IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

A HIGH INTENSITY BEAM DUMP FOR THE TEVATRON BEAM ABORT SYSTEM

J.Kidd, N.Mokhov,[†] T.Murphy, M.Palmer, T.Toohig, F.Turkot and A.VanGinneken
Fermi National Accelerator Laboratory,* Batavia, Illinois 60510

Introduction

The beam abort system proposed[1] for the Fermilab Tevatron Accelerator will extract the proton beam from the ring in a single turn (~20μs) and direct it to an external beam dump. It is the function of the beam dump to absorb the unwanted beam and limit the escaping radiation to levels that are acceptable to the surrounding populace and apparatus. In addition, it is clearly desirable that it be maintenance free and have a lifetime equal to that of the accelerator, 10-20 years. A beam dump that is expected to meet these requirements has been designed and constructed. We describe below the detailed design of the dump, including considerations leading to the choice of materials.

Parameters of the Beam and Dump Specifications

The extreme values of the parameters of a single aborted beam pulse are:

1. energy of protons 1 TeV
2. number of protons 2×10^{13}
3. total kinetic energy 3.2 MJ
4. time duration 20μs
5. transverse beam size (σ of a Gaussian in mm) as a function of drift distance, s (in m), from the downstream end of the CØ long straight section

$$\sigma_x = 0.520\sqrt{1+\frac{(s+55)^2}{60^2}}\ ,\quad \sigma_y = 0.455\sqrt{1+\frac{(s-1.3)^2}{60^2}}$$

$\sigma_{x'} = \sigma_{y'} = 7.5$ μrad.

6. transverse variation of beam position ±1.5 cm.

With regard to repeated beam aborts and the yearly average beam we have the following specifications:

7. Short term continuous operation:
   2×10^{13} ppp at 1 TeV with a 23s cycle time for 4 hours duration <power input> = 139 kW
8. Yearly proton flux: 3.5×10^{17} p/yr at 1 TeV.

The aborted beam line geometry is such that at the end of the CØ long straight section it is directed radially outward by 8.1 mr with respect to the tangent to the circle of the Tevatron and is 2.5 cm above and parallel to the plane of the closed orbit. On average this plane is ~6m below ground level. Given this geometry, there is a minimum distance (s) from the end of the CØ straight section to the dump, dictated by the need to have sufficient transverse separation (2.1 m) between the dump and the superconducting magnets of the Tevatron ring to avoid quenches induced by transient radiation from the dump during beam aborts; $s_{min} = 55$m. The cost of civil construction for the dump argues for keeping s close to s_{min}; the incremental cost was estimated at 10K$/m.

Choice of Material for Dump Core

The reliability of the dump depends critically on the integrity of the material which makes up the upstream five hadronic absorption lengths (λ_a) of the core. Operating experience both at CERN and Fermilab has clearly demonstrated the capability of 400 GeV proton beams of similar size and intensity to fracture or melt solid materials in the immediate vicinity of the line of the beam as a result of high local energy deposition and large temperature gradients. The peak energy density can be reduced by: (a) enlarging the transverse size of the incident beam, (b) going to materials of lower mass density and lower atomic number, and (c) inserting matter-free drift spaces in the absorber. The chance of harmful material damage is reduced by using materials with high melting points and high thermal shock resistance. A measure of the thermal shock resistance of a solid material is given by the temperature differences ΔT_{cc} and ΔT_{ct}:

$$\Delta T_{cc} = \frac{\sigma_c}{\alpha E}(1-\nu)\ ; \qquad \Delta T_{ct} = \frac{6\sigma_t}{\alpha E}(1-\nu) \qquad (1)$$

where α = linear thermal expansion coefficient, E = Young's modulus, ν = Poisson's ration, and σ_c and σ_t are the compressive and tensile strenghts of the material. Given a localized temperature spike in the material with maximum temperature difference ΔT, then ΔT_c is the temperature difference at which the stress in the material equals the strength of the material.

