref. 3) which uses hadron nucleus interaction models. Further we assume that the source of radiation is situated at the center of the target. Thus in our model all gamma-rays undergo attenuation by the same amount of target material irrespective of the place a star is formed in the target before it reaches the detector. This assumption is reasonable one for a cylindrically symmetric target with the beam along the axis and for a target with its dimension much smaller than the distance between the detector and the target surface. The gamma-ray attenuation coefficient, μ, can be obtained by a logarithmic fit to the data, which is shown in Fig. 1. Some of the decay properties of about thirty six nuclei produced by spallation in copper, the energies and intensities of gamma-rays emitted by the daughter nuclei are also given in table 1. The probability for formation of any nuclei p_j is obtained by taking the ratio of production cross section for 'j' and the total inelastic cross section. Total inelastic cross section for copper is 782mb.

Fig. 2 gives a comparison of the prediction and the measured value. The target was used for of 392 days with total of 292 days of irradiation. An average of N_o = 1.0E+12 p/pulse-sec is assumed. By a Monte Carlo with an exact geometry we found the number of stars in the target as 4 per 120GeV proton. There is good agreement with the data. However, there are several uncertainties exist in the method of measurements to get these data points. The radiation detectors used to measure target activities are known to have about 20% instrumental uncertainty in their measured values. Other large source of uncertainty could arise from the estimation of the distances between target to the detector. Also one have to notice that the beam axis in these targets were along a chard of a cylindrical rotating target with axis of rotation perpendicular to beam axis. Under these circumstances it is incorrect to assume the source of the gamma radiation is at the center of the target. Therefore only the data points labeled " dose rate at contact" have been used to compare with the predictions. Carefully measured data is essential to make a better comparison.

Recently target upgrade has been undertaken. Fig. 3 (Ref. 4) shows a target planned to use during the future collider run at Fermilab. In this case beam will go along the symmetric axis of the target. Fig. 4 and Fig. 5 represent predictions of the gamma ray activity of the target for different irradiation time, viz., $t_I = 1$ sec, 10 sec, 60 sec, 1 hr, 1 day, 1 month and 2 months. It is clear that an interaction of a primary proton beam pulse (of 120 GeV with $N_o = 1.0E+12$ protons/pulse) will produce gamma ray dose rate of about 4E-5R/hr at a distance of 50cm and after target being cooled for one hour. For higher intensity beam the dose rate linearly increases.

3 Summary

A theory of induced radioactivity has been developed for pulsed primary high energy beam. The theory is consistent with the formalism for continuous beam by Barbier (see Appendix). Attempt has been made to compare predictions with the available data from targets used in the previous collider runs and a reasonable agreement is achieved. Based on these more predictions have been made for new the target design. Also we propose to make more accurate measurements of the activities of the target.

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REFERENCES

1. M.Barbier,Induced Radioactvity, North-Holland Publishing Company (1969).

2. J. Hudis et al, Phys. Rev. Vol. 129 (1962) 434.
3. N.V. Mokhov, MARS10 Manual, Fermilab, FN-509 (1989).
4. K.Anderson (private communication).

4 Appendix. A: Induced radioactivity by a pulsed high energy beam

Let N_o be the number of incident particle per bunch of the primary beam per one second interval (this notion can be extended to any time intervals). As a result of interaction of the beam with a target many radioactive nuclei are formed. Let p_j be the probability that a any particular radioactive nucleus is formed due the interaction of the high energy particle. The radioactive nucleus thus formed may be in its ground state or in any of its excited states. But they decay to their g.s. very rapidly (with a characteristic life time of the order of few nsec or psec) resulting in a burst of gamma rays within few microseconds after the beam interaction. The nuclei in their ground state or in a meta-stable undergo spontaneous radioactive decay. The number of radioactive nuclei of the type 'j' formed in an elemental volume $d\tau$ = dxdydz at the end of the interaction of the first beam pulse is given by,

$$(dN_j)_1 = N_o dS p_j \tag{1}$$

where dS = $\rho_s(x, y, z)dxdydz$ is the number of stars in the volume $d\tau$. By the end of the second pulse the number of radioactive nuclei 'j' left is given by

