HIGH-INTENSITY BEAM COLLIMATION AND TARGETRY*

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Abstract

Principles, design criteria and realization of reliable collimation systems for the high-power accelerators and hadron colliders are described. Functionality of collimators as the key elements of the machine protection system are discussed along with the substantial progress on the crystal collimation front. The key issues are considered in design of high-power target systems and achieving their best performance. Simulation code requirements are presented.

INTRODUCTION

It is realized nowadays that high-power accelerators tend to be limited by beam losses, not by current limitations. A certain level of beam losses is unavoidable in any existing or future machine. Beam halo is generated due to beam-gas interactions, intra-beam scattering, beam-beam collisions in the interaction points (IP), particle diffusion due to RF noise, ground motion and resonances excited by the accelerator magnet nonlinearities, power supplies ripple and beam tuning errors, Coulomb and nuclear scattering on injection foils and electrostatic septum wires. As a result of halo interactions with limiting apertures, hadronic and electromagnetic showers are induced in accelerator components causing numerous deleterious effects ranging from minor to severe. An accidental beam loss–caused for example by an unsynchronized abort launched at abort system malfunction–can result in catastrophic damage to the machine equipment. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses in the machine to an allowable level [1].

Beam collimation is mandatory at any high-power beam accelerator (Fermilab complex, SNS, J-PARC, ESS), and superconducting hadron (Tevatron, LHC) and e^+e^- (ILC) colliders. The purpose is to protect components against excessive irradiation, minimize backgrounds in the experiments, maintain operational reliability over the life of the machine (quench stability among other things), provide acceptable hands-on maintenance conditions, and reduce the impact of radiation on environment, both at normal operation and accidental conditions. All collimators must withstand a predefined fraction of the beam hitting their jaws and–at normal operation–survive for a time long enough to avoid very costly replacements.

A target at the end of an extraction beam line is another subject of serious concern at high-power beam facilities. Many physics and engineering constraints should be taken into account when designing a target station with a focusing system for Megawatt beams.

BEAM COLLIMATION

The most direct way of collimating a beam of particles is to define the physical aperture with a solid block of absorbing material. Depending on the energy, material and thickness, a certain fraction of the intercepted beam will survive, either by traversing the whole length of the block or being scattered out of the block. The first component can be reduced by using a longer jaw or a denser material. Suppression of the outscattered particles is much more difficult. For a given material, their yield depends upon the impact parameter Δ and particle energy. Δ grows linearly with the halo transverse diffusion velocity v. At Tevatron, v is about 1.5 μm/s and Δ = 0.1-0.5 μm. This results in a probability of outscattering close to 0.5, *i.e.*, low collimation efficiency.

A way out is to catch the outscattering particles by switching to a *two-stage collimation* system. The whole system consists of a primary *thin scattering target*, followed by a few *secondary collimators* at the appropriate locations in the lattice. The purpose of a thin target is to increase the amplitude of the betatron oscillations of the halo particles and thus to increase their impact parameter Δ on the secondary collimators. At Tevatron, $\Delta \approx$ 0.1-0.3 mm on secondary collimators – almost a factor of 1000 larger than on the primary ones. This results in a significant decrease of the outscattered proton yield, total beam loss in the accelerator and jaw overheating as well as in mitigating requirements to collimator alignment. Besides that, the collimation efficiency becomes almost independent of accelerator tuning. With such a system, there are only several significant but totally controllable restrictions of the accelerator aperture, with appropriate radiation shielding in these regions.

In 1995, based on the MARS-STRUCT simulations, the existing scraper in the Tevatron at AØ was replaced with a new one which had two 2.5-mm thick L-shape tungsten targets with a 0.3-mm offset relative to the inner surface on either end of the scraper (to eliminate the misalignment problem). This resulted in reduction of beam loss rate upstream of both collider detectors by a factor of five, in agreement with the modeling predictions [2].

