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CALCULATION OF THE ENERGY DEPOSITION IN A WATER BEAM DUMP

by

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Abstract

The energy deposition per interacting proton in " Gev/cm^3 " and the star density in " star/cm^3 " have been calculated in a water cylinder with a Monte Carlo computer program. These calculations permit to estimate the temperature rise, induced radioactivity, etc. in beam dumps of high energy accelerators and storage rings. We assumed a cylinder of different diameters and lengths and an energy of the incident proton beam of 20, 200, 300 and 400 GeV.

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TABLE OF CONTENTS

1. INTRODUCTION

2. CALCULATIONS

3. RESULTS

4. CONCLUSIONS

REFERENCES

APPENDIX

TABLES

FIGURES

1. INTRODUCTION

Heavy materials are commonly used for the construction of beam dumps in high energy accelerators and storage rings because of their efficiency in absorbing high energy primary and secondary particles. This document reports on the promising behaviour of water as a beam dump substance for high energetic particles. A comparison is made between water and metals as beam dump materials for energies up to 400 GeV¹⁾.

2. CALCULATIONS

The energy deposition in GeV/cm³ proton and the star densities in star/cm³p have been calculated with the Monte Carlo program FLUKA²⁾. For these calculations we assumed a water cylinder of different diameters and lengths and an energy of the incident proton beam of 20, 200, 300 and 400 GeV (see Figure 1). The cross-section of the beam incident on the axis was 0.1×0.1 cm² to 3.0×3.0 cm². In the program FLUKA, the particles and their secondaries are followed in three-dimensional cartesian coordinates. Because of the cylindrical symmetry, the resulting energy and star deposition densities can be accumulated in three dimensions as a function of radial and longitudinal distances. 50 bins are used in the calculations to cover both directions. Tables 1 and 2 summarize the exact values of the assumptions used for the present water and metal cylinders.

3. RESULTS

The calculated energy deposition is presented in the form of graphs in Figures 2 to 12 for water and in Figures 13 to 16 for beryllium, titanium, copper and tungsten, respectively. The graphs are self-explanatory. Tables 1 and 2 show the energy deposition in the first radial bin of the cylinder. The energy

deposition densities can be used to calculate the absorbed dose and the heating in the material due to proton beam losses and secondary interactions (an example is given in the Appendix).

Table 1 also gives the percentage of the total available primary energy absorbed in a water cylinder of various dimensions, and Table 2 gives it for the solid beryllium, titanium, copper and tungsten cylinders of 50 cm radius and 5 m length.

Figures 17 and 18 show examples of the energy absorption of a 400 GeV proton beam incident on a 20 m long cylinder of different radii. From these figures it can be seen that a rather large volume of water is required in order to absorb 90 % of the incident energy compared to heavier materials; on the other hand, the maximum energy deposition on the beam axis is a factor 100 lower than in copper or steel.

Finally, Tables 1 and 2 give the total number of stars produced in the water cylinders considered. This figure enables us to estimate the production of dangerous radioisotopes. In the present case, these are mainly tritium ($t_{\frac{1}{2}} = 12$ years) and Be^7 ($t_{\frac{1}{2}} = 53$ days) which are both produced from oxygen. An example of H^3 and Be^7 production is given in the Appendix.

4. CONCLUSIONS

In order to absorb 80 % of a 400 GeV proton beam, a water cylinder of about 1.0 (or 1.5) meter radius and 15 (or 9) meter length would be required (see Figure 18).

The temperature rise due to energy deposition in the water is about 40°C at 2 cm from the beam axis for 10^{15} incident protons of 400 GeV/c. For a very small volume on the beam axis, this value can be up to 100 times higher. Due to the low energy deposition and high specific heat of water, these values are rather low compared to metals.

The production of the long-lived isotopes Be^7 and H^3 from oxygen has to be considered when using water as beam dump. Their production rate is such that precautions have to be taken for safe disposal. However, it should be mentioned that for water we are concerned with two main isotopes only, whereas in metals a large number of long-lived isotopes are created.

In water at 400 GeV, about 1 star is created per 1 GeV lost.

In the cases considered, the change of the incident proton beam from $0.1 \times 0.1 \text{ cm}^2$ to $3.0 \times 3.0 \text{ cm}^2$ cross-section did not influence the results very much.