$$(dN_j)_2 = N_o dS p_j(1 + e^{-\lambda_j}) \tag{2}$$

where λ_j is the radioactive decay constants for 'j'. Similarly extending this for t number of pulses (i.e. after 't' seconds) the total number of radioactive nuclei left not decayed are

$$(dN_j)_t = N_o dS p_j(1 + e^{-\lambda_j} + e^{-2\lambda_j} + ... + e^{-(t-1)\lambda_j})$$

$$(dN_j)_t = N_o dS p_j \frac{1 - e^{-\lambda_j t}}{1 - e^{-\lambda_j}} \tag{3}$$

Let us assume that the irradiation is stopped after time t = t_i and target is let to cool for time t_c. The the number of radioactive nuclei left are

$$(dN_j) = N_o dS p_j \frac{1 - e^{-\lambda_j t}}{1 - e^{-\lambda_j}} e^{-\lambda_j t_c} \tag{4}$$

Total long term radioactivity comprises essentially that arising from gamma decay alone. To decide this we have to take into account the total number of gamma decays from the parent nucleus, and its decay into an excited state of the daughter nucleus and their subsequent decays, their branching ratios, absolute intensities and, annihilation of antiparticles into gamma rays. Finally these newly emitted gamma ray at (x,y,z) will be self attenuated by the target material. Let X(x,y,z) be the thickness of the target material through which a gamma ray travels before it is being detected by a detector at a distance d from the target. Then

$$dN_j = N_o dS p_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j}} e^{-\lambda_j t_c} \sum_k \omega_k(j) \frac{e^{-\mu_k(j) X(x,y,z)} \rho_s(x,y,z)}{(X+d)^2} d\tau \qquad (5)$$

The instantaneous gamma decay rate of this isotope is obtained by differentiating Eq. 5 with respect to t_c.

$$-\frac{dN_j}{dt_c} = N_o dS p_j \lambda_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j}} e^{-\lambda_j t_c} \sum_k \omega_k(j) \frac{e^{-\mu_k(j) X(x,y,z)} \rho_s(x,y,z)}{(X+d)^2} d\tau \qquad (7)$$

Thus the total gamma-ray activity of the target will be the sum of activities of all gamma rays coming from different types of radioactive nuclei and the star densities integrated over entire target volume. Then we will get

$$-\sum_j \frac{dN_j}{dt_c}$$

$$= N_o \sum_j p_j \lambda_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j}} e^{-\lambda_j t_c} \sum_k \omega_k(j) \int_V \frac{e^{-\mu_k(j) X(x,y,z)} \rho_s(x,y,z)}{(X+d)^2} d\tau \qquad (8)$$

The above equation could be tested for a continuous beam. In Eq. 3 we find that for a continuous beam N_o has to be replaced by $N_o \delta t$ and set the limit δt to zero. Then

$$dN_j = N_o p_j \frac{(1 - e^{-\lambda_j t})}{\lambda_j}$$

which is identical to one in Ref. 1. This confirms the consistency of the formalism for pulsed primary beams.

Table - 1

Radioactive Nuclei formed by Interaction of High Energy Protons with Copper and their Decay Properties

