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ACCELERATOR DEPARTMENT
Informal Report

ISABELLE BEAM STOP PROBLEMS

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Abstract

The "Preliminary Design Study"¹ for ISABELLE briefly discusses some problems related to the instantaneous dumping of 10^{15} 200-GeV protons into a beam stop. The high energy density within the interaction volume of the beam stop material elevates the temperature to a level where serious ablation will occur even if such a highly refractory material as graphite is considered. Efforts to increase the interaction volume (thus decrease the energy density) were not convincingly developed in the design study.¹ A proposal to dump the external proton beam pulse into a tank of water is examined in this report and seems to be satisfactory and economical.

Another problem, omitted in the design study, pertains to the extraction of the beam pulse from vacuum to air through a suitable window ahead of the beam stop. The thermal phenomena associated with the window design have been considered in detail with the consequence that, although they are severe, a window design is possible.

1. Choice of Window Material and its Basic Properties

Considerable study was devoted to the selection of a satisfactory window material to terminate vacuum between the 200-MeV linac and the BLIP facility. Since the requirements for a similar problem related to ISABELLE are not too different, the same alloy is recommended. Without presenting the detailed comparisons made among about a half dozen probable metals during the linac study, the stainless-steel alloy No. 316 is suggested.

This alloy is a mixture of seven elements whose composition in percents is:

C 0.08 max, Mn 2.00 max, Si 1.00 max, Cr 16-18, Ni 10-14, Mo 2-3,
remainder Fe.

1. 200-GeV Intersecting Storage Accelerators, ISABELLE, A Preliminary Design Study, p. 219, May 1972, Brookhaven National Laboratory Report BNL 16716.

The presence of the Mo renders this metal resistant to oxidation at high temperature.

Some of its properties appropriate to this report are:

1. Specific gravity	7.9	
2. Tensile strength	180 kpsi	for cold rolled
3. Yield strength	140 kpsi	for $\Delta l/l < 1\%$
4. Fatigue limit	50 kpsi	for 10^7 cycles
5. Modulus of elasticity	26×10^3 kpsi	
6. Specific heat	0.12 cal/g/°C	20-400°C
7. Coeff. of linear exp.	$10.7 \times 10^{-6}/°C$	20-200°C
8. Melting point	1450°C	

2. Energy Conversion Units

Accelerator energies are usually expressed in multiples of MeV or GeV, but since the concern here is mostly calorimetry, gram calories are more suitable.

$$\begin{aligned}
 1.602 \times 10^{-3} \times \text{GeV} &= \text{ergs} \\
 10^{-7} \times \text{ergs} &= \text{joules} \\
 0.24 \times \text{joules} &= \text{gram calories} \\
 3.84 \times 10^{-11} \times \text{GeV} &= \text{gram calories} \\
 3.84 \times 10^{-14} \times \text{MeV} &= \text{gram calories}
 \end{aligned}$$

The word "calorie" will always mean "gram calorie."

3. Window Heat

It is assumed that when charged particles traverse the vacuum window of thickness δ g/cm², much less than the interaction length, each will deposit an amount of energy, $dE/dx \cdot \delta$, which appears as heat. Furthermore this heat remains localized for a time which is long compared to the transit time for the beam pulse. Two types of particles are considered, (a) the primary protons (10^{15} - 200 GeV), and (b) the charged secondaries from the nuclear interactions within the window.

a) Primary protons

Since the primary proton energy is 200 GeV, the dE/dx is considerably above minimum. Figure 1a is an extrapolation for the dE/dx in Fe with the help of known values² for Pb. Actually the ratio of $(dE/dx)_{Fe}/(dE/dx)_{Pb}$ has been extrapolated on Fig. 1b. The value 2.02 MeV cm²/g has been chosen for Fe and it is believed that the dE/dx for stainless steel No. 316 will not be significantly different. The heat, H_1 , deposited in the window by the primary protons is

$$\begin{aligned} H_1 &= 3.84 \times 10^{-14} \times 10^{15} \times 2.02 \times \delta \\ &= 77.6 \delta \text{ calories}/10^{15} \text{ protons} . \end{aligned} \quad (3.1)$$

b) Secondary charged particles

The number of primary protons interacting in the window

$$N_p = 10^{15} \frac{\delta}{\lambda} = 7.4 \times 10^{12} \delta , \quad (3.2)$$

where λ is the interaction length in the window, about -135 g/cm^2 .

