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INTERNAL BEAM ABORT SYSTEM FOR THE TEVATRON UPGRADE

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INTRODUCTION

In this note we shall examine the properties of an internal beam dump system for the Tevatron running in the pbar-p collider mode. We assume that the beam energy can be as high as 1.8 TeV. The motivation behind this report comes from the fact that the present proton abort system[1,2] is a single-turn fast-extraction system, which becomes progressively more difficult to perform as the beam energy is raised without lengthening the straight section. We examine three different designs (Fig. 1). The first is a system comprised of two beam dumps at each end of the existing straight section, the second dump acting as an absorber for the secondary particles produced in the primary dump as well as functioning as the primary dump for the particles of the opposite sign. The kicker magnets for this scheme are assumed to be outside the straight section in locations similar to the present system. The second layout again consists of beam dumps at either end of the straight section but with the kicker magnets located in the centre of the straight section. In this arrangement both beams are deflected vertically by the same kicker magnets. The advantage of this arrangement is the compact nature of the design with all the components lying within the straight section. The third scenario is similar to the second one with the relative positions of the dumps and kicker magnets reversed. With the dump located in the centre of the free space, the flux of secondary particles hitting the superconducting elements at the end of the straight sections is reduced. The limitations of these schemes will be discussed.

BEAM PARAMETERS

For a given circulating beam current, the more intense the transverse phase-space density the greater the instanteous temperature rise inside the dump. Since the dump lies inside the machine lattice, there is no possibility of blowing up the beam spot at the dump as is customary when using external abort lines. The machine lattice parameters immediately downstream of the straight section quadrupoles have beta values of 60 m and 105 m (H and V) and a horizontal dispersion of 1.8 m. With a normalized transverse beam emittance of 12 π (95%) and a longitudinal energy spread (σ p/p) of 8 x 10-4 (rms) at 150 GeV, this results in a beam spot of 1.68 mm x 1.2 mm (H and V) rms at 150 GeV. The beam spot sizes at higher energies scale in usual fashion from these results.

The presently operating abort system relies on a vertical beam displacement of 24 mm between the circulating and aborted beam trajectories to enter the extraction channel. Under this setup the circulating beam is displaced by 10 mm from the septum magnet. We will assume a similar geometric relation for the scheme with kicker magnets in the arcs, which means that the beam strikes the dump up to 14 mm from the edge. The beam deflection at the dump for schemes 2 and 3 is somewhat less due to the restricted drift length between the kickers and the dump. In both of these cases the beam displacement is up to 10 mm from the edge.

In order to estimate aborted beam intensities we have somewhat arbitrarily assumed a single high-energy full-intensity abort of 2×10^{12} (30 bunches at 6×10^{10} ppb) can occur once per hour, and low energy injection aborts of this intensity can occur every 120 s for a period of four hours per day. Power dissipation and residual radioactivity can be scaled to different operating scenarios from these numbers.

DESIGN CRITERIA

In this study, taking into account the behaviour of the dump materials and optimising the overall scheme, we required the following criteria to be fulfilled:

1. For a single abort the maximum energy deposition in any region of the dump system and corresponding temperature rise have to be less than the melting points and the shock wave limits

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for the given materials.[3]

2. The cooling system should provide the necessary heat transfer from the core to prepare the dump to the next beam abort.

3. The energy deposition in the superconducting quadrupoles immediately downstream of the straight section must be well below the quench limit.[4]

4. The induced radioactivity levels near the dumps should be within the acceptable limits.[5,6]

5. Ground water activation around the abort straight section by hadron fluxes escaping the dumps has to be prevented.

6. Muon fluxes downstream of the abort straight section must be below the tolerable levels.[5,7]

7. The lifetime of the beam dumps should exceed a few years, at least.

8. The dumps should be as compact as possible.

CALCULATIONS

We have carried out the series of the hadronic and electromagnetic cascade calculations in the Tevatron straight section with the present version of the Monte Carlo program MARS10.[8]

The only appropriate material for the core of the considered beam dumps is graphite similar to the existing external abort dump.[2] The core consists of the graphite slabs (thickness ~2 cm, density is 1.71 g/cm^3) to reduce the shock wave creation.

We have examined two beam energies for both cases with corresponding beam spot sizes:

<u>Scheme 1</u> 150 GeV (σ_x = 1.68 mm, σ_y = 1.2 mm) and 1.8 TeV (σ_x = 0.48 mm, σ_y = 0.34 mm).

