Beam Collimation and Shielding in the Fermilab Proton Driver

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BEAM LOSS AND SHIELDING DESIGN STRATEGY

A very high beam power implies serious constraint on beam losses in the machine. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses in the machine to an allowable level. The design strategy of the Proton Driver is that the beam losses are **localized and controlled** as much as possible via the dedicated beam collimation system. This way, the source term for the radiation analysis is a derivative of the collimation system performance with a high loss rate localized in the injection/collimation section **(with components locally shielded to equalize prompt and residual radiation levels in the tunnel)** and drastically lower uncontrolled beam loss rate in the rest of the lattice.

For accidental beam loss, a *credible* accident is considered: a point-like loss of the full beam of 0.1% of the 1-hour beam intensity. The maximum thickness from all cases considered is put into the design as the tunnel shielding in that part of the machine.

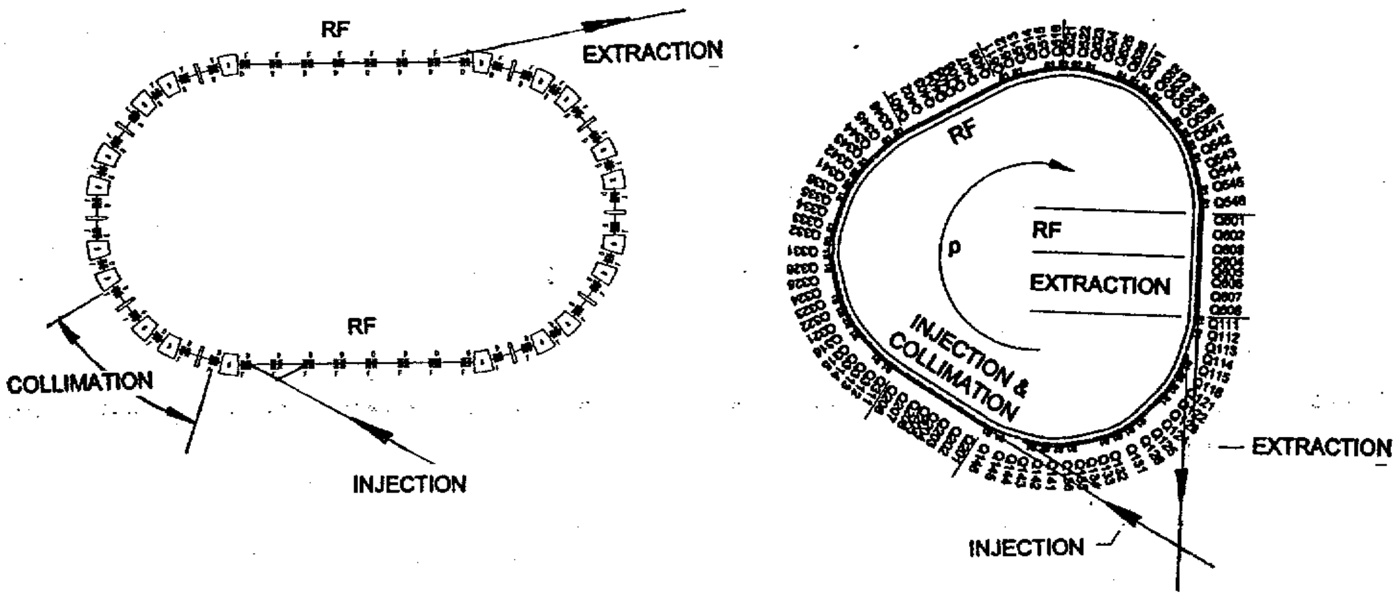


Figure 1: 8 GeV (left) and 16 GeV (right) Proton Driver.

Two possible designs of the new Fermilab proton source that satisfy the demands of the future research program for the next several decades are based on the 16 GeV or 8 GeV high intensity fast cycling synchrotrons. In the 16 GeV machine, the collimation system is located in a specially designed long straight section. In the 8 GeV Proton Driver, due to the space constrains, it is placed in the available drift spaces of the arc.

1 Collimation System Design

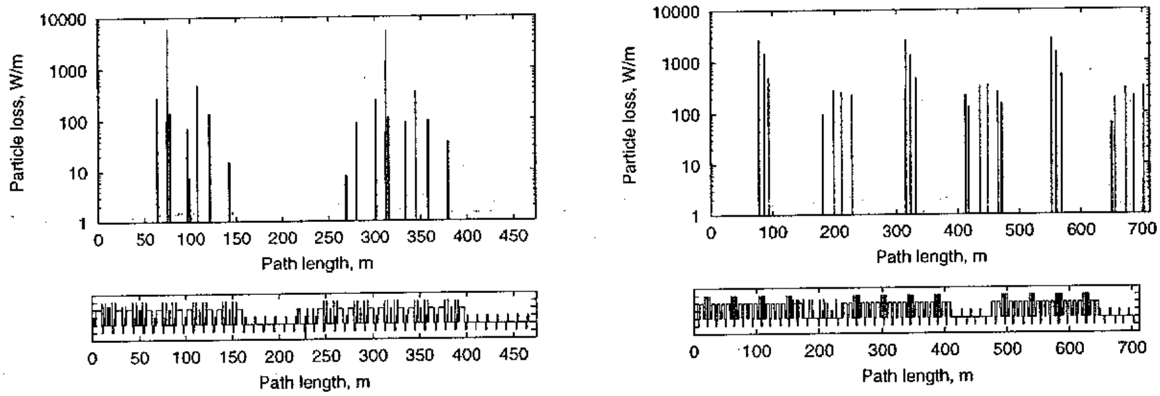


Figure 2: Beam loss distribution in the 8 GeV (left) and 16 GeV (right) without collimators at 1% beam loss at the top energy.