The problem is how to assess the average number of charged secondaries associated with each interaction. An attempt is made to gain some information from "stars" or "jets" observed in nuclear emulsions produced by incident protons with energies in the neighborhood of 200 GeV. Figures 2a through 2h have been reproduced from Ref. 3 and the results summarized in Table I.

2. B. Rossi, High Energy Particles, Chap. 2 (Prentice Hall, 1952).

3. C.F. Powell, P.H. Fowler, and D.H. Perkins, The Study of Elementary Particles by the Photographic Method, Section 15 (Pergamon Press, 1959).

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Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Fig. 2e

Fig. 2f

1000 GeV

Fig. 2g

1000 GeV

Fig. 2h

TABLE I
Summary of Jet Information for
Incident Protons Between 100-1000 GeV

Figure No.	Incident Energy (GeV)	Type of Event
2a	100	1 + 8 p
2b	200	0 + 7 p
2c	200	1 + 18 p
2d	300	2 + 36 p
2e	500	0 + 6 n
2f	1000	3 + 6 p
2g	1000	0 + 7 p
2h	1000	1 + 9 p

The notation $n + mp$ means the event showed n heavily ionizing tracks and m lightly ionizing tracks produced by a proton. Figure 2e was induced by a neutral particle. The average value for n is 1 ± 1 and for m 12 ± 6 . It is a well-known result from jet study that the star prong count is an unreliable indicator for estimating the incident energy. However, the average interaction is estimated to have

$$2 \text{ prongs/star, heavily ionizing, } \frac{dE}{dx} = 10 \text{ MeV} \cdot \text{cm}^2/\text{g}$$

$$15 \text{ prongs/star, lightly ionizing, } \frac{dE}{dx} = 2 \text{ MeV} \cdot \text{cm}^2/\text{g}.$$

The heat, H_2 , delivered to the window from the secondary charged particles using (3.2)

$$H_2 = 3.84 \times 10^{-14} [7.4 \times 10^{12} \delta] (2 \times 10 \times 15 \times 2) \frac{\delta}{2},$$

where $\delta/2$ assumes that all of the interactions occurred at half the window depth.

$$H_2 = 7.1 \delta^2 \text{ calories} \quad (3.3)$$

comparing with (3.1)

$$H_2/H_1 = 0.091 \delta. \quad (3.4)$$

For thin windows, δ is on the order of a few tenths grams/cm² and H₂ can be neglected.

4. Instantaneous Temperature Rise

The temperature rise ΔT at a point in the window depends upon the current density σ (protons/cm²) in the beam pulse. For the case where the protons are distributed symmetrically around the beam axis, the isotherms are circles concentric with the axis and $\sigma = \sigma(r)$ alone. Within a small area dA of the number of protons dN_p traversing dA is

$$dN_p = \sigma(r) dA \quad (4.1)$$

and the heat ΔH deposited dA is

$$\Delta H = 3.84 \times 10^{-14} \frac{dE}{dx} \delta \cdot \sigma(r) dA = C_p dM \Delta T \text{ calories ,}$$

where C_p is the specific heat of the window material and dM is the element of mass, δdA . The temperature rise is

$$\Delta T(r) = \frac{3.84 \times 10^{-14} \frac{dE}{dx} \cdot \sigma(r)}{C_p} \text{ } ^\circ\text{C} \quad (4.2)$$