<u>Scheme 2 & 3</u> 1 TeV (σ_x = 0.77 mm, σ_y = 0.32 mm) and 1.5 TeV (σ_x = 0.63 mm, σ_y = 0.25 mm).

Most results are similar for three schemes; therefore, we will describe in detail only the first one. The main and principle exception (quenching) will be given at the end of this report.

SCHEME 1

The proposed layout of the abort dumps in the straight section is shown schematically in Fig. 2. The system is bi-directional with the downstream abort dump acting as an absorber for the secondary particles produced in the upstream dump. We have found that for a 1.8 TeV beam of 2-5 x 10^{12} protons, the minimum length of such an absorber is 480 cm followed by the endcap of 50 cm aluminum and 50 cm steel.

Energy Deposition and Temperature Rise

Figure 3 shows the two-dimensional energy deposition density distribution in the graphite absorber. The results demonstrate the familiar hadronic cascade properties: the very sharp radial fall off and the relatively slow longitudinal dependence. The instantaneous temperature rise in the absorber can be determined from the data of Fig. 3 and from an enthalpy reserve. Using the data from[3,9] we have calculated the temperature field in the overall beam dump. The results with the core at the initial temperature To = 27°C for the abort of 1.8 TeV 5 x 10^{12} proton beam is shown in Fig. 4. The maximum temperature of ~800°C is reached on the beam axis at a longitudinal distance of 140 cm. Experience with the existing external beam dump system indicates that if the graphite slabs are contained in the inertial (argon) atmosphere their long-life exploitation at such temperatures is possible. Note that the fracture temperature of graphite is ~2200-2300°C.

Figure 4 shows that temperatures at radii >3.5 cm are less than 50°C (one needs to add the temperature rise to the initial temperature 27°C). The maximum temperature rise in the steel endcap is ~100°C. At smaller beam intensities all these numbers are correspondingly less. The maximum instantaneous temperature rise in the graphite core is only 380°C for the 2 x 10^{12} abort. Moreover, the maximum energy deposition and crudely the maximum temperature rise do scale almost linearly with the beam energy, say to 1.5 TeV or 150 GeV. Therefore, one can consider the Fig. 4 data as an extreme case.

On the basis of these calculations the two proposed cross section of the upgraded Tevatron internal beam dump are shown in Figs. 5 and 6.

A. The 13.5 x 9 x 2 cm graphite slabs with 1 mm aluminum beam pipe of 60 x 40 mm aperture. The slabs in an argon atmosphere are contained in an aluminum box with a closed loop cooling system. This box is surrounded by a steel shield. The total length of the dump is 580 cm. Such a dump should work reliably at energies up to 1.8 TeV and aborts up to 6x10^{12} protons.

B. The 6x3x2.5 cm graphite inserts in the aluminum box (Fig. 6). Requirements for beam stability and beam intensity (<3-4 x 10^{12}) are harder for this case.

Both abort dumps in the straight section are identical.

Cooling System

To find the cooling system parameters we use the abort scenarios of Section 2 and results on the total absorbed energy in each dump. Table 1 below gives the energy (in kiloJoules), deposited in the various parts of the dump for the single 2 x 10^{12} protons abort.

Table 1					
Beam Energy TeV	Al Beam Pipe	Graphite	Al Container	Steel Shield	Total
1800	5.4	245.4	57.6	160.0	468.4
150	0.03	13.4	6.7	22.4	42.8

Then, for these scenarios the power of the closed loop cooling system of each internal beam abort dump should be

$P = 468.4 + 42.8 \times 30 = 1752.4$ kJ/hr or ~0.5 kW.

At higher intensity the power should be greater. Say, at 5×10^{12} multiply these numbers by 2.5.

Quenching

To determine the superconducting units heating by the stray radiation escaping the dumps we performed the full scale Monte Carlo simulation for the whole straight section shown in Fig. 2. Two factors are favorable:

1. Because the beam displacement in the dump is large enough, there are practically no high energy protons scattered from the edge of the absorbers, which are the most serious component in the long distance irradiation, for example, as in fast resonant extraction case[4];

2. The second beam dump which is placed at the other end of the abort straight section, just upstream the superconducting quad, serves as a good collimator absorbing particles created in the first dump.