The system was further improved for Run II [3]. It is fully automated now, and for either proton and antiproton beam it consists of

- L-shaped 2.5-mm thick tungsten primary collimators (“blades”, “targets”) at 5 to 6σ from the beam axis,

* Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH03000 with the U. S. Department of Energy.

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two in high-β regions for betatron cleaning and one in a non-zero dispersion region for momentum cleaning.

- L-shaped 1.5-m long stainless steel secondary collimators located at appropriate phase advances (about 30 and 150 degrees) with respect to their primary partner for the vertical and horizontal planes; they are 1σ farther from the beam than the primary ones and aligned parallel to the envelope of the circulating proton and antiproton beams.

- 1-m long stainless steel adjustable tertiary collimator for the proton beam upstream of the low-β region to catch remedies from the secondary collimators and beam-gas interaction products and to protect the inner triplet and the collider detector at abort kicker prefires.

The main mechanisms of the slow beam-halo growth at the Tevatron are the longitudinal beam loss, beam-gas scattering and elastic part of the proton-antiproton collisions. The collimation system intercepts 99.9% of this halo with a 3×10^7 p/s scraping rate.

One of the primary concerns in the operation of high-power accelerators is machine component radioactivation caused by uncontrolled beam loss [4, 5]. Beam collimation plays a crucial role in minimizing such losses. Major sources of beam loss at Megawatt-class machines (e.g., SNS and J-PARC) include front-end optical abberations; mismatches across the linac due to changes in accelerating structure, frequency, focusing strength, and space-charge resonances; physical and momentum aperture limitations; ring-specific items including injection loss, resonances due to space charge and magnetic errors, and collective instabilities [5]. The beam cleaning at such machines is considered in three categories: (1) H^- halo (stripping foils followed by separation magnetic fields and sets of secondary collimators); (2) proton halo (canonical two-stage collimation for betatron and momentum cleaning); and (3) electron cloud (collection of stripped electrons at injection, beam pipe surface treatment to suppress secondary emission, clearing electrodes to suppress electron production, and solenoid windings to suppress multipacting) [5].

Fig. 1 shows that with the optimal two-stage collimation system, most of the ring can become almost "beam loss-free", or much cleaner anyway, with high loss rate observed only in a dedicated region. In some cases, the length of such a region is not negligible. Multi-component systems described above can occupy a significant fraction of the machine. For example, 25% of the ESS accumulator ring circumference and 25% of the LHC straight sections (two out of eight) are devoted to the collimation systems. The LHC beam cleaning system consists of one hundred collimators (primary, secondary, tertiary, shower absorbers etc) with 500 degrees of freedom total. The efficiency of a well-designed collimation system can be better than 99.9% [1]. Higher beam power or beam energy in new projects can require further improvement of collimation performance.

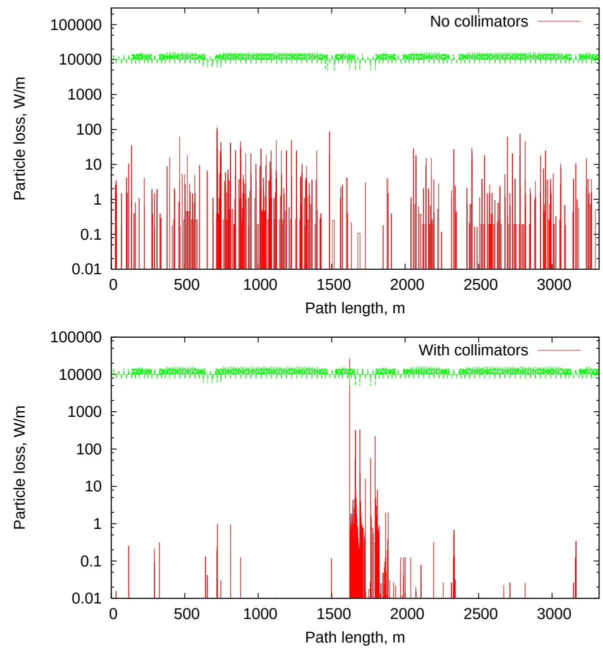

Figure 1: Beam loss distributions in Fermilab Main Injector at slip-stacking injection of 8-GeV protons without collimation (top) and with beam cleaning of 5% of beam intensity (bottom).(STRUCT calculations by A. Drozhdin).