Assuming that 1% of the beam is lost at the top energy, this amounts to 4.8 kW and 11.5 kW (for 8 and 16 GeV machines) of beam loss distributed around the ring with a peak loss of up to several kW/m on a few quadrupoles. This level is more than three order of magnitude higher of that which can be accepted in the machine.

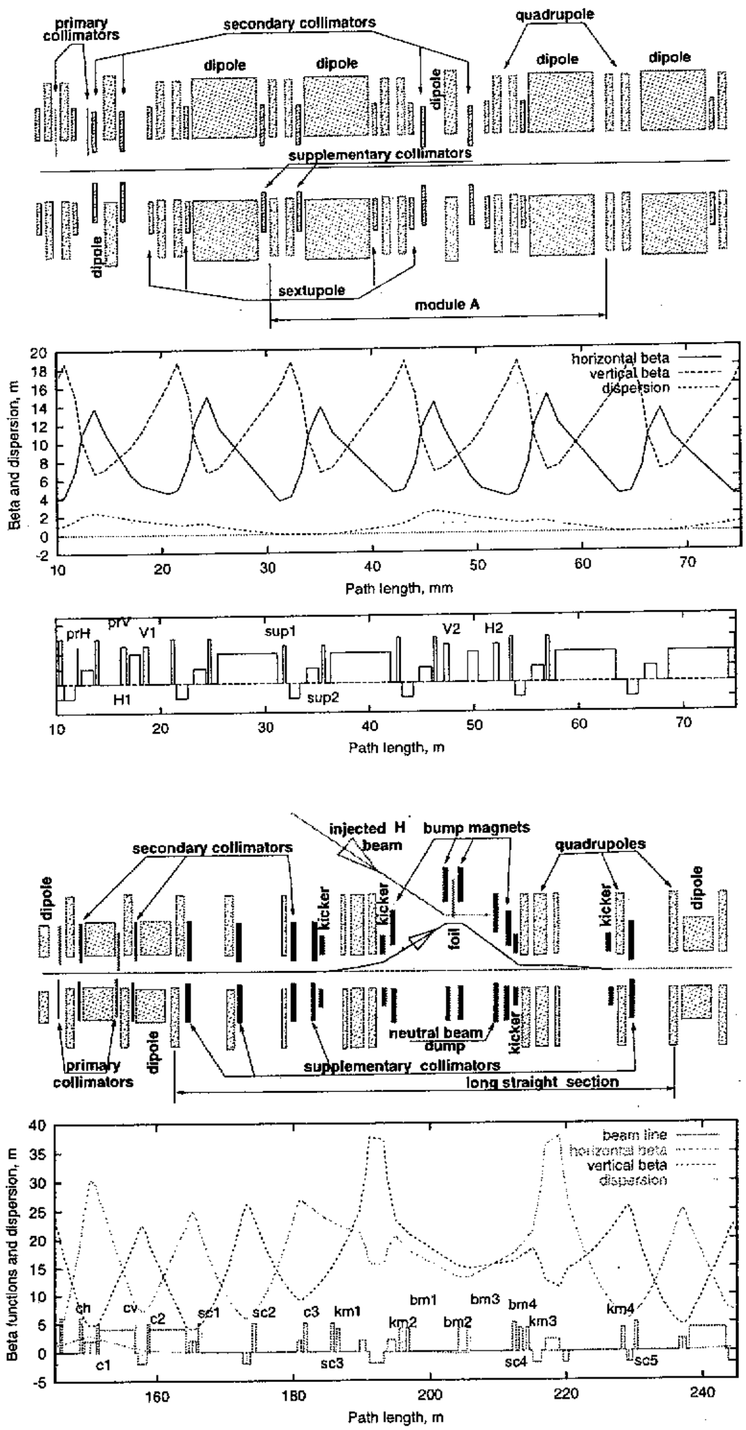


Figure 3: Beam collimation system location, beta functions and dispersion in the collimation section of the 8 GeV (top) and 16 GeV (bottom) synchrotron.