Radio-ctive ucleus	Cross-section (mb)	Decay const. (per hour)	Half-life (hour)	Egamma (MeV) and Intensities
7BE	10.100	0.53890E-03	0.12863E+04	0.477 0.103
32P @	3.100	0.20200E-02	0.34315E+03	
18F	1.500	0.37900E+00	0.18289E+01	0.511 1.940
22NA	2.750	0.30400E-04	0.22802E+05	0.511 1.800 1.275 1.000
24NA	3.480	0.46200E-01	0.15004E+02	1.369 1.000 2.754 1.000
42K	2.830	0.55600E-01	0.12467E+02	1.524 0.180
43K	0.980	0.30900E-01	0.22433E+02	0.373 0.850 0.390 0.180 0.619 0.810 1.010 0.020
44SC	2.400	0.17700E+00	0.39162E+01	0.511 1.880 1.159 1.000
44SC*	2.400	0.11800E-01	0.58743E+02	0.271 0.860 1.140 0.013
46SC	3.600	0.34380E-03	0.20162E+04	0.889 1.000 1.120 1.000
47SC	1.700	0.84200E-02	0.82324E+02	0.160 0.730
48SC	0.330	0.15800E-01	0.43872E+02	0.983 1.000 1.040 1.000 1.312 1.000
48V	7.600	0.18050E-02	0.38403E+03	0.511 1.000 0.983 1.000 1.312 0.970
52MN	4.000	0.52040E-02	0.13320E+03	0.511 0.670 0.744 0.880 0.935 0.880 1.434 0.880
52MN*	0.800	0.19520E+01	0.35511E+00	0.511 1.930 1.434 1.000
54MN	6.500	0.96270E-04	0.72003E+04	0.835 1.000
56CO	5.600	0.37500E-03	0.18485E+04	0.511 0.400 0.990 1.150 1.240 0.660 2.300 0.280 3.260 0.130
57CO	14.000	0.10690E-03	0.64843E+04	0.692 0.002
58CO	17.500	0.40110E-03	0.17282E+04	0.511 0.300 0.810 0.990
55FE @	14.000	0.98230E-02	0.70566E+02	
59FE	1.440	0.63900E-03	0.10848E+04	1.095 0.560 1.292 0.440
38CL	2.200	0.11190E+01	0.61945E+00	1.600 0.380 2.170 0.470
57NI	0.540	0.18700E-01	0.37068E+02	0.511 0.920 1.370 0.960 1.890 0.140
60CU	1.720	0.28900E-01	0.23985E+02	0.511 1.860 0.850 0.150 1.332 0.800 1.760 0.520
61CU	11.100	0.20800E+00	0.33325E+01	0.511 1.200 0.380 0.030 1.190 0.050
62CU	31.000	0.42520E+01	0.16302E+00	0.511 1.950
64CU	52.000	0.54000E-01	0.12836E+02	0.511 0.380 1.340 0.005
65ZN	0.450	0.11788E-03	0.58803E+04	0.511 0.034 1.115 0.490
37AR @	4.800	0.82510E-03	0.84010E+03	
41AR	0.730	0.38080E+00	0.18203E+01	1.293 0.990
45TI	3.040	0.22500E+00	0.30808E+01	0.511 1.700 0.718 0.004 1.408 0.003
52FE	0.110	0.86600E-01	0.80043E+01	0.511 1.120
55CO	0.830	0.38500E-01	0.18004E+02	0.511 1.600 0.930 0.800 1.410 0.130
61CO @	4.000	0.42000E+00	0.16504E+01	
43SC	1.700	0.17800E+00	0.38942E+01	0.511 1.760
47V	1.800	0.13280E+01	0.52197E+00	0.511 1.920

* These nuclei are formed in meta-stable state
@ Contributions of these radioactive nuclei to total radioactivity is negligible