TARGETS

To achieve adequate parameters of secondary beams at any accelerator facility, it is necessary to produce and collect large numbers of particles. Some examples are neutrons at SNS, positrons at linear colliders, antiprotons at Tevatron, and pions/kaons in neutrino experiments. To design high-efficiency target system and achieve its best performance, one needs to address the following issues:

- Production and collection of maximum numbers of secondary particles of interest.

- Suppression of background particles down the beamline.

- Target and beam window operational survivability and lifetime: compatibility, fatigue, stress limits, erosion, remote handling and radiation damage.

- Protection of a focusing system including provision of superconducting coil quench stability.

- Heat loads, radiation damage and activation of components.

- Spent beam handling, and shielding issues from prompt radiation to air and ground-water activation.

These issues are especially challenging for those setups involving intense bunched proton, electron or heavy-ion beams. Most of these issues are addressed in detailed

Monte-Carlo simulations, therefore, predictive power and reliability of corresponding codes are very crucial.

Choice of target material, dimensions, configuration as well as of beam spot size on the target and configuration of the collection system strongly depends on the application. One can mention three types of targets for the following main-stream sub-Megawatt and Megawatt beam applications these days:

- Conventional neutrino experiments: graphite or beryllium segments encapsulated in thin vessels with air or water cooling to generate pion/kaon fluxes decaying into muons and neutrino in a long decay channel.
- Neutrino factory and muon collider projects: tilted mercury jet in high-field solenoids (Fig. 2) aiming again at intense focused fluxes of muons and neutrino [6, 7].
- Spallation neutron sources: large flowing mercury with a reflector/moderator assembly to convert proton beam power into short pulses of low-energy neutrons.

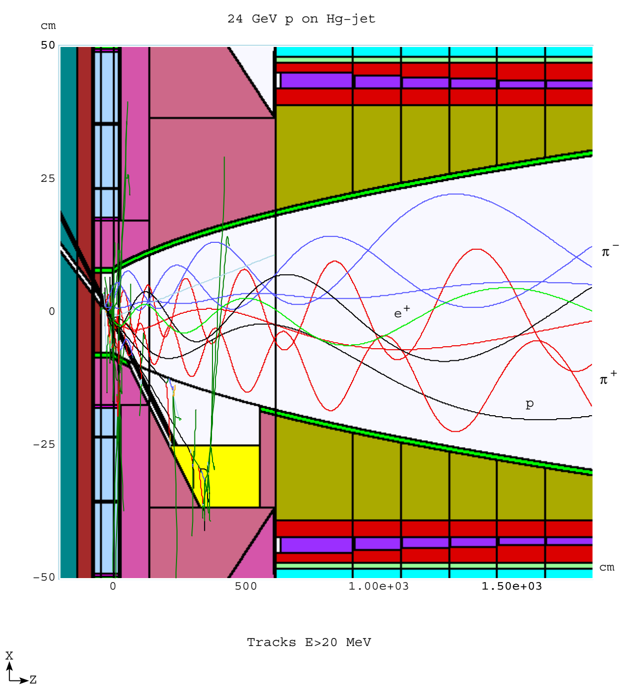

Figure 2: Tilted 24-GeV proton beam on tilted mercury jet target in a 20-T solenoid followed by a matching section with tracks of particles generated and captured.

