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**Photon Dose Rate from Induced Activity
in the Beam Stop of a 400 GeV
Proton Accelerator**

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Neutron Physics Division

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Abstract

Calculated results are presented of the photon dose rate from the induced activity produced in the beam stop of a high-energy proton accelerator. Incident proton energies of 400 GeV, 200 GeV, and 30 GeV are considered. In each case the photon dose rate is given as a function of radius in the beam stop and as a function of time after the beam is turned off for assumed operating times of 90 days and 10 years.

I. Introduction

The photon dose rate from the induced activity produced by the sustained bombardment of accelerator beam stops by high-energy protons may present a significant radiation hazard to personnel who must work in the vicinity of the beam stop very soon after the beam is turned off. To avoid this hazard the beam stop must be so designed that the photon dose rate decays to an acceptable level as soon as possible after the beam is off. Basically, the stop will consist of a cylindrical core designed to absorb the major portion of the energy produced by the high-energy nucleon-meson cascade and this core will be surrounded by shielding to reduce the photon dose rate outside of the shielding to an acceptable level shortly after the beam is turned off. In this paper calculated results are presented that were carried out to aid in the design of the concrete shielding around the beam stops for ISABELLE^{1*}.

In Section II the beam stop configuration is given and the methods of calculation are described. In Section III the results are presented and discussed. In an Appendix the instantaneous dose equivalent rate (i.e., the dose equivalent rate during the time the beam is incident on the beam stop) in the vicinity of the stop is given for the three incident proton energies considered.

* Calculated results for 200 GeV protons incident on a beam stop of quite different construction from that considered here have previously been given by Garbriel and Santoro.²

II. Geometry and Method of Calculation

In Fig. 1, a schematic diagram of the beam stop geometry used in the calculations is shown. The composition and density of the borated concrete used is shown in Table 1. The incident proton beam was, in all cases, assumed to be normally incident and to be uniform over a radial interval of 2 cm.

To obtain the time dependence of the radioactive buildup and decay and the resulting time dependence of the photon dose rate it is necessary to specify in detail the time dependence of the proton current incident on the beam stop. For all three incident proton energies considered, i.e., 400 GeV, 200 GeV, and 30 GeV, the proton pulse length is taken to be 12.6 μ sec, and the proton current is assumed to be uniform during the pulse. For 400 GeV and 200 GeV incident protons the time between pulses is 20 min and for 30 GeV incident protons the time between pulses is 2.5 sec. For incident energies of 400 GeV and 200 GeV it is assumed that there are $6 \cdot 10^{14}$ protons per pulse and for 30 GeV it is assumed that there are $5 \cdot 10^{12}$ protons per pulse.

With this specification of the incident proton current, $I(t)$, the photon dose rate as a function of irradiation time and time after the beam is turned off may be calculated. The production rate of nuclei of type k at a given position, $\vec{r}$, and time, t , by the nonelastic collisions of protons, neutrons, and charged pions, may be written

$$P_k(\vec{r}, t) = \sum_{i=p, n, \pi^\pm} \sum_j \int_{E_{ijk}}^{E_{\max}} dE \Phi_i(\vec{r}, E, t) \sigma_{ijk}(E) n_j(\vec{r}) \quad (1)$$

Fig. 1. Schematic diagram of the beam stop geometry used in the calculations.

Table 1

Composition of Borated ConcreteDensity = 2.39 g cm^{-3}

<u>Element</u>	<u>% by wt.</u>
Fe	1.6
Ca	21.6
Si	10.2
Al	.5
Mg	5.5
Na	1.0
O	51.5
C	7.0
B	0.3
H	.8

where

$P_k(\vec{r}, t)$ = the number of nuclei of type k (defined by charge number Z and mass number A) per unit volume per unit time produced at $\vec{r}$ and t ,

$p, n, \pi^\pm$ = protons, neutrons, and positively and negatively charged pions, respectively,

E_{ijk} = the energy below which the production of nuclei of type k by the interaction of particles of type i with nuclei of type j becomes negligible,

$E_{\max}$ = the maximum energy of any particle being considered,

$\Phi_i(\vec{r}, E, t)$ = the omnidirectional flux per unit energy for particles of type i with energy E at $\vec{r}$ and t ,

$\sigma_{ijk}(E)$ = the microscopic cross section for the production of nuclei of type k by the interaction of particle of type i at energy E with a nucleus of type j ,

$n_j(\vec{r})$ = the number of nuclei per unit volume of type j at $\vec{r}$.

