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Solving Radiation Problems at Particle Accelerators*

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Abstract

At high-intensity high-energy particle accelerators, consequences of a beam-induced radiation impact on machine and detector components, people, environment and complex performance can range from negligible to severe. The specifics, general approach and tools used at such machines for radiation analysis are described. In particular, the world leader Fermilab accelerator complex is considered, with its fixed target and collider experiments, as well as new challenging projects such as LHC, VLHC, muon collider and neutrino factory. The emphasis is on mitigation of deleterious beam-induced radiation effects and on the key role of effective computer simulations.

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1 Introduction

In general, the origin of most of the radiation problems at particle accelerators is operational or accidental beam loss [1]. A fraction of beam lost under normal operation results in radiation load to the machine and detector components, shielding and environment. A localized accidental beam loss can cause severe damage to the machine equipment with an unacceptable impact on the environment. The strategy adopted in existing machines and in new designs is to localize and control beam losses as much as possible via the use of beam collimation systems, with a high loss rate localized at the collimation and drastically reduced beam loss rates in the rest of the lattice. This strategy provides adequate protection of superconducting and conventional machine and detector components, and minimizes the overall radiation effects [2, 3]. The beam transport and loss analysis at high-intensity high-energy particle accelerators is fundamentally important because of the impact on machine performance, conventional facility design, maintenance operations, and related costs. The specific radiation effects are determined by physics of hadronic and electomagnetic cascades with particle energies ranging from many TeV down to a fraction of an electronvolt [4, 5]. Thorough Monte Carlo calculations of prompt and residual radiation caused by particle cascades in and around the accelerator components are done for realistic assumptions and geometry under normal operation and accidental conditions [6]. This allows one to conduct shielding design and analysis to meet regulatory requirements for external shielding, hands-on maintenance and groundwater activation.

2 Regulatory Requirements and Design Goals

Comprehensive radiation protection programs at all accelerator centers, and at Fermilab in particular, include all components needed to keep the radiological impact on the work place and to the environment As Low As Reasonably Achievable (ALARA): a stringent set of radiation limits and design goals for off and on-site radiation exposure, the quantification of radiation source terms, the specification of shielding design criteria, appropriate radiation instrumentation, provision for access, control of residual activation and proper management [7, 8]. Regulatory requirements and design goals include:

1. Prompt radiation: the criterion for dose rate in non-controlled areas on accessible outside surfaces of the shield is 0.05 mrem/hr at normal operation and 1 mrem/hr for the worst case due to accidents [9]. Currently, one requires that the machine designers describe and justify what a possible "credible worst case accident" is, and design the shielding—or modify operation of the machine—accordingly.

2. Hands-on maintenance: residual dose rate of 100 mrem/hr at 30 cm from the component surface, after 100 day irradiation at 4 hrs after shutdown. The averaged dose rate should be less than 10-20 mrem/hr.

3. Ground-water activation: maximum radionuclide concentration limits $C_{i,reg}$ of 20 pCi/ml for ^{3}H and 0.4 pCi/ml for ^{22}Na cannot be exceeded in any nearby drinking water supplies. The sum C_{tot} of the fractions of radionuclide contamination (relative to regulatory limits $C_{i,reg}$) must be less than one for all radionuclides.

Additionally, one sets an the accumulated dose of 20 Mrad/yr, or 400 Mrad over 20 years lifetime in the hot spots of machine components, as an approximate *radiation damage* limit for such materials as epoxy and cable insulation.