REFERENCES

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- 3) E. Bruninx, High energy nuclear reactions cross-sections, CERN Report 61-1 (1961).
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APPENDIX

1. The heating in the cylinder can be calculated by the following formula:

$$\text{Temp (}^{\circ}\text{C)} = 3.85 \times 10^{-11} \text{ cal} \times \frac{\text{GeV}}{\text{cm}^3 \text{ int.prot.}} \times \frac{1}{\rho} \times \frac{1}{C_p} \times N_p$$

where:

$$1 \text{ GeV} = 1.6 \times 10^{-10} \text{ Joule} = 3.85 \times 10^{-11} \text{ cal}$$

$$(1 \text{ Joule} = 0.24 \text{ cal})$$

$$\rho = \text{density in g/cm}^3$$

$$C_p = \text{specific heat cal/g}^{\circ}\text{C}$$

$$N_p = \text{number of interacting protons.}$$

The energy deposition in the water cylinder at 2 cm from the beam axis is $\sim 1 \times 10^{-3} \text{ GeV/cm}^3$ per interacting proton of 400 GeV/c; assuming a stacked beam of 10^{15} protons, we obtain a temperature rise of about 40°C .

In a very small volume near to the beam axis (e.g. at 1 mm), the heat can be about 100 times higher.

2. The absorbed dose in the material can be calculated:

$$\text{Dose (rad)} = 1.6 \times 10^{-5} \frac{\text{rad g}}{\text{GeV}} \times \frac{\text{GeV}}{\text{cm}^3 \text{ int.prot.}} \times \frac{1}{\rho} \times N_p$$

where:

$$1 \text{ GeV/g} = 1.6 \times 10^{-5} \text{ rad}$$

$$\rho = \text{density in g/cm}^3$$

For the same assumptions as in Section 1, we obtain an absorbed dose of $1.6 \times 10^7 \text{ rad}$.

In copper, the maximum energy deposition at 2 cm is about $4 \times 10^{-2} \text{ GeV/cm}^3 \text{ p}^1$; hence, the above value would be about 40 times higher.

3. The H^3 and Be^7 production in the water beam dump can be estimated from the total cross-section of oxygen which is about 300 mb. This value is derived from the interaction length $\lambda = 1/N\sigma$, where $\lambda = 90.1 \text{ g/cm}^2$, N = number of atom/g and σ = cross section in cm^2 .

Knowing that the cross-section for H^3 production is about 30 mb and Be^7 production is about 10 mb³⁾, and assuming that the absorption cross-section remains constant above 20 GeV⁴⁾, we can conclude that about 10 % of the total stars per proton give rise to a production of H^3 nucleides, and about 3 % of the total stars per proton give rise to Be^7 nucleides, with a half life of 12 years for tritium, and 53 days for Be^7 , respectively.

For example, in a water cylinder of 1 m radius and 15 m length, we have a total number of 330 stars created per proton which, according to the above figures, would result in:

$$\begin{aligned} &\sim 33 \text{ } H^3 \text{ nucleides/p} \\ &\sim 11 \text{ } Be^7 \text{ nucleides/p} . \end{aligned}$$

From a given irradiation and cooling time, one can calculate the actual activation of the cylinder volume by means of standard procedures, as described in Ref. 5, for example.

Assuming a repetitive injection of 3×10^{12} p/sec at 400 GeV/c during 30 minutes, we could obtain 0.25 Ci Be^7 and 0.01 Ci H^3 . Dilution of this activity in a water volume of 15 m length and 2 m diameter ($= 47 \text{ m}^3$) would give activity values below the maximum permissible concentration.

TABLE 1

CASE	W1	W2	W3	W4	W41	W42	W43	W51	W52	W53	W61	W7	W8
Computer file No.	74-1	74-2	74-2	74-2	74-4	74-4	74-4	74-5	74-5	74-5	74-5	74-6	74-6
Primary energy (GeV)	20	200	300	400	400	400	400	400	400	400	400	400	400
Incident beam size (cm × cm)	0.5	0.1	0.1	0.1	0.3	0.3	0.3	1.0	2.0	3.0	1.0	1.0	1.0
Material
Density (g/cm ³)
Cylinder length (cm)	1000	1000	1000	1000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Cylinder radius (cm)	50	50	50	50	5	10	20	50	50	50	100	150	200
Bin length ΔZ (cm)	20	20	20	20	40	40	40	40	40	40	40	40	40
Bin length ΔR (cm)	1.0	1.0	1.0	1.0	0.1	0.2	0.4	1.0	1.0	1.0	2.0	3.0	4.0
Energy deposition in rad.bin (10 ⁻³ GeV/cm ³ p)	1.0	3.0	5.0	4.0	100	80	20	4.0	2.5	1.0	2.5	2.0	1.5
Whole energy absorption in element (%)	45	55	55	55	9	17	31	58	58	57	79	85	93
Number of stars produced in cylinder	17	130	180	240	44	81	133	245	245	250	330	350	380
Figure	2	3	4	5	6	7	8	9 17	9	9	10	11	12 18