From Sec. 1, $C_p = 0.12$ calories/g/^oC and dE/dx is 2.02 MeV cm²/g, so (4.2) becomes for stainless steel

$$\Delta T(r) = 6.46 \times 10^{-13} \sigma(r) \text{ } ^\circ\text{C} \quad (4.3)$$

If $\sigma(r)$ has a Gaussian distribution,

$$\Delta T(r) = 6.46 \times 10^{-13} \sigma_0 e^{-(r/r_0)^2} \text{ } ^\circ\text{C} , \quad (4.4)$$

where σ_0 is the proton current density on the beam axis.

5. Maximum Temperature Rise

The melting point for stainless steel is 1450^oC. It is well to keep the $(\Delta T)_{\max}$ as low as practical because at elevated temperatures (a) the mechanical strength of most metals weakens, (b) oxidation is more rapid, and (c) mechanical working of the window from thermal expansion and contraction increases the fatigue. It seems reasonable to limit the $(\Delta T)_{\max}$ to about one-third of the melting point, say 500^oC.

The $(\Delta T)_{\max}$ will be at $r = 0$, and from (4.4)

$$\begin{aligned} (\Delta T)_{\max} &= 6.46 \times 10^{-13} \sigma_0 = 500^\circ\text{C} \text{ and} \\ \sigma_0 &= 7.74 \times 10^{14} \text{ protons/cm}^2 . \end{aligned} \quad (5.1)$$

The total number of protons is

$$N = 2\pi \sigma_0 \int_0^\infty r e^{-(r/r_0)^2} dr = 10^{15} . \quad (5.2)$$

By letting $r = r_0 \sqrt{u}$, Eq. (5.2) transforms into

$$Nr_0^2 \sigma_0 \int_0^\infty e^{-u} du = \pi r_0^2 \sigma_0 = 10^{15} .$$

Using (5.1)

$$r_0 = 0.64 \text{ cm}$$

and the temperature distribution is

$$\Delta T(r) = 500 e^{-2.43r^2} ^\circ\text{C} \quad (5.3)$$

which is plotted on Fig. 3. To satisfy this temperature criterion, the beam pulse should be about 2 cm "in diameter" at the extraction window.

6. Thermal Buckling

Since the window is thin, about 0.01 in., calculation of the thermal stress is meaningless, however the heated portion of the window will very likely buckle into the vacuum from air pressure. Consider a narrow band of window along a diameter in any radial direction. The temperature strain per centimeter

$$\frac{d\ell}{dr} = \alpha \Delta T(r) , \quad (6.1)$$

where α is the coefficient of linear expansion/ $^\circ\text{C}$. The elongation of the band is

$$\Delta\ell = \alpha \int_{-\infty}^{\infty} \Delta T(r) dr = 2 \times 500 \alpha \int_0^\infty e^{-(r/r_0)^2} dr .$$

With the help of

$$\int_0^{\infty} e^{-a^2 x^2} dx = \sqrt{\pi}/2a ,$$

$\Delta l = 500 \alpha \sqrt{\pi} r_0 = 6.1 \times 10^{-3}$ cm or 2.4×10^{-3} in., which does not appear to be a serious source for window fatigue.

However, this raises the question how to protect the vacuum system of the whole complex in case of the window implosion.

Fast-acting gate valves have about a 20 msec delay between signal and closure. The fastest air molecules reach a velocity of about one meter per millisecond, so the vacuum windows should be located about 20 m from the storage rings.

7. Window Stress

The window stress arising from air pressure, 14.7 lb/in.^2 , is

$$S = \frac{14.7 a}{2\delta}$$

where, if we consider a hemispherical window, "a" is the radius. If "a" is 2 in. and $\delta = 0.010$ in.

$$S = 1470 \text{ psi}$$

which is trivial.