3 Controlling Beam Loss

These days, a very reliable multi-component beam collimation system is mandatory at any high-power accelerator, and at superconducting colliders (Tevatron, LHC, VLHC), in particular. Such a system provides [6, 7, 8]: 1) reduction of beam loss in the vicinity of beam-beam interaction points to sustain favorable experimental conditions; 2) minimization of the radiation impact on personnel and environment by localizing beam loss in the predetermined regions and using appropriate shielding in these regions; 3) protection of accelerator components against irradiation caused by operational beam loss and enhancement of reliability of the machine; 4) prevention of quenching of SC magnets and protection of other machine components from unpredictable abort and injection kicker prefires/misfires and unsynchronized abort. During the early Tevatron operations, the first collimation system [10] was designed on the basis of full-scale simulations using the MARS code [11]. The system, consisted of primary and secondary collimators, and after installation immediately made it possible to raise, by a factor of five, the efficiency of fast resonant extraction and the intensity of the extracted 800 GeV proton beam. The data on beam loss rates and their dependence on the collimator jaw positions were in an excellent agreement with the calculated predictions. Modern 3-stage collimation systems, at Megawatt setups (such as the Spallation Neutron Source and the Fermilab Proton Driver) and at multi-TeV superconducting colliders, allow localization of more than 99% of all beam loss in special straight sections.

4 Radiation Analysis

All high-intensity accelerators and experimental halls are placed underground. The shielding analysis for the beam transport lines, arcs and long straight sections is performed both for normal operation and for accidental beam loss. The simplest operational scenario is a 1 W/m beam loss rate distributed uniformly along the beam line. A more realistic scenario is based on the beam loss distributions calculated with a beam collimation system which provides the average rates in the arcs of about 0.2 W/m at the top energy and less than 0.05 W/m at injection. For the worst case catastrophic *incredible* accident one assumes a loss of the full beam at a quasi-local spot. The worst *credible* accident limits the amount of beam lost to 0.1% of that in the *incredible* case. Local shielding is provided around any components where radiation limits of any type are exceeded. This local shielding equalizes (to some extent) the source term used to estimate the average dirt shielding around the entire machine. The thickness of tunnel concrete walls required to avoid ground water activation is in a 0.4 to 2 m range. The typical thickness of dirt shielding around tunnels is about 6 meters for conventional radiation. Fig. 1(left) shows an example of a JAERI 3 GeV ring shielding design, based on a full-scale MARS study. The shielding thickness can be significantly larger if it is required to contain muons: up to several kilometers of dirt downstream of the beam absorbers, and up to several hundred meters radially outward from the arc tunnel enclosure [12]. A unique case of a neutrino-induced radiation is considered in Section 7.

A typical representative of a fixed target experiment of a new generation is the NuMI-MINOS project at Fermilab, with about 3.7×10^{20} 120-GeV protons on target per year. The primary beam is aimed downward at an angle of 3.3 degrees to direct a neutrino beam toward the Soudan Underground Laboratory in Minnesota some 730 km to the Northwest of Fermilab. The pions and kaons decay to muons and neutrinos in a long decay region before being absorbed. Extensive calculations have been performed to design a sophisticated target and focusing system, external shielding, beam absorber, residual activation of components, and soil and groundwater activation. Finally, the experimental halls at the colliders represent unique challenges. Here, the simulations have to be particularly accurate because of the huge size of these underground enclosures.

5 Energy Deposition

Beam-induced effects grow roughly linearly with particle energy. Beam intensities in multi-TeV machines will be as high as 10^{15} protons per pulse, resulting in beam energies of hundreds MJ to several GJ. A circulating beam size will be less than a fraction of a millimeter. Therefore, interaction of even a tiny fraction of such beams with accelerator and detector components results in macroscopic effects: quenching of superconducting magnets, unacceptable temperature rise, melting, shock wave creation destructing the components, density reduction at an absorber and target axis up to a continuous hole drilling, fast buildup of radiation defects deteriorating mechanical and electrical properties and damaging multi-million electronics components etc. For example, the proposed 20 TeV VLHC beam will carry enough energy that in principle it could liquefy 400 liters of steel anywhere in the 233-km ring. Based on thorough Monte Carlo studies, numerous measures have been proposed to mitigate these effects [1, 13]: highly reliable beam abort systems, highly efficient beam collimation systems, beam sweeping systems, light materials (sparse graphite) for targets and absorbers, liquid jets and rotating bands for targets, graphite shadow