TABLE 2

CASE	2.21	2.81	2.111	2.141
Computer file No.	73-3	73-5	73-6	73-7
Primary energy (GeV)	400	400	400	400
Incident beam size (cm × cm)	0.2	0.2	0.2	0.2
Material	Be	Ti	Cu/Fe	W
Density (g/cm ³)	1.85	4.8	8.9/7.8	19.3
Cylinder length (cm)	500	500	500	500
Cylinder radius (cm)	50	50	50	50
Bin length ΔZ (cm)	10	10	10	10
Bin length ΔR (cm)	1	1	1	1
Energy deposition in rad.bin (10 ⁻³ GeV/cm ³ p)	80	150	500	1000
Whole energy absorption in element (%)	90	95	100*	100**
Number of stars produced in cylinder	354	300	300	180
Figure	13	14	15	16

* after 2.5 m

** after 1.5 m

Fig.1 Energy deposition in cylinder
H₂O - Be - Ti - Cu - W

BEAM SIZE: $0.5 \times 0.5 \text{ cm}^2$

MATERIAL: H₂O, $\rho = 1 \text{ g/cm}^3$ MOMENTUM: 20 GeV/c

PROGRAM: FLUKA

FILE N°: 74-1

Fig 2

BEAM SIZE : 0.1 x 0.1 cm²

MATERIAL : H₂O. $\rho = 1 \text{ g/cm}^3$ MOMENTUM : 200 GeV/c

PROGRAM : FLUKA

FILE N° 74-2

Fig. 3

BEAM SIZE : 0.1 x 0.1 cm²

MATERIAL : H₂O. $\rho = 1 \text{ g/cm}^3$ MOMENTUM : 300 GeV/c

PROGRAM : FLUKA

FILE N° 74-2

Fig. 4

BEAM SIZE : 0.1 x 0.1 cm²

MATERIAL : H₂O, $\rho = 1 \text{ g/cm}^3$

MOMENTUM : 400 GeV/c

PROGRAM : FLUKA

FILE N° : 74 - 2

Fig. 5

BEAM SIZE : 0.3 x 0.3 cm²

MATERIAL : H₂O, $\rho = 1 \text{ g/cm}^3$

MOMENTUM : 400 GeV/c

PROGRAM : FLUKA

FILE N° : 74 - 4

Fig. 6

BEAM SIZE . 0.3×0.3 cm²

MATERIAL : H₂O, $\rho = 1$ g/cm³ MOMENTUM : 400 GeV/c

PROGRAM : FLUKA

FILE N° : 74 - 4

Fig. 7

BEAM SIZE . 0.3×0.3 cm²

MATERIAL : H₂O, $\rho = 1$ g/cm³ MOMENTUM : 400 GeV/c

PROGRAM : FLUKA

FILE N° : 74 - 4

Fig. 8

Fig. 9

Fig. 10

BEAM SIZE: $1.0 \times 1.0 \text{ cm}^2$

MATERIAL: H_2O , $\rho = 1 \text{ g/cm}^3$ MOMENTUM: $400 \text{ GeV}/c$

PROGRAM: FLUKA

FILE N°: 74-6

Fig.11

BEAM SIZE: $1.0 \times 1.0 \text{ cm}^2$

MATERIAL: H_2O , $\rho = 1 \text{ g/cm}^3$ MOMENTUM: $400 \text{ GeV}/c$

PROGRAM: FLUKA

FILE N°: 74-6

Fig.12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

ENERGY DEPOSITION PER INTERACTING PROTON :
 $100\% = 6.4 \cdot 10^{-8}$ JOULE FOR 400 GEV
 BEAM SIZE : $1 \times 1 \text{ cm}^2$ MATERIAL : H_2O , $\rho = 1 \text{ g/cm}^3$

MEAN ENERGY FRACTION DEPOSITED AS A FUNCTION OF
 BLOCK LENGTH FOR 5 DIFFERENT RADII

Fig. 17

ENERGY DEPOSITION PER INTERACTING PROTON :
 $100\% = 6.4 \cdot 10^{-8}$ JOULE FOR 400 GEV
 BEAM SIZE : $1 \times 1 \text{ cm}^2$ MATERIAL : H_2O , $\rho = 1 \text{ g/cm}^3$

MEAN ENERGY FRACTION DEPOSITED AS A FUNCTION OF
 BLOCK LENGTH FOR 5 DIFFERENT RADII

Fig. 18