DESIGN CONSTRAINTS AND RADIATION LIMITS

The design constraints for collimation systems and collimator assemblies at high-power accelerators and hadron colliders include [1]:

- Positioning of the primary collimators in high-β regions for betatron cleaning and in high-dispersion regions for momentum cleaning.
- Positioning of the secondary collimators at the optimal phase advances from the primary ones both for horizontal and vertical scraping.
- Minimal outscattering (halo particle leakage) from a primary-secondary collimator couple for each plane.
- Minimal coupling impedance to the beam (tapering steps and sharp edges, jaw surface conditioning, etc).
- Reliable protection of downstream superconducting and normal magnets against quench and excessive radiation loads.
- The apertures do not occlude any beam when in the garage position.
- Muon vectors downstream do not create any problem to the experiments and environment.
- Local shielding provides protection of groundwater and equipment around the unit, and residual dose rate on its outside is kept below 1 mSv/hr (hands-on maintenance).
- Jaw material withstands normal scraping and accidental conditions (integrity and cooling issues).
- Alignment issues.
- Reliable, precise, robust and radiation-resistant movement system.
- Many other engineering constraints.

Most of the design constraints listed are directly applicable to the targets and target stations.

Although somewhat different at different accelerator sites and in different countries, the following radiation considerations and limits (100 mrem/hr = 1 mSv/hr) should be obeyed while one designs a collimation or target system [4]:

- Hands-on maintenance: the peak residual dose rate $<$ 1 mSv/hr in the tunnel at 1 foot from the local shielding outside surface (after 30-day irradiation and 1-day cooling).
- Radiation levels: prompt dose equivalent in non-controlled areas $<$ 0.5 μSv/hr at normal operation and $<$ 0.01 mSv/hr for the worst case due to accidents; it is $<$ 0.05 mSv/hr for limited access areas.
- Environmental impact: site-specific limits on surface (sump) and ground water activation; site-specific limits on air activation.

- Cooling systems and core material integrity: energy deposition levels in a collimator core are kept below radiation damage and fast/slow heating limits with acceptable dynamic heat loads on the cooling system.
- System lifetime: accumulated absorbed doses in cables, motors and diagnostics are kept below corresponding limits for each the sub-system.

INNOVATIONS

Channeling-Crystal Collimation

At the SSC, an innovative solution was proposed to increase collimation efficiency. It has been shown [8] that it is promising to apply a bent crystal technique to a beam-halo scraping at high-energy colliders. An aligned bent crystal is used to coherently deflect the beam halo particles out into a collimator with a very high deflection per unit length, with little effective septum width. Later calculations [9] have shown that implementation of a silicon bent crystal, instead of amorphous primary collimators (targets), can improve the Tevatron collimation system efficiency by: (1) a factor of two with one (horizontal) target replaced, and with contribution from beam-gas scattering unsuppressed; (2) a factor of three with one (horizontal) target replaced, and with contribution from beam-gas scattering suppressed; and (3) up to a factor of ten for the horizontal scraping itself.

Recently, a dedicated experiment has been conducted at the Tevatron with a horizontal primary tungsten collimator replaced with an “O”-shaped silicon crystal with the bend in a (110) plane [10]. The thickness of the crystal along the beam was 5 mm with the bending angle of 0.44 mrad. The measured channeling efficiency for the 980-GeV proton beam was found to be 78±12% including the effects of multiple passes, with an angular scan being in a very good agreement with results of simulations by the CATCH code. What is most amazing, however, is that the beam loss rate in the CDF detector on the opposite side of the ring (3.15 km from the collimation region) was found to be a factor of two lower than with the original amorphous primary collimator in the full agreement with the expectations described in the previous paragraph for the corresponding case (1). This proof-of-principle experiment confirms the predicted improvement in collimation performance. Preparation for the follow-up experiments are underway.

Radioactivation Reduction with Marble

Massive shielding is needed around collimators while localizing most of the beam losses in a few pre-determined regions. One of the main problems arising there is residual dose rate on the local shielding outer surface and around that drives the hands-on maintenance scenarios. A substantial mitigation of this problem can be achieved by using marble as in recently built collimators for the Fermilab MI-8 beam transfer line [11] and in a newly designed Fermilab Main Injector collimation system.