8. Radiation Damage

D. Gurinsky and J.G.Y. Chow of the BNL Department of Applied Science estimate that stainless steel will not show mechanical weakening for proton exposures less than 5×10^{21} protons/cm². ISABELLE operating at 30 pulses/h will yield

$$2.63 \times 10^5 \text{ pulses/yr .}$$

If the central proton intensity is $7.78 \times 10^{14} \text{ cm}^{-2}$

$$1.63 \times 10^5 \times 7.78 \times 10^{14} \times \text{years} = 5 \times 10^{21} \text{ years} \sim 25 .$$

9. Water Stop, Gross Calculations

Suppose that the water stop reduces the original 10^{15} protons to 1% (10^{13}) at the end of the water where the residual protons enter the solid beam stop (sand). The length of the tank, L , can be found from

$$e^{-L/\lambda} = 0.01 \quad \text{or}$$

$$L = 4.60 \lambda .$$

The mean absorption length for high energy protons has been measured as 2.12 ft in sand (specific gravity 1.8). Therefore the absorption length in water is about

$$\lambda = 1.8 \times 2.12 = 3.8 \text{ ft (117 cm)} \quad (9.1)$$

giving the tank length

$$L = 17.5 \text{ ft (533 cm)} .$$

Assume the water in the tank is at equilibrium temperature, i.e., 100°C when it receives an additional beam pulse. The increment in energy is

$$200 \text{ GeV} \times 10^{15} \times 3.84 \times 10^{-11} = 7.7 \times 10^6 \text{ calories} .$$

The amount of exploded water is

$$\begin{aligned} 7.7 \times 10^6 / 540 \text{ cal/g} &= 14.3 \times 10^3 \text{ g} \\ &= 31.5 \text{ lb} . \end{aligned} \quad (9.2)$$

Saturated steam at 250°C has a vapor density of about 1 lb/ft^3 and a pressure of 560 lb/in.^2 (gauge). If we take 35 ft^3 for the explosion volume and a depth of water as 6 in. in the bottom of a cylindrical tank 17.5 ft long, the question is the radius of the tank (see Fig. 4).

Fig. 4

If A is the unshaded area

$$35 \text{ ft}^3 = A \times 17.5 \text{ ft} \quad \text{or}$$

$$A = 2 \text{ ft}^2$$

The result after integration is

$$A = (R - d) \sqrt{d(2R - d)} + R^2 \left(\sin^{-1} \frac{R - d}{R} + \frac{\pi}{2} \right) = 2 \text{ ft}^2, \quad (9.3)$$

where R is the radius of the tank and d the depth of the water, both in feet.

If $d = \frac{1}{2} \text{ ft}$, the result from trial and error gives

$$R = 0.912 \text{ ft} \sim 11 \text{ in.} \quad (9.4)$$

In the foregoing it has been implied that the instantaneous explosion pressure will be uniform along the length of the tank, however such is not likely to be the case. The momentary pressure distribution within the water stop is probably closely related to the rate of energy release from the low energy charged particles developed from the high energy cascade to which attention is now given.

10. One-Dimensional Cascade

Assumptions

1. The particles in the cascade are assumed to be divided into distinct groups, G_n , and have an average energy, $\bar{E}_n$, each. The primary group, G_1 , is the 200-GeV protons with $\bar{E}_1 = 200 \text{ GeV}$. The primaries interact with the water creating G_2 with $\bar{E}_2$ and average multiplicity M_2 . These in turn generate G_3 with $\bar{E}_3$ and M_3 and so on until an average $E_n = 20 \text{ MeV}$ is reached.

2. The interaction length, λ , is a constant for all energies, $\lambda = 117 \text{ g/cm}^2$ in water.

3. The particles are parallel to the beam insofar as they are assumed to remain in the water.

4. The average multiplicity for the secondaries varies with $M_2 = 12$ at 200 GeV (Sec. 3). Below 20 GeV empirical results are used,⁴ including evaporation theory.