For a given beam and a given absorber material and geometry (including possible drift spaces), ΔT is calculated using a Monte Carlo nuclear cascade program called MAXIM[2]; more precisely the program calculates the spatial distribution in the absorber of the energy density, ε, deposited by ionization from the charged particles produced in the cascade. The specific heat, C_p, of the material is then used to calculate the temperature distribution corresponding to ε(r) (ε_{max} is the significant quantity); idealy if $(T_{max} - T_{initial}) < \Delta T_c$, then the material will not be damaged. For ductile materials, such as Al, Cu, and Fe, it may be permissible to exceed the criterion; however, for

TABLE I. Properties (T = 25°C)

Material	ρ g/cm³	λ_a cm	λ_{rad} cm	C_p CAL/°C-g	α 10^{-6}/°C	E 10^6 psi	σ_c 10^3 psi	σ_t 10^3 psi	λ w/cm-°C
Graphite (H-489)	1.71	45.1	25.0	0.19	2.3⁺ 3.0^Δ	1.2 0.95	6.5 6.5	2.1 2.0	1.42
BeO	2.85	27.0	14.6	0.25	9	53	225	25	2.6

[+] with grain, [Δ] across grain. Graphite softens at 2600°C, BeO softens at 1800°C.

*Operated by Universities Research Association, Inc. under contract with the U.S.Department of Energy.

[†] Institute for HEP, Serpukhov, USSR

0018-9499/81/0600-2774$00.75 © 1981 IEEE

TABLE II. $N_p = 2\times10^{13}$, $\sigma_x = 1.20$ mm, $\sigma_y = 0.68$ mm

Material	ΔT_{cc} °C	ΔT_{ct} °C	ρH* kJ/cm^3	ε_{max} kJ/cm^3	$\Delta T(\varepsilon_{max})$ °C	$\frac{\varepsilon_{max}}{\rho H}$	N_{pmax} 10^{13}
BeO (I)	471	314	2.08	7.15	1400	3.44	0.6
BeO (II)	471	314	2.08	3.53	750	1.70	1.2
Graphite	2280	4210	6.89	2.40	880	0.35	5.7

(I) solid BeO

(II) 90 cm of BeO spaced over 215 cm

$$* \ \rho H = \rho \int_{298}^{298+\Delta T_{cc}} C_p \, dT$$

brittle materials which do not tolerate plastic deformations, it would appear to be a reasonable criterion.

A number of studies[3] have been made of the suitability of various materials; only solid forms were considered because of the additional problem of conducting away the maximum average power input of 139 kW. The best candidates were Be, BeO ceramic, and graphite; they all fall in the brittle category. The approach adopted was to explore what absorber geometry would be required for BeO and graphite for the natural beam size at s = 70 m (the first logical location beyond s_{min} = 55 m from the point of view of interconnections between dump and existing tunnel). Some properties of these materials[4] are given in Table I. The results of the nuclear cascade calculation are given in Table II.

Calculations with a graphite absorber were made[5] for a range of incident proton energy, E, (0.1 to 5.0 TeV) and as a function of $B(\equiv 4\pi\,\sigma_x\sigma_y$, an area which contains 86.5% of the beam for $\sigma_x = \sigma_y$; range 10^{-2} to 10^4 mm^2). The dependence of ε_{max} on E and B were found as follows:

$$\varepsilon_{max}(B = 12\ \text{mm}^2) = C_1 E^{1.44}, \quad E = .3 - 3\ \text{TeV}$$
$$\varepsilon_{max}(E = 1\ \text{TeV}) = \frac{C_2}{B^{.34}}, \quad B = 3 - 100\ \text{mm}^2 \qquad (2)$$