If it is assumed that the nucleon-meson cascade takes place in times that are negligible compared to the times of interest then

$$\Phi_i(\vec{r}, E, t) = \Phi_i(\vec{r}, E) I(t), \quad (2)$$

where

$\Phi_i(\vec{r}, E)$ = the steady-state omnidirectional flux per unit energy for particles of type i with energy E at $\vec{r}$ per unit incident proton current,

$I(t)$ = the incident proton current as a function of time, and $P_k(\vec{r}, t)$ may be written in the form

$$P_k(\vec{r}, t) = P_k(r)I(t), \quad (3)$$

where

$$P_k(\vec{r}) = \sum_{i=p,n,\pi^\pm} \sum_j \int_{E_{ijk}}^{E_{\max}} dE \Phi_i(\vec{r}, E) \sigma_{ijk}(E) n_j(\vec{r}) . \quad (4)$$

Nuclei of type k may or may not be radioactive and produce photons. If a subscript ℓ is used to denote a particular type of produced nuclei that decays with decay constant λ_ℓ then the number, $Q_\ell(\vec{r}, t)$, of radioactive nuclei of type ℓ per unit volume at $\vec{r}$ and t , must satisfy the equation

$$\frac{d}{dt} Q_\ell(\vec{r}, t) = -\lambda_\ell Q_\ell(\vec{r}, t) + P_\ell(\vec{r}, t) , \quad (5)$$

which may for convenience, be written

$$Q_\ell(\vec{r}, t) = P_\ell(\vec{r}) R_\ell(t) \quad (6)$$

where

$$\frac{d}{dt} R_\ell(t) = -\lambda_\ell R_\ell(t) + I(t) . \quad (7)$$

For the time dependence of I specified previously, the solution of Eq. (7) may easily be obtained and is used here in the form

$$\begin{aligned} R [mt_d + (n_p - 1)t_0 + t_s] = & R_\ell(t_d) \left[\frac{1 - e^{-\lambda_\ell t_d}}{1 - e^{-\lambda_\ell t_s}} \right] e^{-\lambda_\ell [(n_p - 1)t_0 + t_s]} \\ & + e^{-\lambda_\ell t_s} \left[I_0 \left(\frac{1}{\lambda_\ell} \right) (e^{\lambda_\ell t_p} - 1) \right. \\ & \left. + R_\ell [(n_p - 1)t_0] \right] \end{aligned} \quad (8)$$

$$\begin{aligned}
 R_{\ell}(t_d) = & e^{-\lambda_{\ell}[t_d - (n_p - 1)t_0]} \\
 & \cdot \{I_0(\frac{1}{\lambda_{\ell}})[e^{\lambda_{\ell}t_{p-1}}] \\
 & + R_{\ell}[(n_p - 1)t_0]\}
 \end{aligned} \tag{9}$$

$$\begin{aligned}
 R_{\ell}[(n_p - 1)t_0] = & I_0(\frac{1}{\lambda_{\ell}}) \left[\frac{1 - e^{-\lambda_{\ell}(n_p - 1)t_0}}{1 - e^{-\lambda_{\ell}t_0}} \right] \\
 & \cdot e^{-\lambda_{\ell}(n_p - 1)t_0} (e^{\lambda_{\ell}t_{p-1}})
 \end{aligned} \tag{10}$$

$$t = mt_d + (n_p - 1)t_0 + t_s, \tag{11}$$

where

m = the number of days of operation,

$t_d = 24$ h,

n_p = the total number of incident proton pulses
in an 8 h period,

t_0 = the time between incident proton pulses,

t_s = time after the last pulse on the $m + 1$ day of
operation (strictly speaking, t_s is measured
from the start of this last pulse, but the
pulse length is very small (12.6 μ sec) compared
to the times of interest so this is of little
significance),

I_0 = the value of $I(t)$ during a pulse,

t_p = the pulse length (= 12.6 μ sec),

t = the total time that has elapsed since the
beam was turned on.