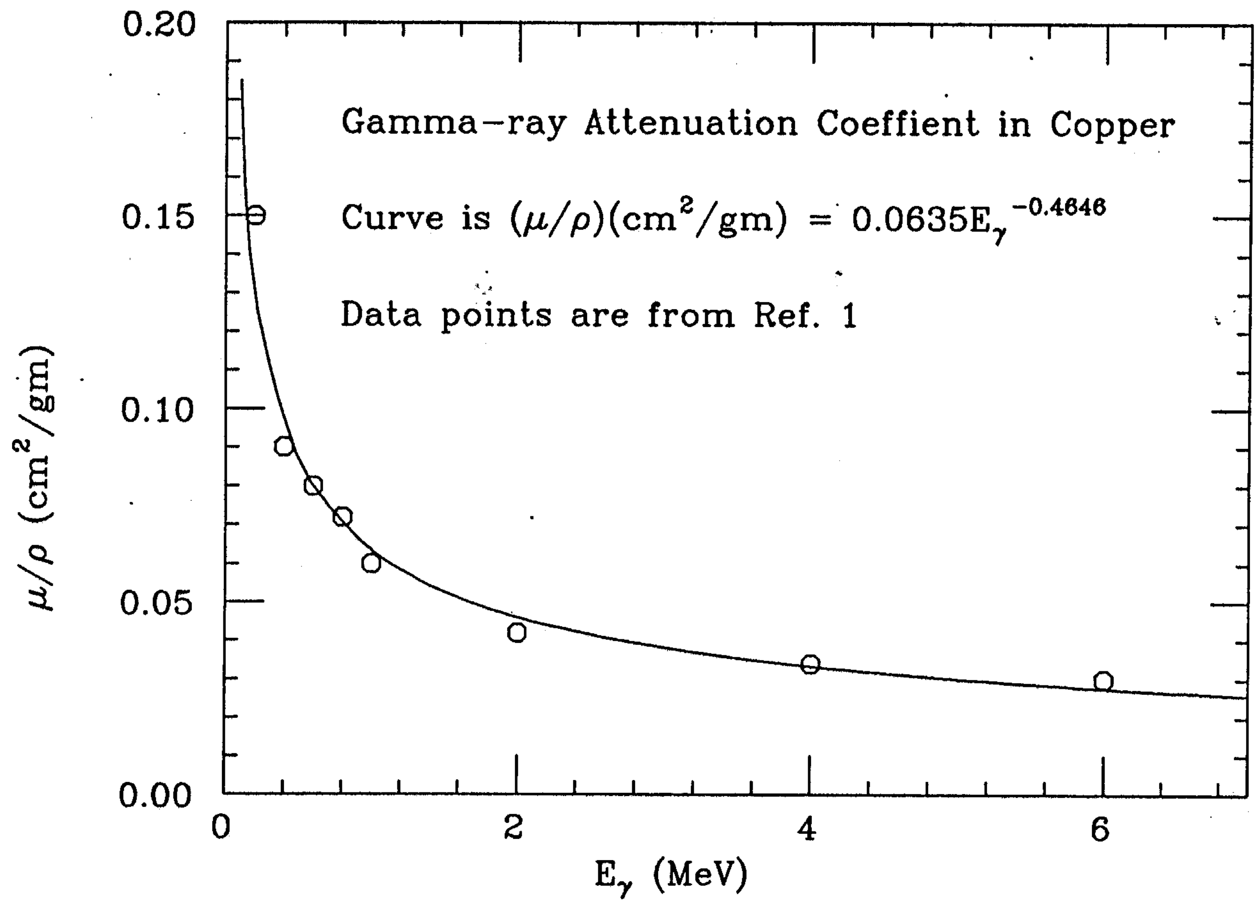
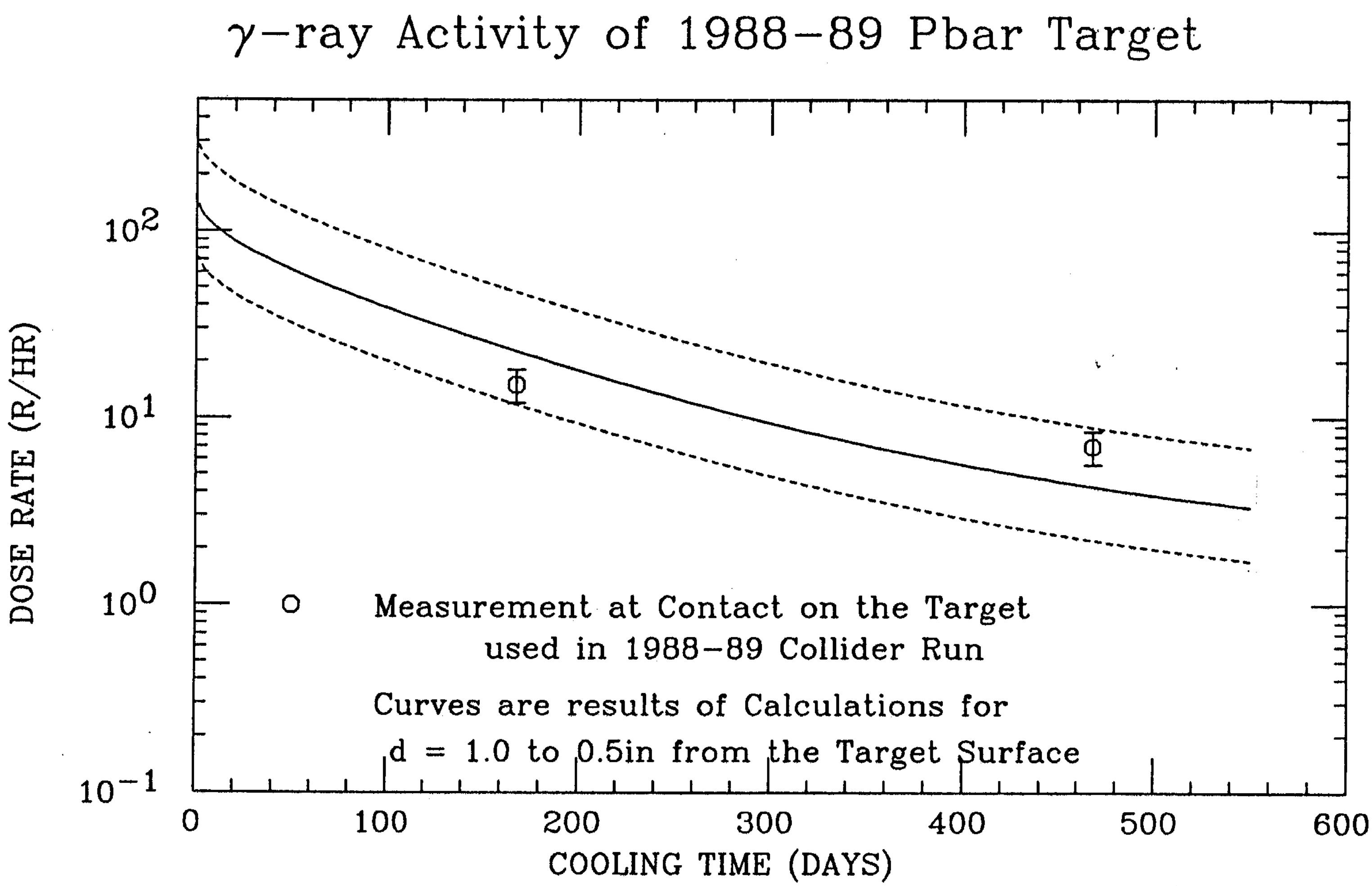