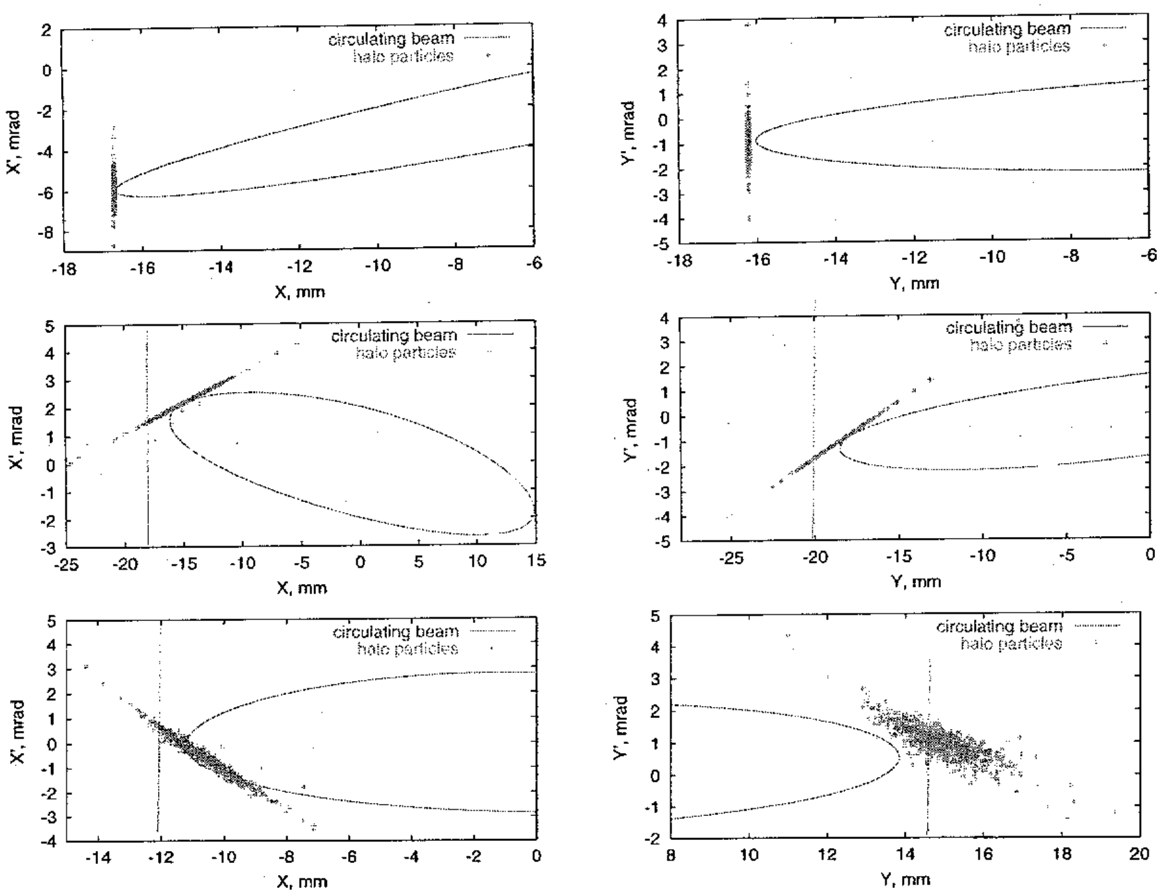


Figure 4: Horizontal (left) and vertical (right) phase space at the primary collimators (top), secondary collimators 1H and 1V (middle) and 2H and 2V (bottom).

At normal operation conditions, a circulating beam size grows slowly with a small step size per turn of the order of few μm. A thin primary collimator increases proton amplitude as a result of multiple Coulomb scattering, drastically increasing the impact parameter on the secondary collimators. This results in a significant reduction of the out-scattered proton yield, decreases collimator jaws overheating and mitigates requirements to the collimator alignment.

Table 1: β-functions, dispersion and phase advance between the primary and secondary collimators in the 8 GeV machine.

Collimator	β-function (m)		Disper-sion (m)	Phase advance between primary and secondary collimators (deg)	
	horizontal	vertical		hor.	vert.
Horizontal primary	8.9	12.6	1.9	0	-
Vertical primary	8.0	8.5	1.9	-	0
Secondary 1H	7.8	9.2	1.9	24	-
Secondary 1V	5.2	12.6	1.5	-	14
Supplementary 1	3.9	17.9	0.0	176	84
Supplementary 2	12.2	7.0	0.0	203	105
Secondary 2V	10.7	7.7	2.1	-	172
Secondary 2H	4.0	15.0	1.4	348	-

Secondary collimators are placed at an optimal phase advances to intercept most of particles out-scattered from the primary collimators during the first turn after the halo interaction with the primary collimator. Secondary collimators generate out-scattered particles lost later in the accelerator. One can reduce this component with a 3-stage collimation system positioning several main secondary collimators close to the beam to deal with protons scattered in the primary collimator and several supplementary collimators farther from the beam to catch particles out-scattered from the main secondary collimators.