The production rate of photons may be written

$$S_{\gamma}(\vec{r}, E_{\gamma}, t) = \sum_{\ell} \lambda_{\ell} P_{\ell}(\vec{r}) R_{\ell}(t) \Gamma_{\ell}(E_{\gamma}) \quad (12)$$

where

$S_{\gamma}(\vec{r}, E_{\gamma}, t)$ = the number of photons produced per unit volume
per unit energy per unit time at $\vec{r}$, E_{γ} , and t
by the decay of all nuclei at $\vec{r}$ and t .

$\Gamma_{\ell}(E_{\gamma})$ = the number of photons per unit energy per decay
emitted at E_{γ} by nuclei of type ℓ ,

and the photon dose rate at $\vec{r}$ and t can, neglecting the time for the
photon transport, be expressed as

$$\begin{aligned} D(\vec{r}, t) = & \int dE_{\gamma} C(E_{\gamma}) \\ & \cdot \int d\vec{r}' dE'_{\gamma} S(\vec{r}', E'_{\gamma}, t) \\ & \cdot V(\vec{r}, E_{\gamma}; \vec{r}', E'_{\gamma}) \end{aligned} \quad (13)$$

where

$D(\vec{r}, t)$ = the photon dose rate at $\vec{r}$ and t ,

$C(E_{\gamma})$ = the photon flux-to-dose rate conversion factor,

$V(\vec{r}, E_{\gamma}; \vec{r}', E'_{\gamma})$ = the value function for the photon flux, i.e.,
the photon flux per unit energy range at $\vec{r}$ and
 E_{γ} due to one photon per unit time leaving $\vec{r}'$
with energy E'_{γ} .

Equation (13) may be written using Eq. (12) as

$$D(\vec{r}, t) = \sum_{\ell} \lambda_{\ell} R_{\ell}(t) \left\{ \int dE_{\gamma} C(E_{\gamma}) \cdot \int d\vec{r}' dE'_{\gamma} P_{\ell}(\vec{r}) \Gamma_{\ell}(E_{\gamma}) V(\vec{r}, E_{\gamma}; \vec{r}', E'_{\gamma}) \right\} \quad (14)$$

In Eq. (14) the bracket quantity is time independent and contains all of the information that must be obtained by rather lengthy transport calculations. In the work reported here the bracket term was calculated for each ℓ value and then the time dependence was introduced and the sum over ℓ carried out.

The transport calculation for neutrons with energy > 15 MeV and all charged particles were carried out with the nucleon-meson transport code HETC.³ This code has been described in detail elsewhere⁴ and therefore will not be discussed here. It is a feature of the code, however, that it provides the type and spatial distribution of all residual nuclei produced by the nonelastic collisions of neutrons with energy > 15 MeV and all charged particles and it is these residual nuclei that are photon emitters - including the annihilation photons from positron emitters - that are of primary interest here.

The low energy (< 15 MeV) neutrons that are produced by the high-energy nuclear reactions were transported with the Monte Carlo code MORSE.⁵ The cross section data for the low energy neutron transport were taken from the compilation of Plaster *et al.*^{6,7} The production of radioactive residual nuclei by neutrons with energy (< 15 MeV) was obtained by integrating over energy the product of the neutron flux per unit energy obtained from MORSE and the macroscopic residual nuclide

production cross section. The macroscopic residual nucleus production cross sections were taken from the MONTAGE library of Muir.⁸ In the high-energy (> 15 MeV) transport calculations the most abundant isotope of each element was used to represent the element. In the low energy (< 15 MeV) transport calculations the natural isotopic abundance of each element was used.