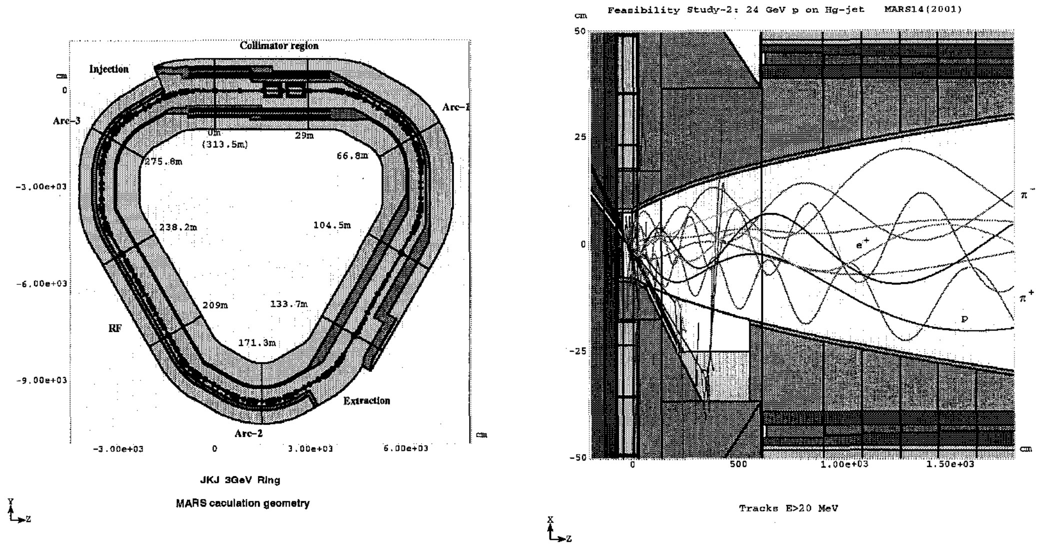

Figure 1: The 3 GeV JKJ ring lattice, collimators and shielding as described in the MARS model (left) and a fragment of the MARS model of a neutrino factory target/capture system with tilted 24 GeV proton beam, mercury jet and secondary particle tracks (right).

masks and sacrificial objects in front of the crucial components, new radiation resistant materials and electronics, special shielding and arrangement for expensive electronics components.

An interesting example is a target/capture system for a muon collider and neutrino factory, designed for a 1 MW proton beam of 24 GeV energy (upgradable to 4 MW) [14] (see Fig. 1(right)). The system starts with a proton beam impinging on a thick liquid target sitting in a high-field hybrid solenoid (20 T, about 1-m long, aperture radius R_a=7.5 cm), followed by a matching section and a superconducting solenoid decay channel (1.25 T, 50-100 m in length, R_a=30 cm) which collects muons resulting from pion decay. The beam intensity is 1.7×10^{13} ppb $\times6$ $\times2.5$ Hz = 2.55×10^{14} p/s, resulting in 5.1×10^{21} p/yr at 2×10^{7} s/yr. A sophisticated solenoid coil shielding, 38 m long and 1.8 m radius is made of water-cooled tungsten-carbide balls at z<6 m and water-cooled copper at z>6 m. A proton beam (σ_x=σ_y=1.5 mm, σ_z=3 ns, 67 mrad) interacts with a 5 mm radius mercury jet tilted by 100 mrad, which is ejected from the nozzle at z=-60 cm, crosses the z-axis at z=0 cm, and hits a mercury pool at z=220 cm, x=-25 cm. With such a beam-jet crossing, about 97% of protons have a probability to interact with target material, generating pions and resulting in significant energy deposition in material that can at some conditions destroy solid or liquid target. A 8-cm wide mercury pool (210<z<550 cm) is a core of a sophisticated spent beam absorber. The coil shielding provides an adequate protection, experiencing itself huge radiation loads of about 50 GGy/yr of maximum accumulated dose and 1 kSv/hr of residual dose rate.