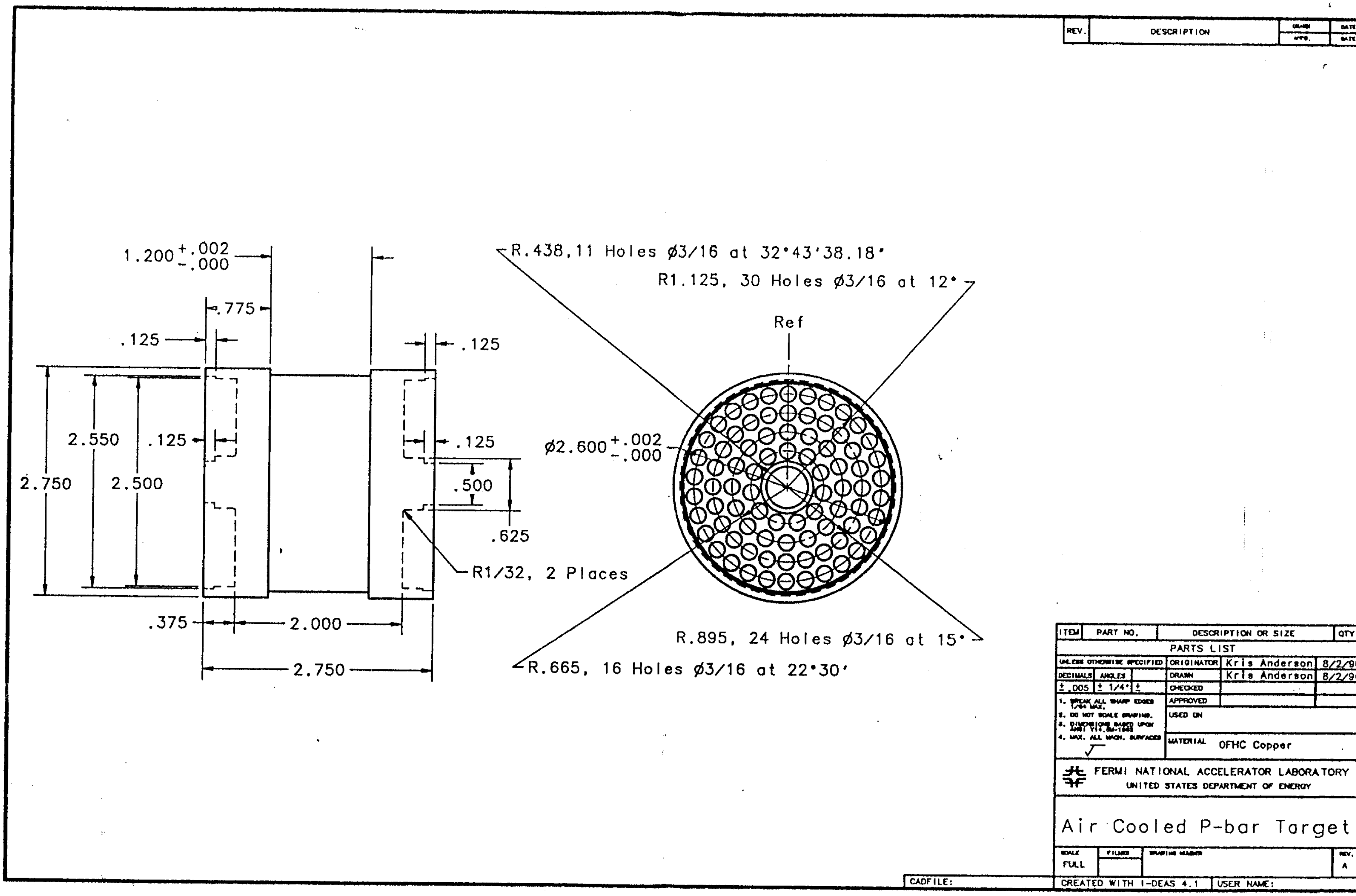