The lowest activation in materials used in such cases is found in marble ($CaCO_3$, ρ = 2.7 gcc). It was considered for the SSC collimators and dumps and will be used for the LHC beam dumps. The idea is to replace the outer layer of steel shielding with a marble shell. We have found that its optimal thickness is about 10 cm: there is negligible activation in marble itself, and it provides 1/10 attenuation for 1-MeV photons leaking from the hot steel core. As one can see from Fig. 3, residual dose is reduced by tens times with such a replacement. One needs to be sure, however, that impurities in the material do not become so radioactive as to negate these advantages. Fortunately, none of the impurities found in real marble used in [11] deteriorate the marble properties exploited here.

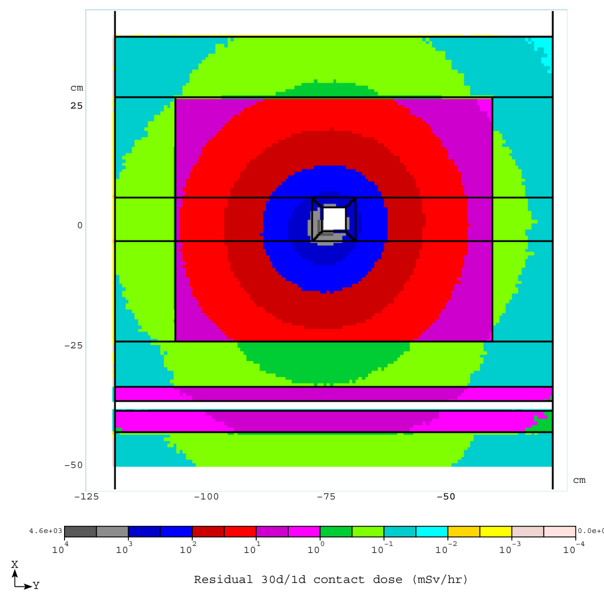

Figure 3: Residual dose transverse isocontours in the MI-8 collimator at longitudinal maximum after 30 days of irradiation at 5×10^{11} p/s and 1 day of cooling. The marble regions on the steel core outside are where the color is light-blue and green (less than a fraction of mSv/hr levels).

SIMULATION CODE REQUIREMENTS

Only with a very reliable and accurate simulation code based on modern physics models and data can one perform computer modeling to meet the needs of collimation and target system designs for Megawatt beam projects. It is a modern approach for accelerator complexes like LHC and J-PARC to build a realistic model of the machine for multi-turn beam loss, energy deposition and activation studies: read in MAD lattice, create complete geometry and magnetic field model in the framework of such codes as FLUKA, MARS and GEANT. Among the most important features of the corresponding simulation codes are:

- Reliable description of cross-sections and particle yields from a fraction of eV to many TeV for hadron, photon and heavy-ion projectiles (event generators).

- Precise modeling of leading particle production and low-momentum transfer processes (elastic, diffractive and inelastic).
- Reliable modeling of π^0-production (electromagnetic showers), K^0-production (neutrinos), proton-antiproton annihilation, and stopped hadrons and muons.
- Nuclide inventory, residual dose, displacement-per-atom (DPA), hydrogen and helium production.
- Precise modeling of multiple Coulomb scattering with projectile and target form-factors included.
- Reliable and CPU-efficient modeling of hadron, lepton and heavy-ion electromagnetic processes with knock-on electron treatment and–at high energies–bremsstrahlung and direct pair production.
- Full accurate modeling of electromagnetic showers with hadron/muon photo-production.
- Accurate particle transport in arbitrary geometry in presence of magnetic fields with objects ranging in size from microns to kilometers.
- User-friendly geometry description, histograming and Graphical-User Interface.
- Interfaces to MAD, ANSYS and hydrodynamics codes.

The experience says that such realistic modeling takes time and substantial efforts but always pays off.

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