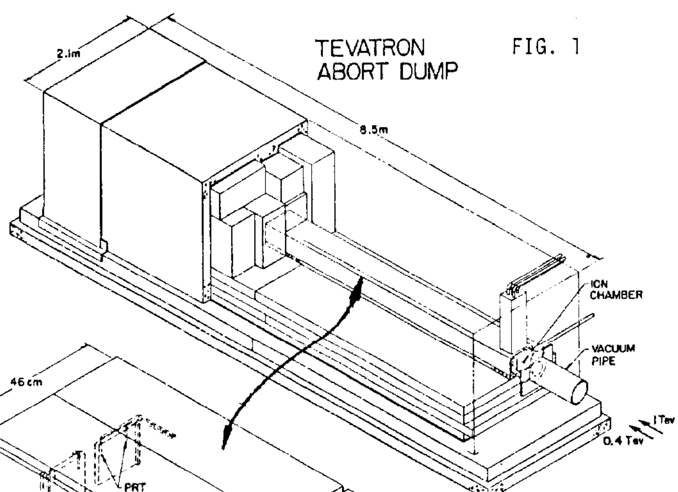

FIG. 1

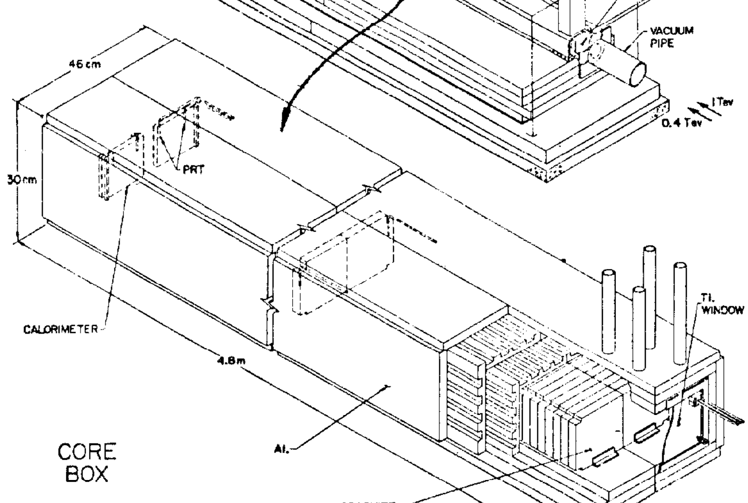

FIG. 2

ε_{max} approaches a $(B)^{-1}$ behavior only for rather large $B(>10^4$ mm$^2)$. As a consequence one gains rather slowly in reducing ε_{max} by increasing s; e.g. to decrease ε_{max} by a factor of 2 requires changing s from 70 m to 275 m (B increases by a factor 7.4).

The results in Table II clearly indicate the superiority of a solid graphite absorber; if taken literally, this material has the capability of absorbing 5.7×10^{13} ppp without fracturing. It should not be taken literally for several reasons: (1) the calculation of ε_{max} is uncertain to at least ±30%, (2) the quasi-static stress analysis is clearly a crude approximation to the real situation.

Several of its physical properties must be taken into account in utilizing graphite as an absorber. Firstly, it oxidizes at elevated temperatures, losing 1% of its weight per day at 450°C; the presence of radiation or radiation damage enhances the oxidation rate. This argues for a dry argon atmosphere at the graphite. Secondly, graphite undergoes dimensional change under irradiation; e.g., if subjected to a flux of 1×10^{20} neutrons/cm^2 (~1 MeV) at 30°C, <u>some</u> graphite expands ~1% in the "across grain" direction. If the exposure takes place at 200°C, the expansion is a factor 10 smaller. In the neighborhood of ε_{max}, the probability of an interaction of a carbon nucleus with a high energy hadron summed over the dump lifetime (5×10^{18} p's) is comparable to that ($\sim10^{-4}$) for a 1×10^{20} n/cm^2 flux at 1 MeV. It seems plausible that there will be significant radiation damage effects near ε_{max}, but that they will be confined to a few mm from the beam axis, and are unlikely to cause a large-scale change in volume. In an absorber of close packed blocks, the graphite has "no place to go" even if it should become pulverized along the beam axis; heat conductivity would clearly decrease.