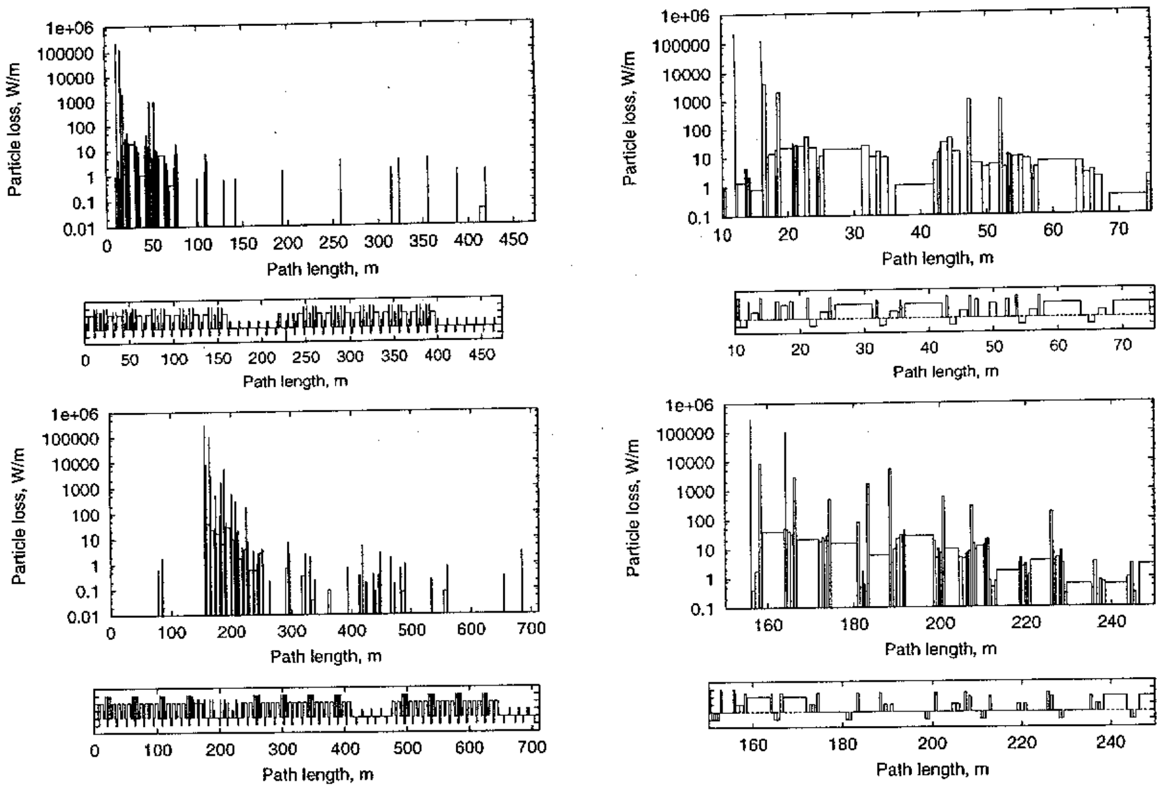


Figure 5: Beam loss at the top energy in a 8 GeV (top) and 16 GeV (bottom) machines.

With the proposed system, ~99% of the beam halo is intercepted in the collimation section. About 1% is lost in the rest of the machine with the mean rate of 0.2 W/m. At several locations the beam loss is noticeably higher (~2 W/m), exceeding the tolerable rates of 0.6 W/m. The above 'hot' locations should be taken care of via local shielding or fencing.

Beam loss rates in the collimation section itself are very high implying a special shielding design. Collimators and magnets of this section require special cooling as well as fast disconnects and remote control.