Calculations show that the maximum energy deposition density in the first quadrupole superconducting coils is 3×10^{-7} GeV per gram per incident proton at the reference beam offset 14 mm. For the 2×10^{12} beam abort it gives 0.1 mJ per gram, which is a factor of 5 to 10 below the instantaneous quench limit.[4]

Figure 7 gives the dependence of energy density in the superconducting coil on the beam displacement in the dump. Also shown is maximum energy deposition in the horizontal part of the inner aluminum tube of the dumps. One can conclude that for 1.8 TeV 2×10^{12} abort the minimum beam offset is about 5-7 mm. The corresponding maximum temperature in the aluminum is ~100°C.

Shielding

The averaged over a year tolerable flux of hadrons with E >10 MeV at the outer surface of a shield is about 10^7 hadrons/cm^2 sec.[5-8] This value gives ~100 mrad/hr of contact dose of induced radioactivity and is acceptable from ground water activation point of view (flux 10^6 to the water). For the considered abort scenarios and 50% "collider year" we have

1.8 TeV:
$24 \times 365 \times 0.5 = 4380$ aborts per year
Averaged over year abort intensity is
$2 \times 10^{12} * 4380/3.15 \times 10^7 = 2.8 \times 10^8$ p/sec
Tolerable flux $= 10^7/2.8 \times 10^8 = 3.6 \times 10^{-2}$ per cm^2 per proton

150 GeV:
$30 \times 4 \times 365 \times 0.5 = 2.19 \times 10^4$ aborts per year
Averaged abort intensity $= 1.4 \times 10^9$ p/sec
Tolerable flux $= 7.1 \times 10^{-3}$ per cm^2 per proton.

Comparing these numbers to the results of cascade calculations we find that aluminum containers must be surrounded with the steel shield (density 7.86 g/cm^3) of the outer radius 25 cm as shown in Fig. 3.

Muons

Calculations[7] show that for the design parameters one needs to have 1.5 km of wet soil shield in the direction of aborts to provide on the surface the muon annual dose of 10 mrem.[5] The maximum thickness of the soil above the aborted beam axis is ~4 m, and may be higher (5 m) at the first 100 meters near the CØ straight section dependently on the specific abort design. The Fermilab site is fulfilled to this condition and the only requirement is to kick the aborted beam down.

Lifetime

The integrated over a year hadron flux in the "hottest" point of the dump for given scenarios is in the range of $1.5\text{-}4 \times 10^{18}$ cm^{-2}. The tolerable flux is about 10^{20} cm^{-2}. The present abort dump with the similar maximum hadron flux is exploited for seven years. The necessary requirement is the argon atmosphere for graphite. The beam offset could be different at 150 GeV and 1800 GeV say, 10-14 mm at 1.8 TeV and 7-10 mm at 150 GeV.

SCHEME 2

We have studied two dump designs for this scheme, which are similar to Figs. 5 and 6, but both with inserts and in the last case with aperture 50 × 20 mm.

Considering the maximum beam parameters as 1.5 TeV and 2×10^{12} ppp, we have found that the core insert should consist of 360 cm graphite followed by 40 cm steel and 140 cm tungsten. Maximum temperature in all parts (C, Fe, W) is about 300°C. Shielding and other requirements are the same.

The energy deposition in superconducting coil is extremely high however and even with the aperture of the dump restricted, the quench levels in the superconducting magnets are exceeded by at least an order of magnitude (Table 2). Results of this table show that neither of these arrangements result in a viable design option.

SCHEME 3

The third alternative is similar to scheme 2 in that all the abort elements are confined within the straight section, but is slightly less elegant in the fact that it uses two sets of kicker magnets at each end of the long straight and a double ended dump in the centre, thus losing the operationally desirable feature of a single set of kicker magnets aborting both beams. Each system of kickers consists of five modules similar in design to the existing Tevatron magnets. This results in a beam deflection of 1.3 mrad which corresponds to a beam displacement of 20 mm at the face of the dump. The dump is constructed in three sections. The cross-section is the same as that outlined in scheme 1.

Table 2 Structure of the Central Absorber in Scheme 3

Section No.	1	2	3
Extent, meters	0-4.2	4.2-4.8	4.8-9
Core 6 x 2.5 cm	Graphite	Steel	Graphite
Container r<6 cm	Aluminum	Steel	Aluminum
Shield 6<r<25 cm	Steel	Steel	Steel

The energy deposited in the various sections of this dump is shown in Table 3. These data can be used for determination of closed loop cooling system.