0.20
0.15
0.10
0.05
0.00
0
2
4
6
μ/ρ (cm^2/gm)
E_γ (MeV)
Gamma-ray Attenuation Coeffient in Copper
Curve is $(\mu/\rho)(cm^2/gm) = 0.0635E_\gamma^{-0.4646}$
Data points are from Ref. 1

Fig. 1



γ−ray Activity of 1988−89 Pbar Target
DOSE RATE (R/HR)
10^2
10^1
10^0
10^−1
0
100
200
300
400
500
600
COOLING TIME (DAYS)
Measurement at Contact on the Target used in 1988−89 Collider Run
Curves are results of Calculations for d = 1.0 to 0.5in from the Target Surface

Fig. 2



1.200 +.002 −.000
.775
.125
.125
2.550
.125
2.750
2.500
.125
.500
.625
R1/32, 2 Places
.375
2.000
2.750
R.438,11 Holes ø3/16 at 32°43'38.18"
R1.125, 30 Holes ø3/16 at 12°
Ref
ø2.600 +.002 −.000
R.895, 24 Holes ø3/16 at 15°
R.665, 16 Holes ø3/16 at 22°30'
REV.
DESCRIPTION
ITEM
PART NO.
DESCRIPTION OR SIZE
QTY.
PARTS LIST
ORIGINATOR Kris Anderson 8/2/90
DRAWN Kris Anderson 8/2/90
CHECKED
APPROVED
USED ON
DECIMALS ANGLES
± .005 ± 1/4°
MATERIAL OFHC Copper
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
Air Cooled P-bar Target
FULL
A
CADFILE:
CREATED WITH I-DEAS 4.1
USER NAME:

Fig. 3

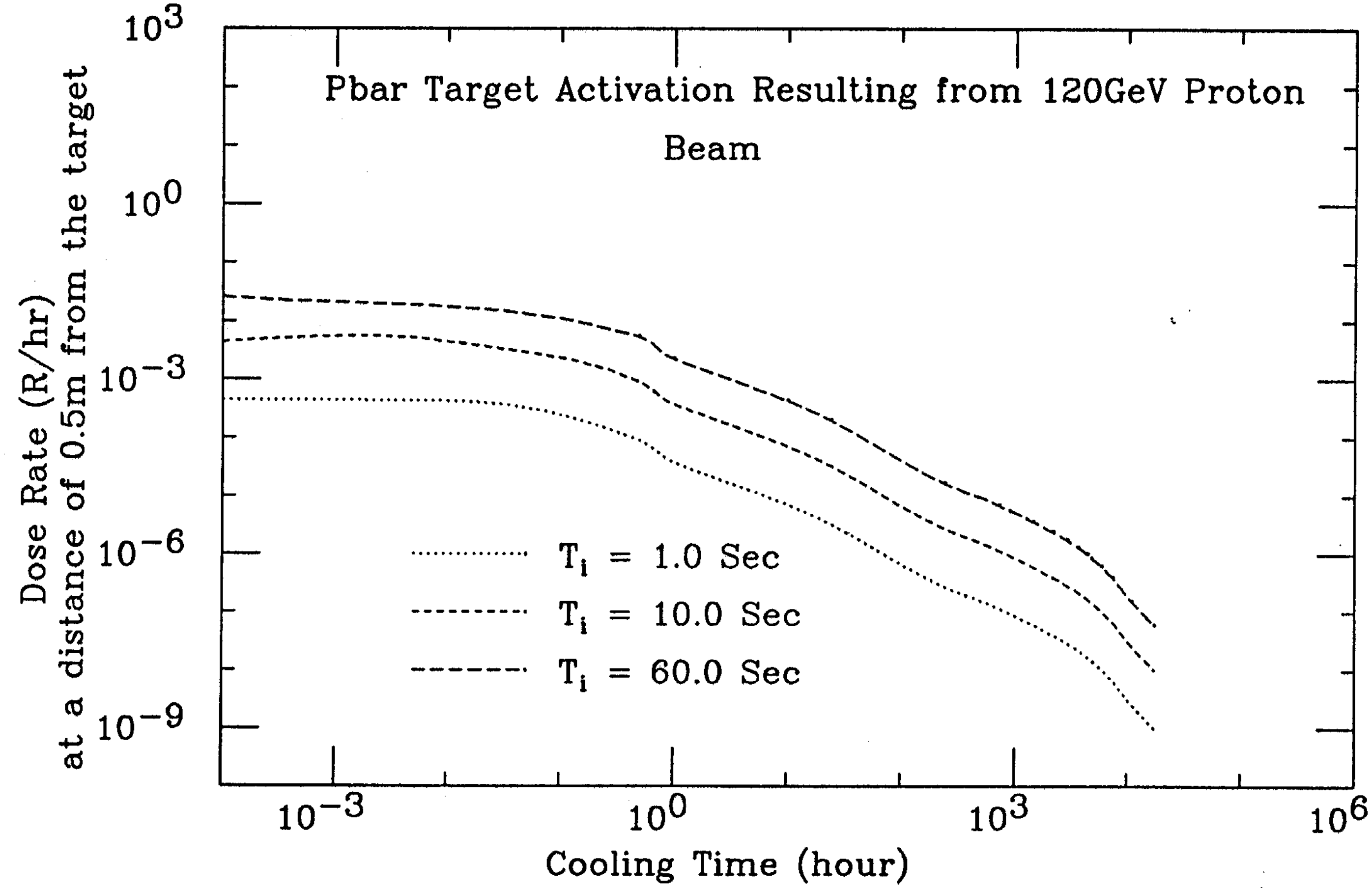

Pbar Target Activation Resulting from 120GeV Proton Beam
Dose Rate (R/hr) at a distance of 0.5m from the target
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
T_i = 1.0 Sec
T_i = 10.0 Sec
T_i = 60.0 Sec
10^{-3}
10^{0}
10^{3}
10^{6}
Cooling Time (hour)