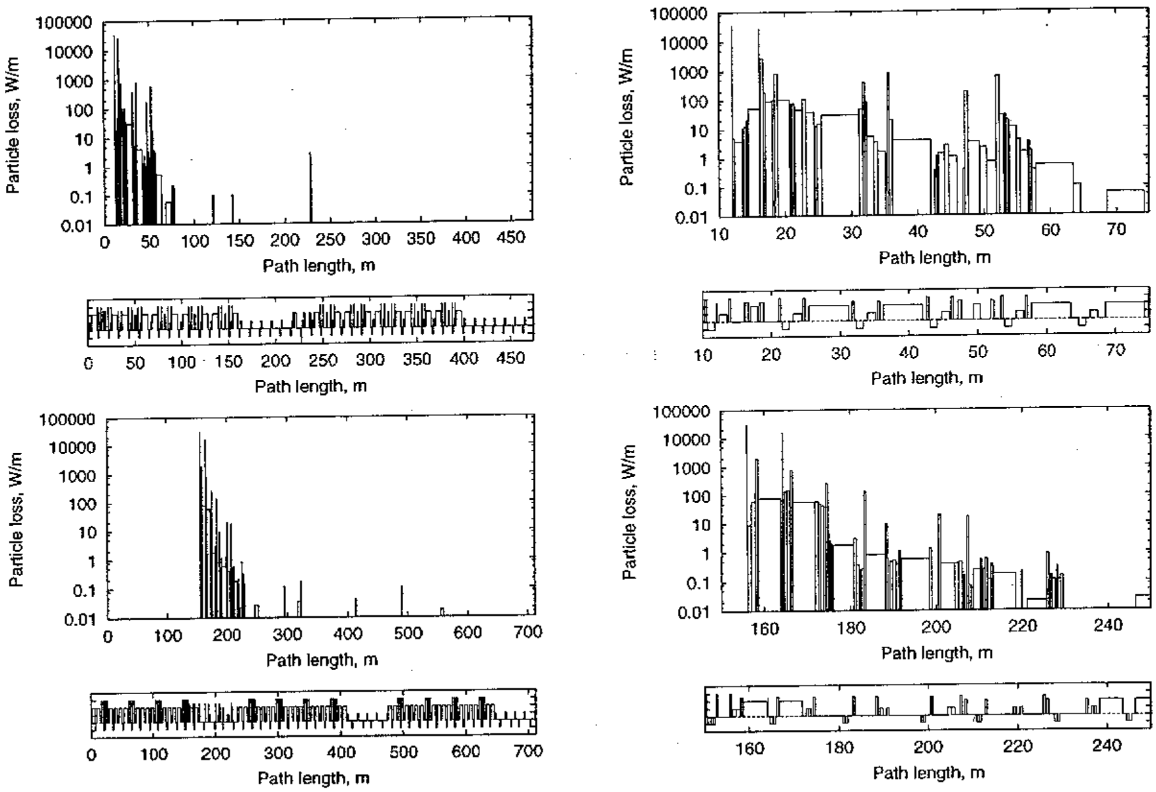


Figure 6: Beam loss at injection in the 8 GeV (top) and 16 GeV (bottom) Proton Driver.

Table 2: Collimation system optimisation.

Collimators	Beam loss		
collimation system	collimation section	Rest of the ring	Peak loss rate in the ring
	kW	kW	W/m
8 Gev synchrotron			
at the top energy four secondary at 2 mm	4.753	0.048	7
at the top energy four secondary at 2 mm two supplementary at 4 mm	4.778	0.024	2
at injection four secondary at 2 mm two supplementary at 4 mm	3 596	0.005	0.2
16 Gev synchrotron			
at the top energy three secondary at 1 mm	11.246	0.274	26
at the top energy three secondary at 2 mm five supplementary at 5 mm	11.453	0.067	7
at the top energy three secondary at 1 mm five supplementary at 3 mm with bump	11.503	0.017	4
at injection three secondary at 1 mm five supplementary at 3 mm	2.879	0.001	0.1

All collimators are in a fixed position close to the beam edge after painting. In an ideal case, the circulating beam should be kept close to the collimators during the total cycle. This requires rather complicated bump, created by several fast magnets. To simplify the system, we propose to keep the beam close to the primary and first secondary collimators using only three fast magnets for each direction.

2 Sensitivity Analysis

Table 3: Beam loss in the 16 GeV machine as a function of closed orbit deviation.

	Beam loss		
Maximum closed orbit deviation	collimation section	Rest of the ring	Peak loss rate in the ring
mm	kW	kW	W/m
-4	11.348	0.172	49.6
-2	11.436	0.084	14.8
0	11.470	0.050	5.4
2	11.454	0.066	10.9
4	11.466	0.054	16.7

Table 4: Beam loss in the 16 GeV machine as a function of accelerator tune.

	Beam loss		
tune	Collimation section	Rest of the ring	Peak loss rate in the ring
	kW	kW	W/m
$\nu_x = 11.443, \quad \nu_y = 11.351$	11.473	0.047	134.7
$\nu_x = 11.431, \quad \nu_y = 11.369$	11.460	0.060	14.9
$\nu_x = 11.407, \quad \nu_y = 11.407$	11.463	0.057	127.7
$\nu_x = 11.378, \quad \nu_y = 11.416$	11.477	0.043	14.5
$\nu_x = 11.363, \quad \nu_y = 11.421$	11.484	0.036	14.5

