Beam Collimation and Shielding in the Fermilab Proton Driver[1]

A.I. Drozhdin, N.V. Mokhov[2]

FNAL, Batavia,IL 60510, USA

Abstract.
A high beam power in the proposed Fermilab Proton Drivers – 1.2 MW in 16-GeV PD-I and 0.48 MW in 8-GeV PD-II – implies serious constraints on beam losses in these machines. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses in the machine to an allowable level. The entire complex must be well shielded to allow acceptable hands-on maintenance conditions in the tunnel and a non-controlled access to the outside shielding at normal operation and accidental beam loss. Collimation and shielding performances are calculated and compared for both Proton Drivers.

BEAM LOSS AND SHIELDING STRATEGY

The Proton Driver design strategy 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. A high loss rate is localized in the collimation section with components locally shielded to equalize prompt and residual radiation levels in the tunnel and drastically lower uncontrolled beam loss rates in the rest of the lattice [2, 3]. The radiation transport analysis is fundamentally important because of the impact on machine performance, conventional facility design, maintenance operations, and related costs. Results of this paper are based on detailed Monte Carlo simulations with the STRUCT [4] and MARS [5] codes.

The Fermilab regulatory requirements imply that: 1) prompt dose rate in non-controlled areas on accessible outside surfaces of the shield is $\leq$0.05 mrem/hr at normal operation and $\leq$1 mrem/hr for the worst case due to accidents; radionuclide concentration of 20 pCi/ml for ^{3}H and 0.4 pCi/ml for ^{22}Na in any nearby drinking water supplies are not exceeded; and anywhere in the machine, residual dose rate $P_\gamma \leq 100$ mrem/hr=1 mSv/hr at 30 cm from the component surface, after 100 day irradiation at 4 hrs after shutdown (averaged over all the components, $P_\gamma \leq$10-20 mrem/hr=0.1-0.2 mSv/hr.

The radiation analysis for the arcs and long straight sections is performed both for normal operation and for accidental beam loss. The maximum shielding thickness from the both cases is put into the design as the tunnel shielding in that part of the machine. In normal operation, the source term is based on the beam loss distributions calculated with a beam collimation system described in the next section. For accidental beam loss, a *credible* accident is considered: a point-like loss of 0.1% of the full beam intensity during one hour. This is about 10^{15} protons. Once such an accident happens, the machine is shut down within 1 second to analyze the cause and undertake appropriate measures.

COLLIMATION SYSTEM

Assuming 1% of beam loss at the top energy, one gets total beam power of 11.5 kW and 4.8 kW lost in PD-I and PD-II, respectively. Calculations show that the peaks (at some quadrupoles) in the beam loss distribution can reach several kW/m that is a few thousand times higher than the tolerable levels [2, 3]. Therefore, multi-component beam collimation systems are designed for the projects. In PD-I, the system is located in a dedicated long straight section, while in the 8 GeV machine, due to space constrains, it is placed in the drifts available in the beginning of the arc. The systems consist of horizontal and vertical primary collimators, and several secondary and supplementary collimators as shown in Fig. 1. Secondary collimators generate out-scattered particles lost later in the lattice. This component is reduced with a *3-stage collimation system* positioning three (PD-I) or four (PD-II) secondary collimators close to the beam to deal with protons scattered in the primary collimator and five (PD-I) or two (PD-II) *supplementary* collimators farther from the beam to catch particles out-scattered from the main secondary collimators.

Secondary collimators need to be placed at phase advances which are optimal to intercept most of particles out-scattered from the primary collimators during