4. W.R. Yucker, Empirical Formulae for Secondary Nucleon Production and Cross Sections, Douglas Paper No. 3590, Nov. 1965.

5. The average energy, $\bar{E}_n$, is 0.1 of the energy of the particle initiating the interaction.

6. The charged particles deliver energy to the water at the rate $d\bar{E}_n/dx$ which is assumed to be localized (in the water) appearing as heat.

Let x be some depth in the water and at $x' < x$, consider an element of length, dx' , Fig. 5.

Fig. 5

The fraction of primary protons, $G_1(x')$, surviving at x' is

$$G_1(x') = e^{-x'/\lambda} \quad (10.1)$$

and in traversing dx' , they create the secondaries

$$dG_2(x') = M_2 e^{-x'/\lambda} dx'/\lambda$$

and the number of these surviving to x is

$$\begin{aligned} dG_2(x) &= M_2 e^{-x'/\lambda} \frac{dx'}{\lambda} \cdot e^{-(x-x')/\lambda} \\ &= M_2 e^{-x/\lambda} dx'/\lambda \end{aligned}$$

The total number $G_2(x)$ at x generated between $0 \leq x' \leq x$ is

$$G_2(x) = M_2 e^{-x/\lambda} x/\lambda \quad (10.2)$$

The tertiaries $dG_3(x')$ created by $G_2(x')$ in dx' and surviving to x is

$$dG_3(x') = M_3 G_2(x') \frac{dx'}{\lambda} \cdot e^{-(x-x')/\lambda}$$

or from (10.2)

$$G_3(x) = M_2 M_3 e^{-x/\lambda} \cdot \frac{x^2}{2\lambda^2}$$

Repeating this process an indefinite number of times, n

$$G_n(x) = \prod_{j=1}^n M_j \frac{x^{n-1}}{(n-1)! \lambda^{n-1}} e^{-x/\lambda} \quad (10.3)$$

where

$$\prod_{j=1}^n M_j = M_1 M_2 M_3 \dots M_n$$

with $M_1 = 1$ meaning that the multiplicity of the primary G_1 group is unity.

Associated with each group of particles is the average energy, $\bar{E}_n$, which is delivering energy to the water at a constant rate dE'_n/dx per particle or

$$\frac{dE_n(x)}{dx} = G_n(x) \frac{dE'_n}{dx}$$

and summing over all $G_n(x)$

$$\frac{dE(x)}{dx} = \sum_{n=1}^n G_n(x) \frac{dE'_n}{dx}$$

From (10.3)

$$\frac{dE(x)}{dx} = e^{-x/\lambda} \sum_{n=1}^n \frac{dE'_n}{dx} \cdot \prod_{j=1}^n M_j \frac{x^{n-1}}{(n-1)! \lambda^{n-1}} \quad (10.4)$$

The total energy, E_T , delivered to the water per incident proton is

$$E_T = \sum_{n=1}^n \frac{dE'_n}{dx} \prod_{j=1}^n M_j \left[\frac{1}{(n-1)! \lambda^{n-1}} \int_0^\infty x^{n-1} e^{-x/\lambda} dx \right] \quad (10.5)$$

By letting $x = \lambda t$, the [] in (10.5) becomes

$$[] = \frac{\lambda}{(n-1)!} \int_0^\infty t^{n-1} e^{-t} dt$$

which is the gamma function and

$$[] = \frac{\lambda}{(n-1)!} \Gamma(n) = \frac{\lambda}{(n-1)!} \cdot (n-1)!$$

since n is a positive integer. The total energy in (10.5) reduces to

$$E_T = \lambda \sum_{n=1}^n \sum_{j=1}^n P_j M_j \frac{dE_n'}{dx} \quad (10.6)$$

Ideally $E_T = 200$ GeV/incident proton. How nearly the calculated value of E_T , using the following numerical estimates, agrees with 200 GeV is a measure of the collective validity of the assumptions.