3 Collimator

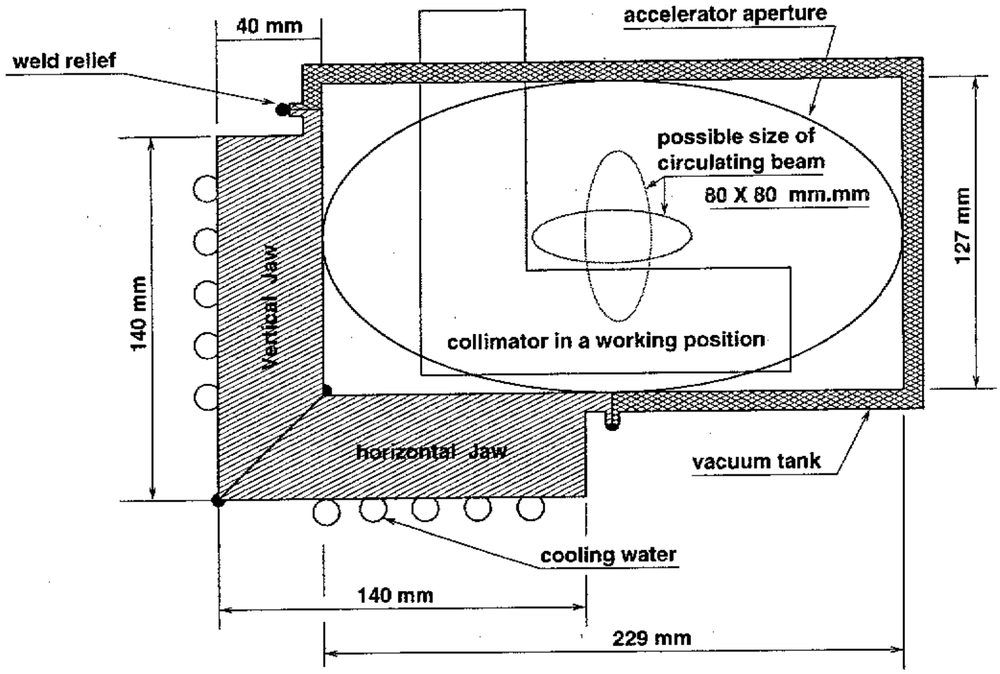
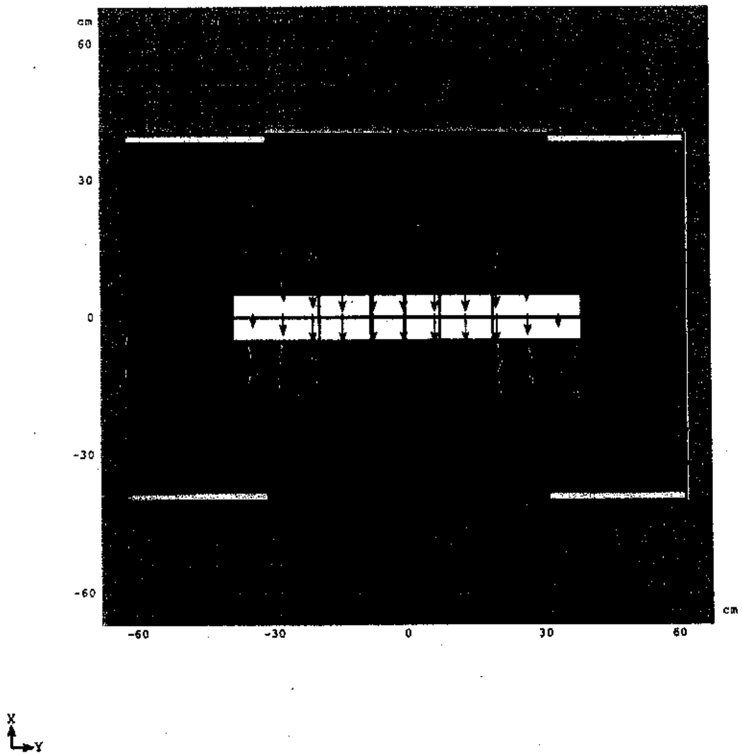
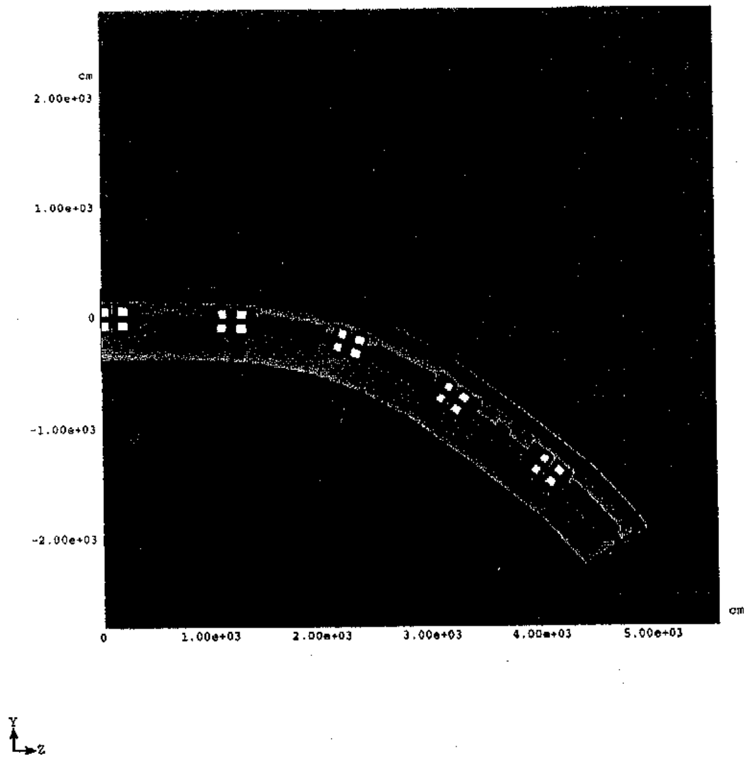


Figure 7: Secondary collimator cross section.

The mechanical design of the collimators and targets will be similar to those already built and installed in the Tevatron for Collider Run II. The collimators consist of two pieces of stainless steel, 0.5 m long, welded together in an "L" configuration. A total of 11.5 KW of DC power is expected to be dissipated in the collimators. This power can be removed from a single collimator by circulating low conductivity water through cooling channels on the outside of the collimator box.