Overall Dump Design

The internal structure of the dump is seen in Fig. 1. The core consists of two identical side-by-side stacks of graphite blocks; a block has dimensions $15.2\times15.2\times2.54$ cm^3; 350 blocks make up the core. Longitudinal segmentation of the graphite helps reduce dynamic stress enhancement[3] that could occur from the shock wave propagating in a single long block ($v_{sound} \times 20$ μs = 3.9 cm in H489). Main Ring aborted beam impinges on the left-hand stack, Tevatron beam on the right. The graphite is contained in an aluminum box (see Fig. 2) which has cooling water flowing through its walls. The concrete "skin" which covers the steel is itself covered with a watertight Melnar (plastic) membrane. The asymmetric horizontal location of the core box in the dump is compensated by an extra row of steel blocks between dump and tunnel; this stratagem was adapted in order not to undercut the existing tunnel during excavation for foundation work.

Graphite-Filled Aluminum Core Box

Some details of the core box are given in Fig. 2. It is welded up out of 2.54 cm thick, 4.8 m long aluminum plate (type 5083 H112[6]). The wall is made of three plates; water passages are milled in the inner two. The left and right halves of the box were fabricated separately and leak tested. The horizontal inside surfaces were then milled flat and parallel to ±0.05 mm. The transverse dimensions of the graphite blocks were milled to fit the transverse dimensions of the box; the 15 cm × 15 cm surfaces of the graphite were saw-cut (as provided by the manufacturer). The inner surfaces of the box were given a thin coating of graphite paint (alcohol base) and then the two half-boxes were stacked with graphite. The two halves were then clamped together and the outside center welds made. The interior of the box is hermetically sealed; a 2 cm thick plate closes the downstream end, a 0.6 mm titanium window closes the upstream end. Two gas lines and six temperature transducer leads exit through the titanium window.

Thermal Considerations

The cascade calculations by MAXIM on the spatial distribution of heat energy deposition in the graphite (let Z = distance into graphite from front face) yields:
1. When integrated over transverse dimension, the distribution has a broad maximum at Z = 2.2 m (Z_M), FWHM = 2.5 m; the energy per graphite block at Z_M is 16.0 kJ (a $\Delta T = 20°C$ if uniform over the block) corresponding at 700 w per block average power at a 23 s cycle.
2. The maximum, $\Delta T = 880°C$, occurs on axis at Z = 1.2 m.

Measurements were made of the heat transfer properties of the graphite-to-aluminum interface. A saw-cut graphite surface on a smooth aluminum surface under low pressure (3.5 psi) gave a thermal transfer coefficient, K, of 0.03 w/cm^2-°C; milling the graphite to a flat finish increased K to .08 w/cm^2-°C. With increasing pressure, K rises smoothly reaching 0.16 w/cm^2-°C at 35 psi; a thin coat of graphite paint increased K by 11%.

In order to make an estimate of temperature build up under continuous beam aborts with a 23 s cycle, a steady-state analysis (see Ref. 3) with a cylindrical geometry model of the core box was made. Assuming K = 0.15 w/cm^2-°C, heat transfer over 54% of the edge area of the block, and a cooling water temperature of 35°C, this calculation gives a central temperature of 140°C. Immediately following the next abort pulse, the peak temperature becomes 790°C (at Z_M). Using the thermal diffusivity of graphite at 800°C (0.15 cm^2/s) and a 1 mm length, the thermal spike will halve in about 30 ms. The unconstrained thermal expansion of a graphite block in the 15 cm dimension is estimated to be 0.04 mm.

Each of the two independent water cooling circuits in the aluminum core box has a measured flow rate of 72 gpm (110 psi drop). An average power input of 139 kW into one cooling loop at this flow rate makes a 7.2°C temperature rise.