The photon spectrum from the decay of each type of produced radioactive nucleus was obtained from the Evaluated Nuclear Structure Data Files of the Nuclear Data Project.⁹ Photons produced by radioactive nuclei with half-lives less than 15 sec were neglected since only times ≥ 15 min after the proton beam is turned off are considered. The photon transport calculations were carried out with MORSE⁵ using cross section data obtained from Ref. 6 and 7. The photon flux-to-dose rate conversion factors used in the calculations were taken from the work of Claiborne and Truby.¹⁰

III. Results and Discussion

The photon dose rates from 400 GeV, 200 GeV, and 30 GeV incident protons are shown as a function of time after the beam has been turned off in Figs. 2, 3, and 4, respectively. The dose rates in each of these figures have been averaged over the depth interval 0 to 6 m, i.e., over the entire length of the beam stop (see Fig. 1). In each of the figures results are given for operating times of 90 days and 3650 days and as a function of radial concrete thickness. It should be noted that all of the calculations were performed with a radial concrete thickness of 150 cm so the values in Figs. 2, 3, and 4 for a concrete radial thickness Δr (< 150 cm) are larger because of albedo contributions than they would

Fig. 2. Photon dose rate for various radial concrete thicknesses vs time after shutdown for 400 MeV incident protons and operating times of 90 and 3650 days. All of the results shown have been averaged over the entire length of the beam stop (see Fig. 1).

Fig. 3. Photon dose rate for various radial concrete thicknesses vs time after shutdown for 200 MeV incident protons and operating times of 90 and 3650 days. All of the results shown have been averaged over the beam stop (see Fig. 1).

Fig. 4. Photon dose rate for various radial concrete thicknesses vs time after shutdown for 30 MeV incident protons and operating times of 90 and 3650 days. All of the results shown have been averaged over the entire length of the beam stop (see Fig. 1).

be if the calculations were carried out for a radial concrete thickness of Δr . The error bars where given in Figs. 2, 3, and 4 are statistical only and represent one standard deviation.

For the three incident energies considered the dose rates with no concrete are quite high but are reduced by several orders of magnitude by the addition of the 150 cm of concrete. In all cases, the photon dose rates decrease rather rapidly during the first hour or two after the beam is turned off, but only slowly thereafter. The buildup of the dose rates with operating time is relatively small. Since the same incident proton current as a function of time was used for 400 GeV and 200 GeV incident protons, the results in Figs. 2 and 3 provide direct information on the dependence of the activation dose rates on proton energy. For a given operating time and time after shutdown the dose rate at a given location in the beam stop from 400 GeV incident protons is very approximately a factor of two larger than the dose rate from 200 GeV incident protons.

The photon dose rates in Figs. 2-4 have been averaged over the length of the beam stop and thus provide no information of the variations of the dose rates with depth in the beam stop. In Table 2 some information of these variations are given for the three incident energies considered and for a radial concrete thickness of 100 cm. In the case of 400 GeV and 200 GeV incident protons the photon dose rates are larger by a factor of 2 or 3 in the 2-4 m depth interval than in the 0-2 m and 4-6 m depth intervals. In the case of 30 GeV incident protons the dose rates in the 0-2 m and the 2-4 m depth intervals are approximately comparable and are somewhat larger than those in the 4-6 m depth interval. For all incident energies the dose rates in Table 2 averaged over the length of the beam

Table 2

Photon Dose Rate Averaged Over Various Depth Intervals
for a Radial Concrete Thickness of 100 cm