Table 3 Energy (kJoules) Deposited per a Single 2×10^{12} Abort

Element		Eo=1500 GeV	Eo=150 GeV
Core	Sec 1	115.2	5.17
	Sec 2	25.2	0.32
	Sec 3	1.3	0.05
	Total	141.7	5.54
Container	Sec 1	111.0	11.24
	Sec 2	21.8	0.90
	Sec 3	9.0	0.40
	Total	141.8	12.54
Steel shield	Sec 1	160.7	25.47
	Sec 2	8.3	0.50
	Sec 3	7.5	0.45
	Total	176.5	26.42
TOTAL		460.0	44.50

Total power: P = 460 + 44.5 x 30 = 1795 kJ/hr. For antiproton abort numbers for Sections 1 and 3 are exchanged.

The quenching behavior of this design is shown in Table 4. Placing the dump in the centre of the straight section results in a dramatic decrease in the energy deposition in the superconducting elements. There are two reasons for this: the superconducting magnets are further away from the source of the radiation and hence subtend a smaller solid angle, but more importantly the kicker magnets themselves, with their reduced aperture, make excellent absorbers resulting in a greatly reduced flux into the superconducting elements.

CONCLUSIONS

Two of the three internal abort designs considered result in satisfactory behaviour and fulfill the criteria outlined in Section 3. A beam dump positioned directly in front of the superconducting magnets cannot absorb a sufficient number of the secondary particles outscattering from the face of the dump to avoid quenching these magnets at the kind of intensities likely to be encountered during the collider upgrade. Other features of the abort design appear to be within adequate operational tolerances.

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Table 4 Quenching Summary for 2 x 10^{12} Abort

Scheme	1		2			3
Eo, TeV	1.8		1.5			1.5
Dump aperture, mm	60x40		60x40		50x20	60x30
Beam offset, mm	10	14	10	14	14	10
Max. energy density in SC coil, mJ/g	0.18	0.1	100	50	13	< 0.01
Energy deposited in the first meter of Quad, Joules	6	3.2	3962	1958	330	< 0.005
Number of hadrons* in Quad aperture at 1 meter						
with E > 10 MeV	1.E9	6.E8	3.2E12	1.7E12	2.2E11	9.E7
with E > .75 Eo	100	96	255	241	249	168

*Mean hadron energy = 8-35 GeV

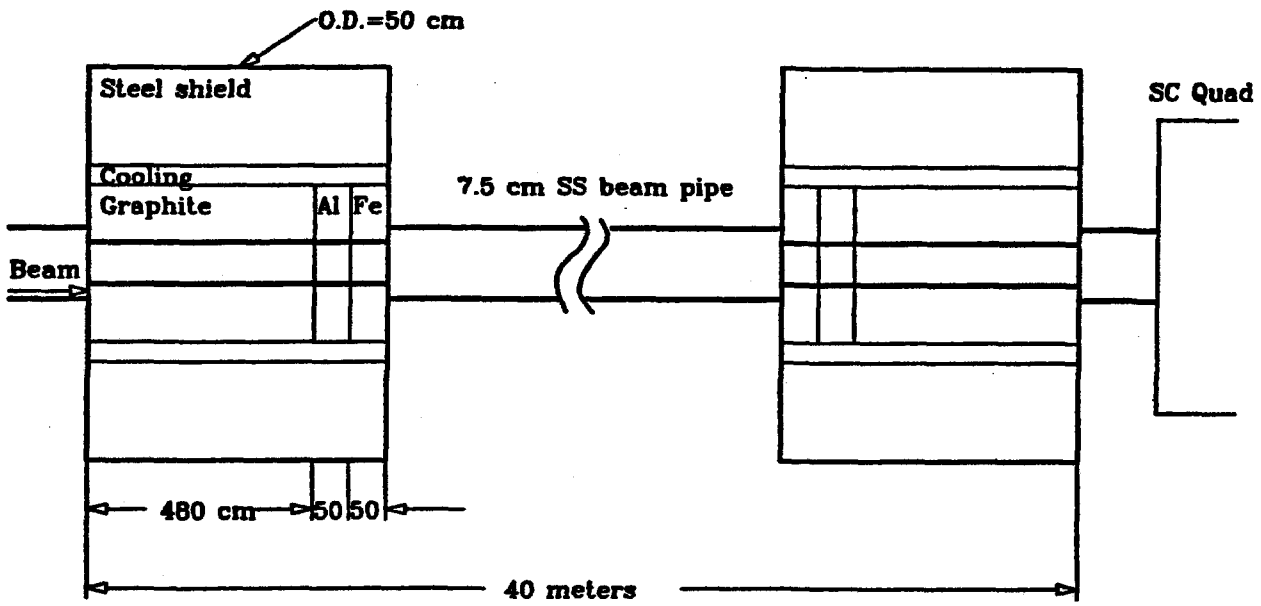

Figure 2 Schematic view of two beam abort dumps placed in the CO straight section.