6 Detector Backgrounds

At $p\bar{p}$, $e^+e^-$and $\mu^+\mu^-$colliders the combined effect of the radiation environment produced by beam-beam collisions and by beam losses is one of the key issues in the design of the interaction region and detectors [15]. Particles originating from the interaction point (IP) and the cascades initiated by them are known to be the major source of background and damage in the detectors at hadron colliders, in the experimental halls and in the final focus triplets. Beam loss in the IP vicinity is the second source of background, and will dominate at future $e^+e^-$and $\mu^+\mu^-$colliders. The overall collider detector performance is strongly dependent on the details of the machine-detector interface. Efforts were made at Fermilab to optimize the DØ and BØ interaction regions. Over the last 14 years, MARS has been used to help design shielding, collimators and other items in an effort to reduce radiation levels in the DØ experimental hall due to 2 TeV $p\bar{p}$-collisions and beam losses; measurements of prompt and residual radiation after such items were installed have been in excellent agreement with the predictions. Both the *pp*- and accelerator-related backgrounds in the LHC detectors for the 7 TeV beams have been studied in detail with the FLUKA [16] and MARS codes. The necessity for sophisticated collimators and significant amount of shielding has been proven [15, 17] and these were implemented into the design. A serious study of radiation and background environments has been recently done with the MARS code for the Fermilab E-872 experiment (DONUT) for the direct observation of ν_τ. A very complex shielding design around a 800 GeV tungsten beam dump, through passive and active magnetic elements in a 60 m long channel, up to a nuclear emulsion target, followed by a spectrometer, was optimized to reduce the background levels by a factor of 50 to 100. The MARS calculations were verified at several stages with dedicated measurements.

7 Neutrino-Induced Radiation

New proposals for muon colliders and storage rings (neutrino factories) are actively under study, and—surprisingly—neutrinos play an increasingly important role in radiation physics problems [12]. Neutrinos interacting in the human body or its immediate surroundings produce charged particles which may cause biological harm. These neutrinos propagate almost tangentially to the muon direction in a relatively narrow disk with negligible attenuation. The dose at a given location grows with muon energy roughly as E^3 due to three factors: increase with E of the neutrino interaction cross section, and of total energy deposited while the decay angle decreases roughly as m_μ/E. The transverse dimensions of the neutrino disk may be smaller than human dimensions and one must distinguish between *maximum* and *whole body dose* which has legal as well computational ramifications. A useful concept is that of *equilibrium* dose, i.e. dose is proportional to neutrino fluence in the vicinity of its maximum. This applies when a minimal thickness of material (a few meters of soil or equivalent) is present immediately upstream of the volume to which dose is delivered so as to allow the ν-induced cascades to develop fully in the material. The 'non-equilibrium' dose, calculated for a bare phantom, is much less than the equilibrium dose—a factor of three at 1 GeV and up to three orders of magnitude for 10 TeV neutrinos. Neutrino doses become surprisingly large for some of the more ambitious muon devices contemplated. For proposed muon storage rings located underground, the off-site dose limit of 0.1 mSv/yr is met 50 m outward from the arc tunnel, but downstream of a 600-m long straight section only at 1.8 and 4.2 km for the 30 and 50 GeV muons, respectively (Fig. 2(left)). Fig. 2(right) shows the large distances (up to 60 km) needed to reduce neutrino dose to this level around a high energy $\mu^+\mu^-$collider, requiring placement such a ring at about 250-m depth. An additional requirement for 'unaccessible pencil' hundreds kilometers long and several meters in diameter downstream of the straight sections, implies building of such a machine in a desert or at an isolated island or a mountain. Significant mitigation can be achieved by beam wobbling, i.e., by expressly perturbing the orbit in the vertical plane to achieve the necessary dilution in dose delivered off-site. This wave or perturbation is expected to vary in strength and phase over the course of a year—perhaps aided by feedback from detectors in the field—so as to stay everywhere under the limit.