Time After Shutdown (h)	Photon Dose Rate (rem h ⁻¹)			
	Avg. Over the Depth Interval	Avg. Over the Depth Interval	Avg. Over the Depth Interval	Avg. Over the Depth Interval
	0-2 m	2-4 m	4-6 m	0-6 m
<u>400 GeV Protons Incident 90 Days of Operation</u>				
.25	1.1·10 ⁻¹ (49)*	2.7·10 ⁻¹ (38)	1.0·10 ⁻¹ (44)	1.6·10 ⁻¹ (26)
2.	2.9·10 ⁻² (63)	6.4·10 ⁻² (26)	3.3·10 ⁻² (45)	4.2·10 ⁻² (21)
12.	2.1·10 ⁻² (69)	3.8·10 ⁻² (28)	2.0·10 ⁻² (45)	2.6·10 ⁻² (24)
<u>400 GeV Protons Incident 3650 Days of Operation</u>				
.25	1.1·10 ⁻¹ (49)	2.8·10 ⁻¹ (37)	1.1·10 ⁻¹ (44)	1.7·10 ⁻¹ (26)
2.	2.9·10 ⁻² (63)	7.5·10 ⁻² (26)	3.6·10 ⁻² (48)	4.7·10 ⁻² (22)
12.	2.2·10 ⁻² (63)	4.9·10 ⁻² (27)	2.4·10 ⁻² (51)	3.1·10 ⁻² (24)
<u>200 GeV Protons Incident 90 Days of Operation</u>				
.25	4.5·10 ⁻² (27)	2.0·10 ⁻¹ (43)	1.0·10 ⁻¹ (43)	1.1·10 ⁻¹ (34)
2.	1.5·10 ⁻² (29)	3.6·10 ⁻² (26)	1.3·10 ⁻² (33)	2.1·10 ⁻² (21)
12.	9.2·10 ⁻³ (32)	2.2·10 ⁻² (26)	7.4·10 ⁻³ (37)	1.3·10 ⁻² (22)
<u>200 GeV Protons Incident 3650 Days of Operation</u>				
.25	6.1·10 ⁻² (28)	2.1·10 ⁻¹ (42)	1.0·10 ⁻¹ (44)	1.2·10 ⁻¹ (32)
2.	3.1·10 ⁻² (44)	4.5·10 ⁻² (26)	1.7·10 ⁻² (37)	3.1·10 ⁻² (24)
12.	2.5·10 ⁻² (50)	3.2·10 ⁻² (27)	1.1·10 ⁻² (44)	2.3·10 ⁻² (27)
<u>30 GeV Protons Incident 90 Days of Operation</u>				
.25	6.7·10 ⁻² (28)	5.9·10 ⁻² (32)	1.3·10 ⁻² (60)	4.6·10 ⁻² (23)
2.	3.4·10 ⁻² (37)	1.5·10 ⁻² (26)	9.2·10 ⁻³ (80)	1.9·10 ⁻² (25)
12.	2.2·10 ⁻² (37)	1.0·10 ⁻² (27)	5.8·10 ⁻³ (80)	1.3·10 ⁻² (25)
<u>30 GeV Protons Incident 3650 Days of Operation</u>				
.25	6.7·10 ⁻² (28)	7.4·10 ⁻² (30)	1.4·10 ⁻² (59)	5.2·10 ⁻² (21)
2.	3.4·10 ⁻² (37)	3.0·10 ⁻² (45)	9.3·10 ⁻³ (79)	2.4·10 ⁻² (25)
12.	2.2·10 ⁻² (37)	2.5·10 ⁻² (52)	5.9·10 ⁻³ (78)	1.8·10 ⁻² (28)

*The values in parentheses give the statistical error (one standard deviation) expressed in percent.

stop are never more than a factor of two smaller than the dose rates in any one of the 2 m intervals. Because of poor statistical accuracy results similar to those shown in Table 2 are not available for the larger radial concrete thicknesses, but it seems reasonable to assume that the variations of the dose rates with depth at the larger radial concrete thicknesses (> 100 cm) are no greater than those shown in Table 2.