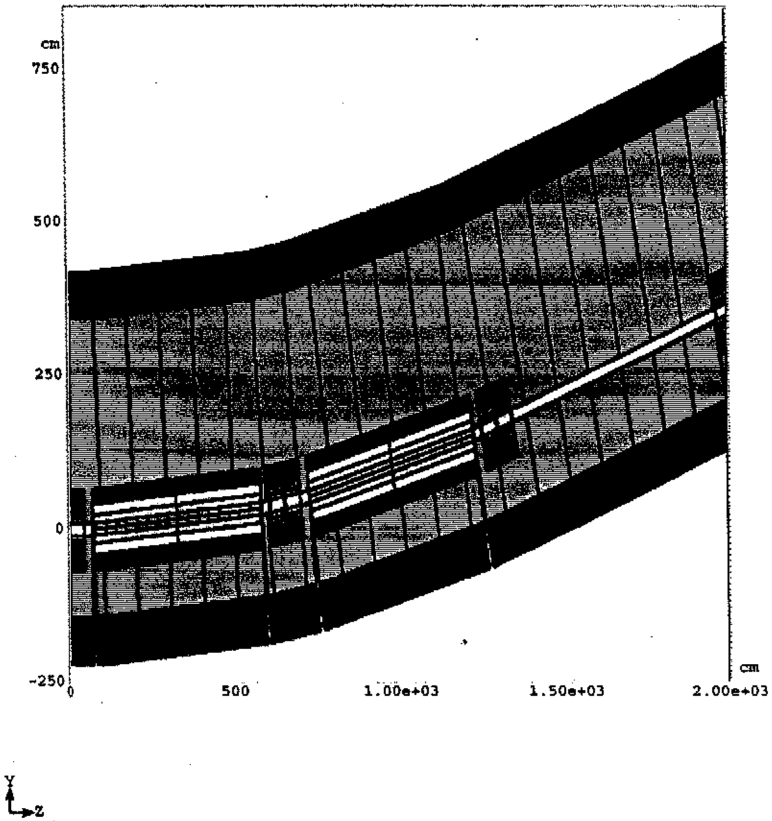
PROTON DRIVER-2 MARS MODEL

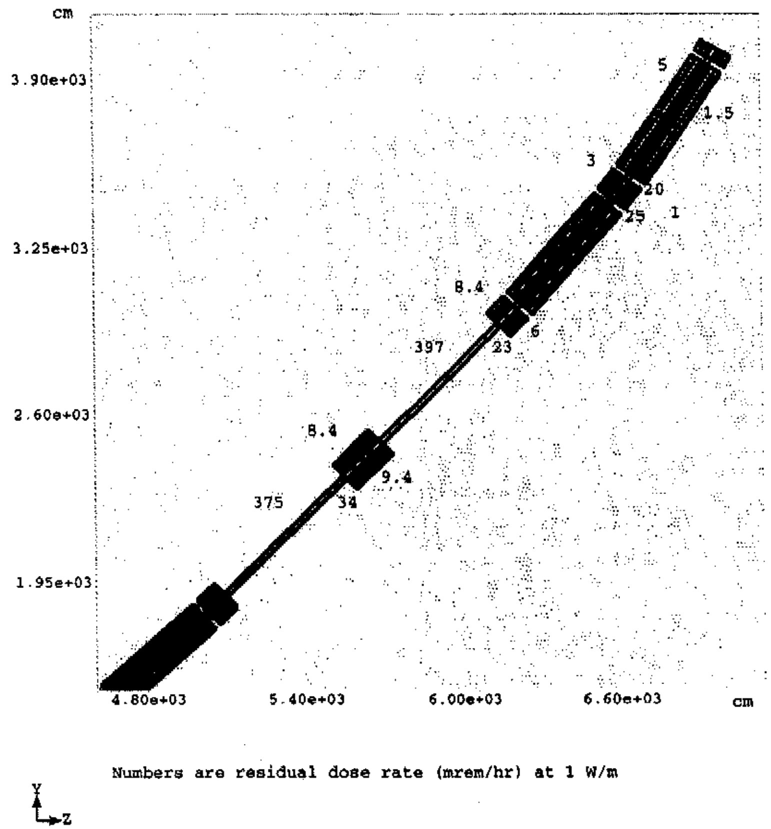




MARS model of dipole magnet (left) and arc region (right).

ARC





Plan view of the modeled arc (left) and peak residual dose rates (mrem/hr) on the arc elements at 1 W/m beam loss rate (right).