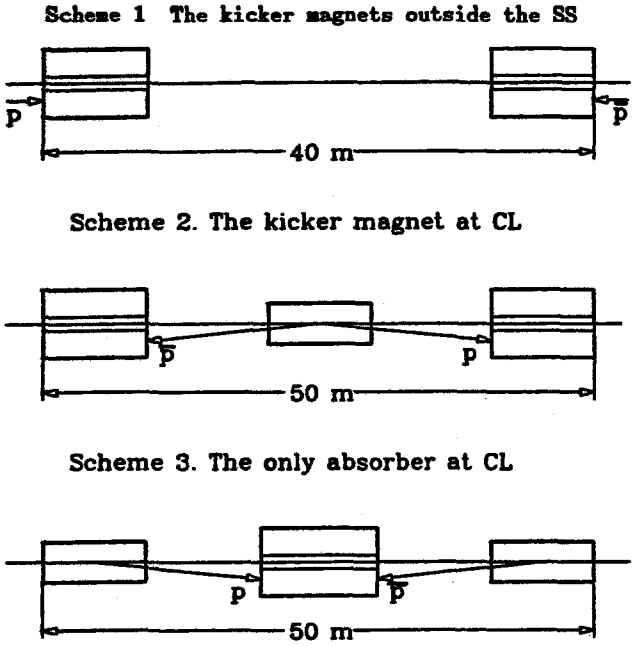

Figure 1 Three examined designs for the Tevtron internal beam dump system.

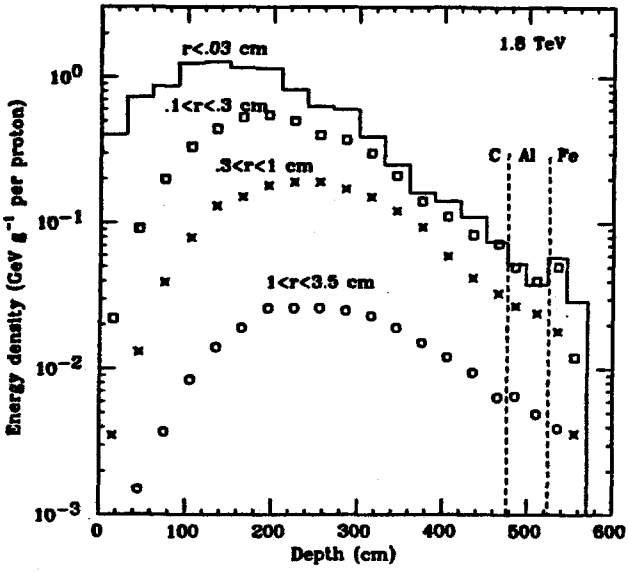

Figure 3 Longitudinal distributions of energy deposition density in the various radial bins of the core of the internal beam dump at the 1.8 TeV proton abort with a beam spot of 0.48*0.34 mm (H*V) rms.

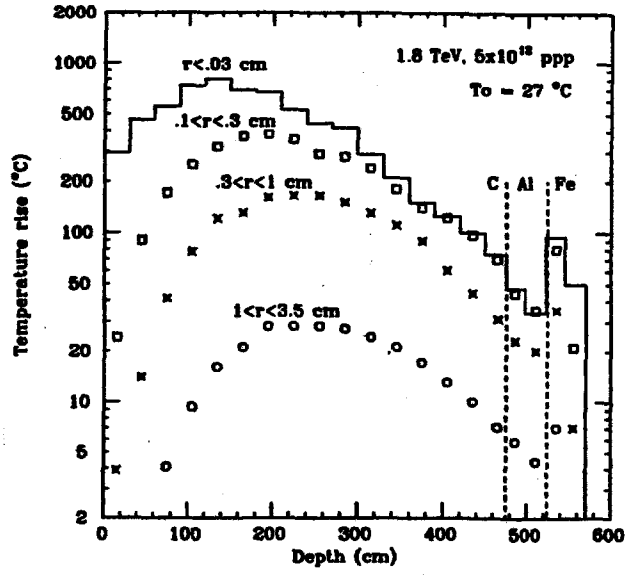

Figure 4 Instantaneous temperature rise distribution corresponding to Fig. 3 for the beam abort of 5×10^{12} protons.