In Figs. 5, 6, and 7 the total dose rate and the contributions to the total dose rate from individual nuclei for 400-, 200-, and 30-GeV incident protons, respectively, are shown for a radial concrete thickness of 100 cm. In the figures only the major contributors are shown; there are, of course, many small contributions from other nuclei that were calculated and are not shown. The dose rates in these figures have been averaged over the length of the beam stop as in Figs. 2-4.

In Figs. 5-7 at short times (~ 1 to 2 h) after shutdown there are contributions to the total dose rate from several nuclides with short half-lives, but at larger times the dose rate is due almost completely to the decay of ^{24}Na . For 400 GeV incident protons there are contributions to the total dose rate for a radial concrete thickness of 100 cm from the decay of ^{52}Mn and $^{52\text{m}}\text{Mn}$. Contributions from these nuclides are present at the smaller concrete thicknesses for 200 GeV and 30 GeV incident protons and for 400 GeV incident protons there is no contribution from these nuclides at radial concrete thicknesses of 125 cm and 150 cm. A substantial part of the ^{24}Na production in the concrete is from the reaction $^{24}\text{Mg}(n,p)^{24}\text{Na}$, but there are also non-negligible contributions from a variety of other reactions. The increase of the dose rates with

Fig. 5. Total photon dose rate and contributions to the total photon dose rate from various nuclei vs time after shutdown for 400 MeV incident protons and operating times of 90 and 3650 days. The results shown are for a radial concrete thickness of 100 cm and have been averaged over the entire length of the beam stop (see Fig. 1).

Fig. 6. Total photon dose rate and contributions to the total photon dose rate from various nuclei vs time after shutdown for 200 MeV incident protons and operating times of 90 and 3650 days. The results shown are for a radial concrete thickness of 100 cm and have been averaged over the entire length of the beam stop (see Fig. 1).

Fig. 7. Total photon dose rate and contributions to the total photon dose rate from various nuclei vs time after shutdown for 30 GeV incident protons and operating times of 90 and 3650 days. The results shown are for a radial concrete thickness of 100 cm and have been averaged over the entire length of the beam stop (see Fig. 1).

operating time is due primarily to the production and decay of ^{22}Na that has a half-life of 2.6 y. The contributors to the total dose rates at the other radial concrete thicknesses are, except for very small thicknesses, similar to those shown in Figs. 4-6.

Appendix: Dose Equivalent Rate During a Pulse

The dose equivalent rate as a function of position in the beam stop can be obtained from the flux per unit energy of the various types of particles and flux-to-dose rate conversion factors. In this appendix the dose equivalent rate during a pulse is given as a function of radial position in the beam stop for the three incident proton energies considered in the body of the paper.

The neutron flux-to-dose rate conversion factors were taken from the recommendations of the ICRP.¹¹ The proton, charged pion, and muon fluxes were converted to dose equivalent rate using the charged particle stopping powers in tissue¹² and the dose equivalent as a function of linear energy transfer.¹³ The photon flux-to-dose rate conversion factors were taken from Ref. 10.

In Fig. A.1 the instantaneous dose equivalent rate is given as a function of radial concrete thickness for 400 GeV, 200 GeV, and 30 GeV incident protons. The results in the figure have been averaged over the depth interval 0-6 m. In obtaining the results in Fig. A.1, as in the body of the paper, all of the calculations were carried out with a radial concrete thickness of 150 cm so the results for concrete thicknesses < 150 cm are inside the shield.

The error bars in Fig. A.1 are statistical only and represent one standard deviation. For all incident energies and all concrete thicknesses, a large fraction ($\sim .9$) of the dose equivalent rate is due to neutrons. The results in the figure do not, strictly speaking, include the dose rate due to π^0 photons, but an approximate estimate of the dose rate

Fig. A.1. Instantaneous dose equivalent rate vs radial concrete thickness for 400-, 200-, and 30-GeV incident protons. All of the results shown have been averaged over the entire length of the beam stop (see Fig. 1).

from the π^0 photons produced by 400 GeV incident protons has been made and they have been found to contribute only a small amount ($\lesssim 1\%$) to the dose equivalent rate.

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