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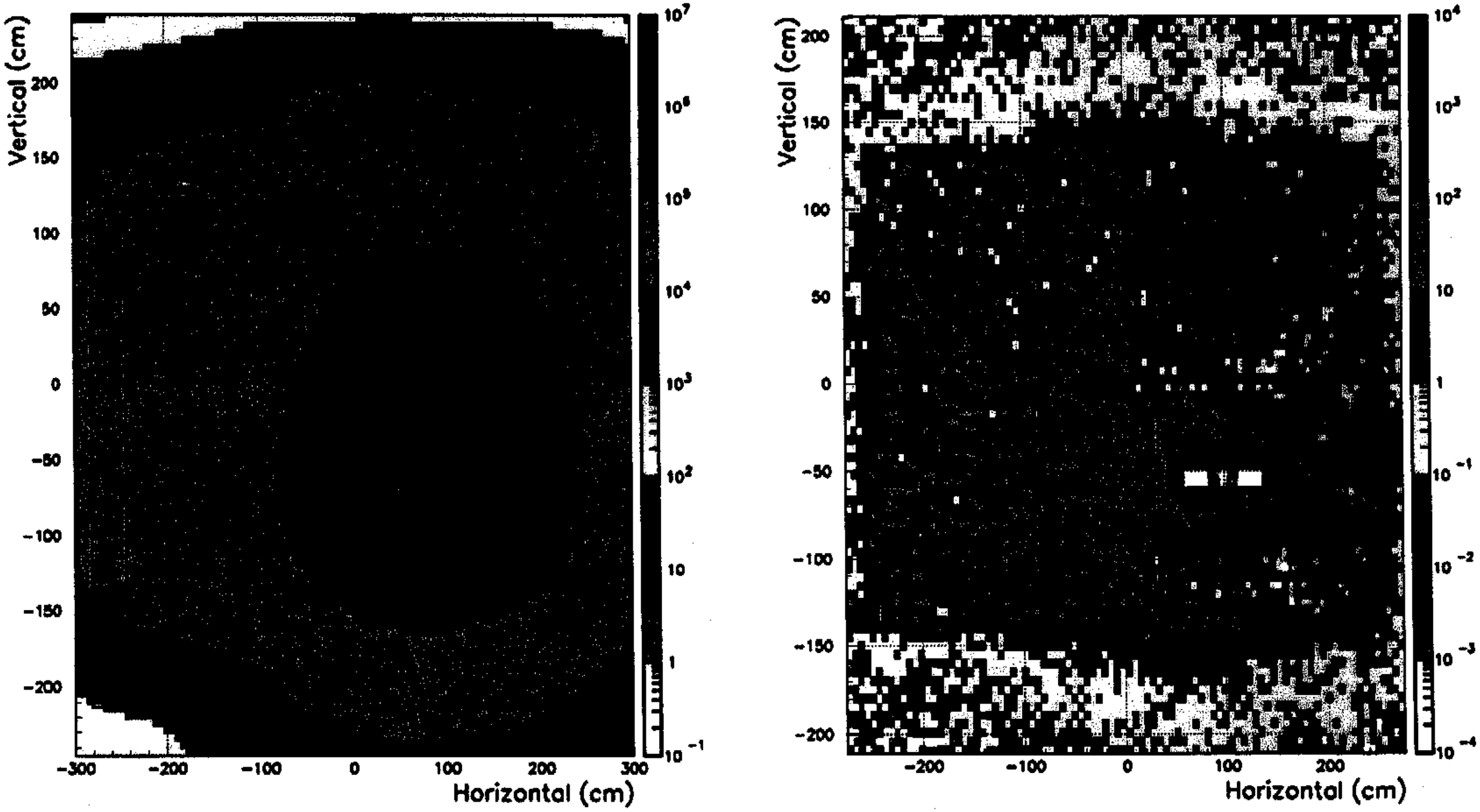
RADIATION IN ARCS



Hadron (E>20 MeV) isofluxes ($cm^{-2}s^{-1}$ at 1 W/m) at peak at a long drift (left) and isodose distribution (krad/yr at 1 W/m) at peak at a dipole magnet (right).

PROTON DRIVER-1 RADIATION SUMMARY

Despite variation in realistic beam loss distribution along the lattice and remembering the fact that the shield thickness is driven by accidental beam loss which can take place in an arbitrary lattice location, **a uniform shielding design along the arcs** is suggested. With the worst case point-like loss of the full beam of 0.1% of the 1-hour beam intensity at 16 GeV—**a credible accident for the arcs and long straight sections**—the shield thickness required is 18.5 feet of Fermilab wet dirt. At normal operation, it is about 14 feet. Assuming a safety factor of 3, the thickness of dirt shielding above the arcs is 20 feet. Phase II (4 MW) will require about 21.5 feet of dirt.

At 1 W/m beam loss rate, the maximum dose accumulated in the coils is about 2 Mrad/yr which is acceptable with use of appropriate materials for insulation. The maximum annual dose at cable locations at the ceiling is about 0.1-0.2 Mrad/yr above the magnet hot spots, and is about 0.4 Mrad/yr above long bare beam pipes.

4 Conclusions

Detailed energy deposition studies performed in the machine elements give the tolerable beam loss in the Proton Driver. At the top energy in the arc for the proposed lattice, hands-on maintenance limits are 0.25 W/m in the open long beam pipes and 3 W/m in the magnets, while the ground-water limit is 0.6 W/m.

A proposed 3-stage collimation system allows localization of 99% of beam loss in a collimation section. Beam loss in the rest of the machine is on average 0.2 W/m. Local shielding is proposed to install in the hottest 20-m part of the collimation section. Overall, despite challenging parameters of the proposed new Proton Driver, beam loss and induced radiation effects can be controlled and reduced to allowable levels.