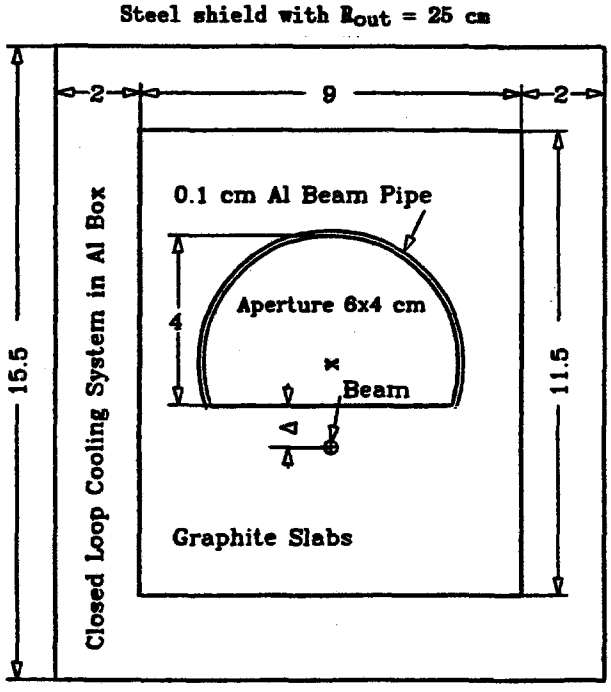

Figure 5 Core of the internal beam abort dump, Scheme 1(A). All dimensions are in cm.

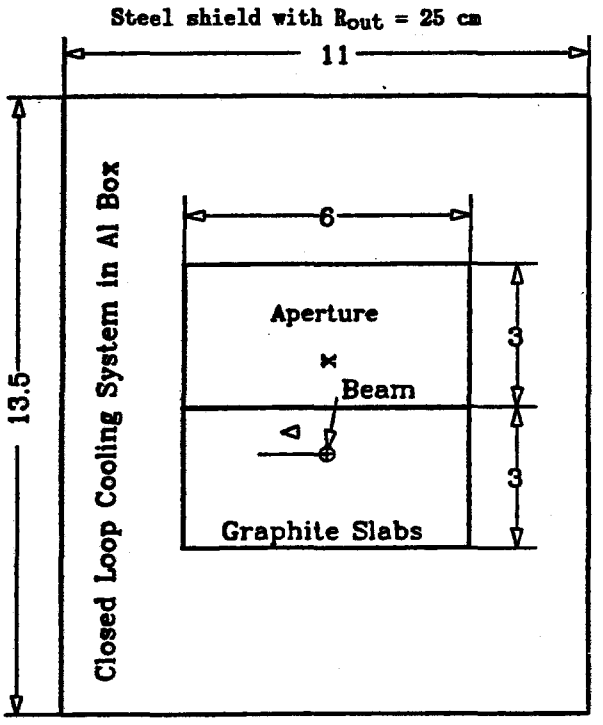

Figure 6 Core of the internal beam abort dump, Scheme 1(B). All dimensions are in cm.

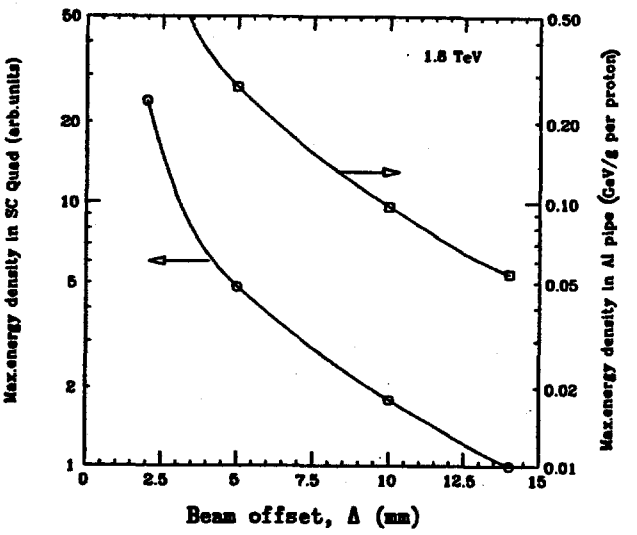

Figure 7 Maximum energy deposition density in the first downstream quadrupole superconducting coils and in the aluminum beam pipe inside the internal abort dump versus beam displacement in the dump.