Radiation Considerations

The basic dump block in Fig. 1 has dimensions $2.1 \times 2.6 \times 8.5$ m^3 (W×H×L); in terms of hadronic absorption lengths it is equivalent to a block of Fe $1.67 \times 2.08 \times 4.77$ m^3 with an additional 0.46 m at beam level on the tunnel side. Hence in units of λ_a, it has 6.1 λ_a transverse to the beam and 27.9 λ_a along the beam (15 of the 2×10^{13} protons make it through unscathed). The program CASIM was used to evaluate pulsed and residual radiation levels in various locations.

1. Tunnel Radiation - The superconducting wire of the Tevatron dipoles is 2.5 m distance from Z_M. At full field, fast (<1 ms) heat energy deposition of ~0.5 mJ/g will induce a quench. Calculations give an energy dump of only 2 μJ/g at the inner edge of the tunnel wall. The residual radiation in the tunnel after a 30 d irradiation (average of 1.1×10^{10} p/s) and a 1 d cooldown is calculated to be 5 mrem/hr.
2. Soil Activation - The program computes the total number of "stars," nuclear interactions, produced in the "unprotected" soil (soil below the level of the drain tile). It yields 3.2×10^{16}/yr, about 13% of the limit for the total Fermilab site. A 10 cm diameter drain pipe has been placed in the soil beneath the dump for the purpose of monitoring the activity level in the ground water there.
3. Above Ground Dose Rates - The earth coverage directly above the dump is 6 m; the maximum expected dose rate there is 1 mrem/hr. A substantial beam of muons, about 2×10^{11} (E>1 GeV) per abort, emerges from the downstream face of the dump. A modified version of CASIM was used to calculate the dose rate of the Fermilab site boundary, a horizontal distance of 1.7 km beyond the dump, taking into account the existing earth overburden along the 1.7 km. At the boundary it predicts dose rates of 14 mrem/yr at grade level and 70 mrem/yr for 15 m above grade. The self-imposed Fermilab limit is 10 mrem/yr. The problem arises from muons scattering out of the earth and propagating in the atmosphere; about 450 m downstream of the dump the earth overburden falls to 2.4 m; it will probably be necessary to increase the overburden for a distance of ~1 km beyond the dump.

Dump Instrumentation

The position of the incident beam is measured by a segmented ion chamber placed at Z = -15 cm. Temperature is measured at five points in the dump using platinum resistance transducers (PRT).

In order to measure the integrity of the graphite with respect to beam absorption a thermal calorimeter is placed just beyond the end of the stack at Z = 4.47 m. A ΔT in the calorimeter of ~4°C is expected from a single 1 TeV beam abort; a larger ΔT would signal a "hole" in the upstream graphite absorber. A more complete description of the instrumentation is given in a following paper.

Acknowledgement

We thank H.Edwards, P.Sievers, S.Baker, and D.Cossairt for helpful discussions; the invaluable work of D.Breyne and the Fermilab machine shops also merits mention.

References

1. Design Report, 1979 Superconducting Accelerator, Fermilab (1979).
2. N.V.Mokhov and A.VanGinneken, "Calculations of Energy Deposition Densities in High Energy Accelerator Targets," TM-977, Fermilab (1980).
3. W.Kalbraier, W.C.Middelkoop, P.Sievers, "External Targets at the SPS," CERN Lab II/BT/74-1 (1974); K.Teutenberg, P.Sievers, W.C.Middelkoop, "Absorber Blocks for Internal and External Beam Dumping at the SPS," CERN Lab II/BT-74-4 (1974); C.Hauviller, H.Schonbacher, A.VanSteenbergen, "Beam Dump Absorber for the 400×400 GeV^2 $\bar{p}p$ Superconducting Large Storage Rings," CERN-ISR-GE/79-4 (1979).
4. The BeO ceramic is "Berlox K-150" of the National Beryllia Corp; H-389 graphite is a fine grain (0.08 mm), isostatically molded graphite made by Great Lakes Carbon Corp.
5. N.V.Mokhov, "Energy Deposition in Targets and Beam Dumps at 0.1-5 TeV," FN-328, Fermilab (1980).
6. An alloy with good corrosion resistance, typically used in marine welded structures.