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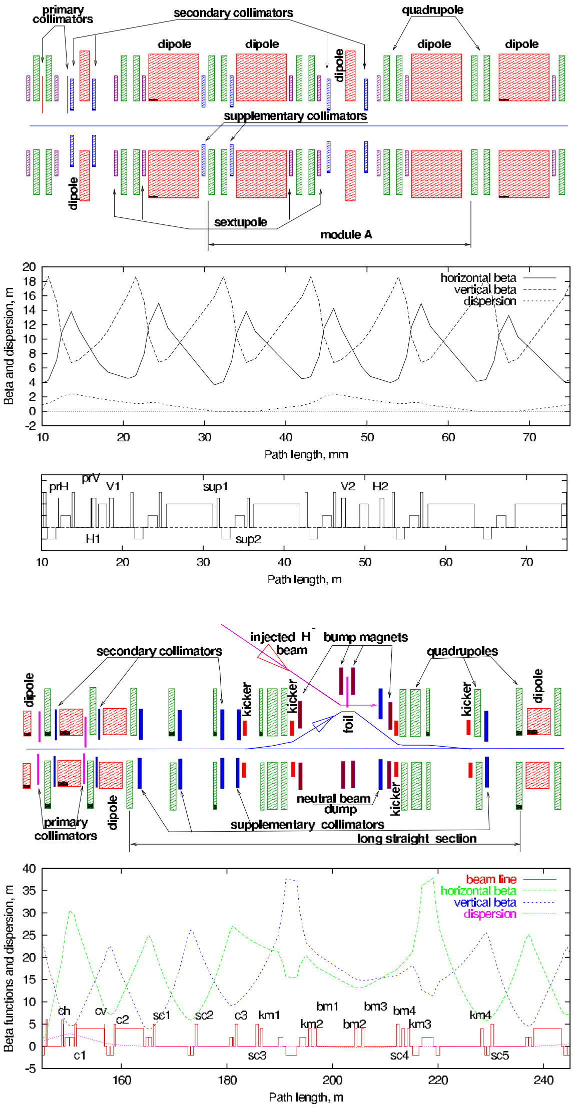

FIGURE 1. Beam collimation system layout, beta functions and dispersions in the 8 GeV (top) and 16 GeV (bottom) synchrotrons.

the first turns after the halo interaction with the primary collimator. The optimal phase advances are around $k \cdot \pi \pm 30^o$. The horizontal and vertical primary collimators are placed at the edge of the beam after painting, with secondary collimators father from this position by an offset d. Beam loss distributions at injection and top energies are shown in Figs. 2 and 3 for the systems with 0.3-mm thick tungsten primary collimators, four secondary collimators (0.5-m long stainless steel or copper) positioned at d = 2 mm and two 0.3-m long supplementary collimators at d = 4 mm. The right sides of the Figures show details of beam loss in the collimation regions. It is assumed in calculations that 10% of the beam is lost at injection and 1% at the top energy, and 2/3 of these amounts interact the horizontal primary collimator (a half for off-momentum protons with $\Delta p/p = \pm 0.002$ and a half for on-momentum protons) and 1/3 the vertical primary collimator. The β-function varies along the secondary collimators, therefore the collimator apertures are tapered to follow the beam envelope after painting.

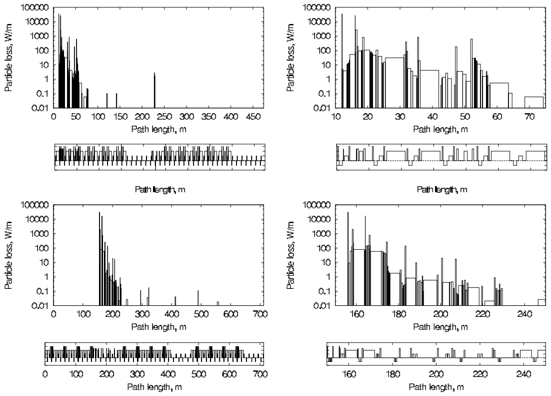

FIGURE 2. Beam loss at injection in PD-II at 0.6 GeV (top) and PD-I at 0.4 GeV (bottom).

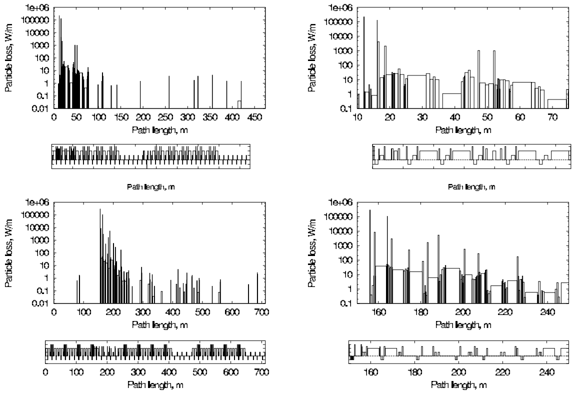

FIGURE 3. Beam loss in PD-II at 8 GeV (top) and PD-I at 16 GeV (bottom).