11. Numerical Estimates

The interaction length, λ , in water is taken as 117 g/cm^2 , a constant for all energies, which is a very good assumption down to a few hundred MeV. It then decreases to a minimum of 80 g/cm^2 for 35-MeV protons and then rises to about 100 g/cm^2 for 20-MeV (protons).⁵

The principal parameters for the one-dimensional cascade are listed in Table II.

TABLE II
Principal Parameters for a
One-Dimensional Cascade in Water

G_n	$\bar{E}_{inc}$ GeV	$\bar{E}_n$ GeV	M_j	PM_j	dE_n'/dx GeV/g-cm ²
G_1	200	200	1	1	2.5×10^{-3}
G_2	200	20	12	12	2.4
G_3	20	2.0	2.7	32	2.1
G_4	2.0	0.2	1.7	55	4.6
G_5	0.2	0.02	0.8	44	26.6

The second column is the energy or assumed average energy for the particles inducing the interaction. For G_2 , the secondaries $\bar{E}_{inc}$ is 200 GeV because the primaries have not interacted. For $n > 2$ the incident energy for G_{n+1} is assumed to be 0.1 for G_n .

Column three assumes for all $n > 1$ that the average energy of the particles after the interaction is 0.1 that for the parent particle.

5. W.H. Moore, "The Application of 200 MeV Protons to Biomedical Research," BNL Accelerator Dept. Report AGSCD-48, Aug. 18, 1971

Column four is the estimated multiplicity for the charged particles from the interaction. For $1 \leq n \leq 3$, M_j was calculated from

$$M = 12 \sqrt{E/E_0} = 0.85 \sqrt{E} ,$$

where the 12 was taken from the results of Table I and $E_0 = 200$ GeV. For G_4 , the $M_4 = 1.7$, and for G_5 , $M_5 = 0.8$ were taken from Ref. 4.

Column five, PM_j , is the cumulative product of the M_j from $n = 1$ to n .

Column six, the dE'_n/dx for protons in water were taken from Rich and Madey.⁶

Returning to (10.6)

$$E_T = \lambda \sum_{n=1}^5 \frac{dE'_n}{dx} \cdot \prod_{j=1}^5 M_j . \quad (11.1)$$

Multiplying columns five and six in Table II for each n and summing through $n = 5$, we find

$$E_T = 1.53 \lambda , \text{ and for } \lambda = 117 \text{ g/cm}^2$$

$$E_T = 178 \text{ GeV/incident proton} .$$

Although this is about 12% lower than the "ideal" 200 GeV, it is probably too high because the one-dimensional model ignores the neutral radiations. Below 1 GeV, the angular distributions become more and more isotropic as the energy decreases and many neutrons leave the water to deposit their energy in the solid beam stop.

Each component, G_n , of the cascade has a population distribution along the water stop which varies, according to (10.3), as

$$G_n(x) \sim x^{n-1} e^{-x/2} \quad (11.2)$$

which has zeros at $x = 0, \infty$, and a maximum at

$$x_n = (n-1)\lambda \quad n = 1, 2, 3, \dots \quad (11.3)$$

6. M. Rich and R. Madey, "Range Energy Tables," Lawrence Radiation Laboratory Report UCRL-2301, Mar. 1954.

In order to show how each component contributes to the heating along the tank, Fig. 6 has been plotted.

The components on Fig. 6 have been summed and the result appears on Fig. 7. The average values for dE/dx as measured at half integral values of k is 0.171 GeV/cm. The total energy

$$\begin{aligned} E_T &= 0.171 \times 10 \lambda \\ &= 200 \text{ GeV/incident proton} \end{aligned}$$

which is fortuitous and means that collective assumptions have erred on the safe side. The maximum dE/dx occurs at about 4λ where the temperature rise and hence the pressure will also be maximum. At this point, $4\lambda = 15.2$ ft, the tank should be vented to atmospheric pressure.

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Fig. 6