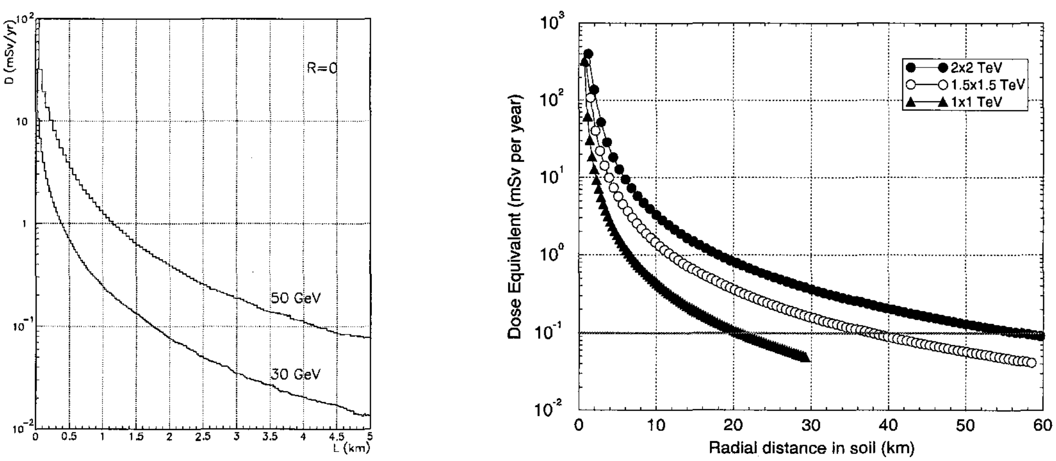

Figure 2: Annual maximum dose equivalent (mSv/yr) in a phantom embedded in soil *vs* distance downstream of 30 and 50 GeV muon storage ring straight sections (left) and in a $\mu^+\mu^-$collider orbit plane with 1.2×10^{21} decays per year *vs* distance from ring center (right).

8 Monte Carlo Codes

The key role of effective computer simulations of the accelerator radiation environment is quite obvious from that described in this paper. Earlier versions of the main Monte Carlo codes used in this field—CASIM [18], FLUKA [16] and MARS [19]—provided adequate tools for conventional shielding design and basic study of high-energy cascades [4, 20, 21]. Modern versions—MARS14 and FLUKA—allow complete simulation of hadronic and electromagnetic cascades in an arbitrary 3-D geometry of shielding, accelerator and detector components with energy ranging from a fraction of an electronvolt up to 100 TeV. The MARS14 code [11] combines the best theoretical models for strong and electromagnetic interactions of hadrons and leptons with a system which can contain up to 10^5 objects, ranging in dimensions from microns to hundreds kilometers, made from up to 100 composite materials, with arbitrary 3-D magnetic and electric fields, and a powerful user-friendly Graphical-User Interface for visualization of the geometry, materials, fields, particle trajectories and results of calculations. Many processes in MARS14—such as electromagnetic showers, most of hadron-nucleus interactions, decays of unstable particles, emission of synchrotron photons, photohadron production, $\gamma Z \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \mu^+\mu^-$—can be treated either analogously or inclusively with corresponding statistical weights. Many variance reduction techniques are implemented in the code. It also includes physics of the MCNP4C2 code for low-energy neutron transport, and interfaces to ANSYS for thermal and stress analyses, MAD for accelerator and beam-line lattice description, and STRUCT for multi-turn particle tracking in accelerators. The reliable performance of the code has been demonstrated in numerous applications at Fermilab, CERN, KEK and other centers as well as in special international benchmarking in the framework of SARE/SATIF meetings.

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