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 mean rate of 0.2 and 0.12 W/m in PD-I and PD-II, respectively. At several locations the beam loss is noticeably higher (∼2 W/m), exceeding the tolerable rates. Such "hot" locations need special care. Beam loss rates in the collimation system section itself are very high requiring a special shielding design.

A practicality of a rapid cycling proton synchrotron dictates a stationary collimator approach with collimator jaws in a fixed position with respect to the beam orbit during the entire cycle. In an ideal case, the circulating beam should be kept close to the collimators edge during the cycle. This requires rather complicated horizontal and vertical bumps, created by several fast magnets for each direction. To simplify the system, we propose to keep the beam at the edge of the primary collimators and close to the first secondary collimators using only three fast magnets for each direction. Most of the particles scattered out of the primary collimators are intercepted then by these secondary collimators, with other collimators intercepting the larger amplitude and off-momentum protons. Such a scheme allows to localize a majority of the beam loss in a short region.

A detailed sensitivity analyses were performed for the collimation systems in the two machines. Closed orbit deviations during the cycle and from cycle to cycle change a secondary collimator offset with respect to the primary one. In the worst case, the beam can hit initially a secondary collimator. This will result in a lower collimation efficiency and can cause damage of the collimator. Positioning secondary collimators 1 to 3 mm farther from the beam increases slightly beam loss rates in the ring, but allows larger closed orbit deviations (up to ±3 mm) at these locations. The tune causes change of phase advances between the collimators and distance to the resonances. As betatron amplitudes of protons after interaction with primary collimators are large, the second factor can cause collimation efficiency degradation. We found that tune deviations affect mostly the beam loss peaks increasing them by up to a factor five.

The mechanical design of the secondary collimators is similar to that of those already built and installed in the Tevatron for Collider Run II. The collimator jaws consist of two pieces 30-40 mm wide welded together in an 130-mm "L" configuration. Primary collimators are made of tungsten 1 mm thick. Secondary and supplementary collimators are made of stainless steel or copper (choice will be the subject of further thermal analyses) 0.5 m (secondary) and 0.3 m (supplementary) long. These dimensions will accommodate the full beam size, after painting, as well as maximum impact parameters. Machining and assembly tolerances of 25 μm are easily met for the collimator jaws. All collimators will be in a fixed position during the machine cycle, but motion control is required in order to adjust collimators to their optimum position. The collimator assembly is welded inside a stainless steel box with bellows on each end.

RADIATION ANALYSIS

MARS calculations show that residual dose rates on the collimators and magnets of the collimation system significantly exceed the hands-on maintenance limits (Fig. 4). To reduce these levels and protect ground water outside the tunnel walls, the entire region needs to be shielded. The configuration found for PD-II, consists of steel shielding uniform in two sections of the 58-m region: first, 5-m long, starts 0.5 m upstream of the secondary collimator H1 and second is in the remaining downstream region. The first section is 1 m (vertically) and 1.3 m (horizontally) thick on each side of the secondary collimators and 0.6-m around magnets. The second section is 0.65-m (vertically) and 0.95-m (horizontally) thick on each side of the collimators, 0.25-m around dipoles, and 0.4 m (vertically) and 0.7 m (horizontally) around quadrupoles. This reduces residual dose rates below the limits, provides adequate protection of cables and other components in the tunnel and ground water around the tunnel, and equalizes (to some extent) the dirt shielding needed around the entire machine. Therefore, the same external shielding design in the arcs and straight sections is applied. Taking maximum of the normal operation and beam accident cases, the thickness of dirt shielding above the tunnel (with a safety factor of three) is 5.8 m or 19 feet. The maximum dose accumulated in the collimators and hottest spots of the magnet coils reaches 200 Mrad/yr. The maximum yearly dose at cable locations is about 150 krad per year.

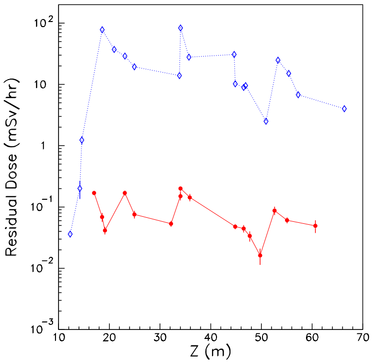

FIGURE 4. Maximum contact residual dose on site surfaces of the PD-II collimation section components (diamonds) and shielding (circles).

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