Fig. 4

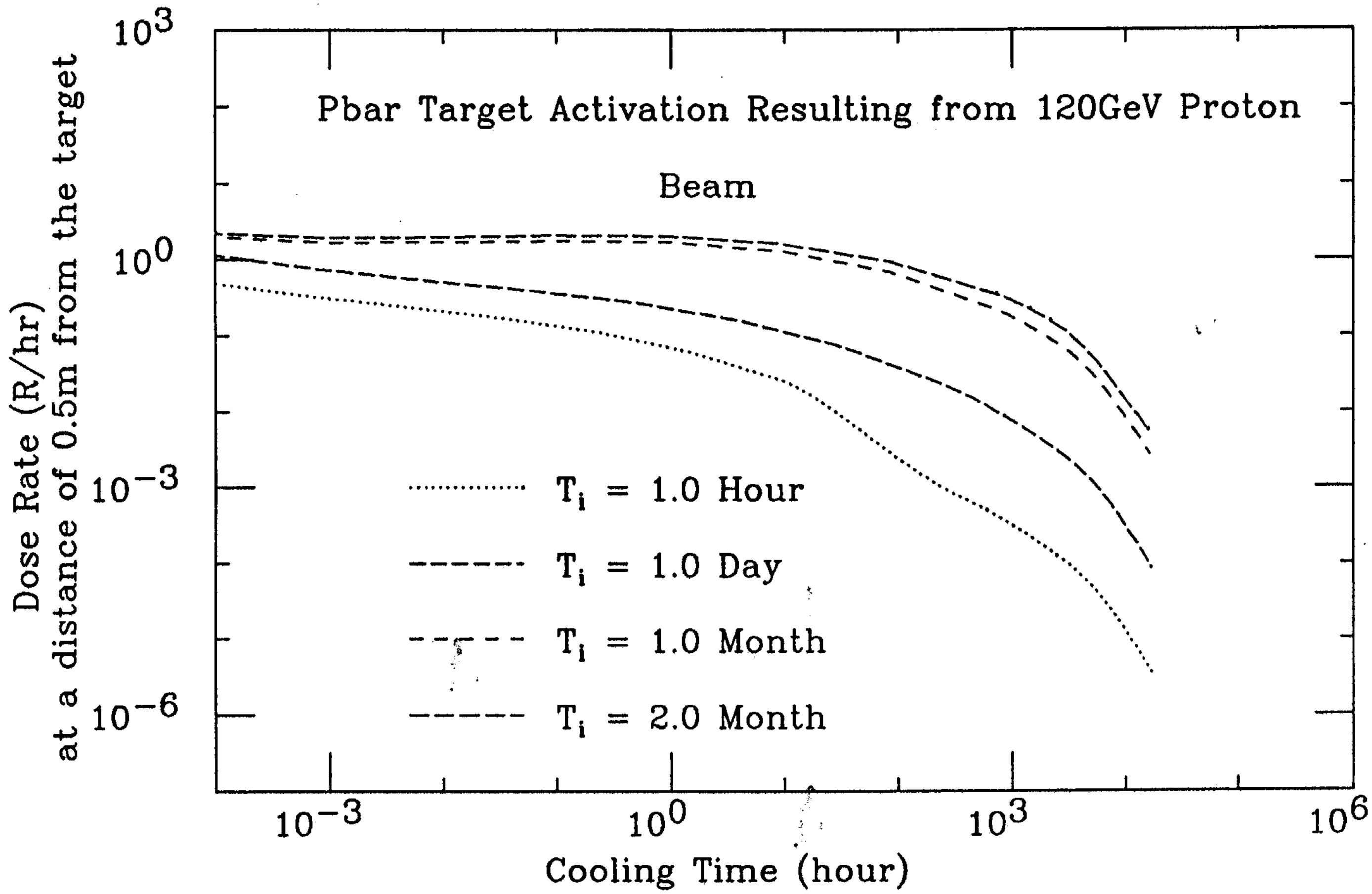

Pbar Target Activation Resulting from 120GeV Proton
Beam
Dose Rate (R/hr)
at a distance of 0.5m from the target
10^3
10^0
10^{-3}
10^{-6}
T_i = 1.0 Hour
T_i = 1.0 Day
T_i = 1.0 Month
T_i = 2.0 Month
10^{-3}
10^0
10^3
10^6
Cooling Time (hour)

Fig. 5