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Abstract

Beam halo scraping schemes have been explored in the 50×50 GeV and 2×2 TeV $\mu^+\mu^-$ colliders using both absorbers and electrostatic deflectors. Utility sections have been specially designed into the rings for scraping. Results of realistic STRUCT-MARS Monte-Carlo simulations show that for the low-energy machine a scheme with a 5 m long steel absorber suppresses losses in the interaction region by three orders of magnitude. The same scraping efficiency at 2 TeV is achieved only by complete extraction of beam halo from the machine. The effect of beam-induced power dissipation in the collider superconducting magnets and detector backgrounds is shown both for the first few turns after injection and for the rest of the cycle.

Introduction

High background rates in the detectors are one of the most serious problems on the road towards a high-luminosity $\mu^+\mu^-$ collider [1, 2]. It was shown at an early stage [3] that detector backgrounds originating from beam halo can exceed those from decays in the vicinity of the interaction point (IP). Only with a dedicated beam cleaning system far enough from the IP can one mitigate this problem [4]. Muons injected with large momentum errors or betatron oscillations will be lost within the first few turns. After that, with active scraping, the beam halo generated through beam-gas scattering, resonances and beam-beam interactions at the IP reaches equilibrium and beam losses remain constant throughout the rest of the cycle. Two beam cleaning schemes are studied in this paper: beam halo extraction with an electrostatic deflector and standard collimation (see Fig. 1,2). The resulting effect on the

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superconducting (SC) magnets and detector backgrounds is described in detail for a 50×50 GeV $\mu^+\mu^-$collider, plus some results and conclusions for the 2×2 TeV case (see for more details [4]).

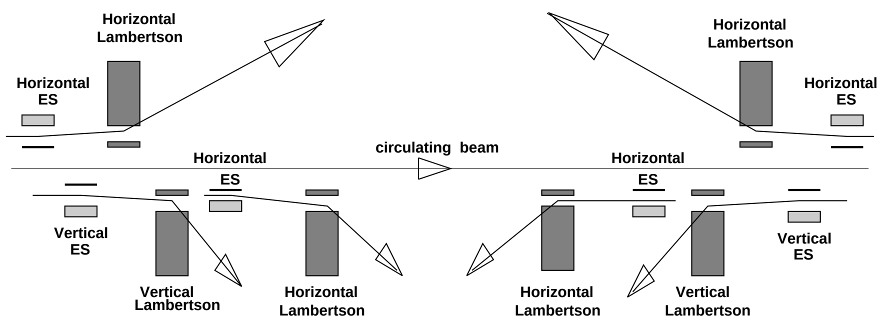

Figure 1: Schematic view of a $\mu^+\mu^-$collider beam halo extraction.

Beam Halo Extraction

A 3-m long electrostatic deflector (Fig. 1) separates muons with amplitudes larger than 3σ and deflects them into a 3-m long Lambertson magnet, which extracts these downwards through a deflection of 17 mrad. A vertical septum magnet is used in the vertical scraping section instead of the Lambertson to keep the direction of extracted beam down. The shaving process lasts for the first few turns. To achieve practical distances and design apertures for the separator/Lambertson combinations, β-functions must reach a kilometer in the 2-TeV case, but only 100 m at 50 GeV. The complete system consists of a vertical scraping section and two horizontal ones for positive and negative momentum scraping (the design is symmetric about the center, so scraping is identical for both μ^+ and μ^-). Always, the halo is extracted down into the ground downstream of the utility section (US).

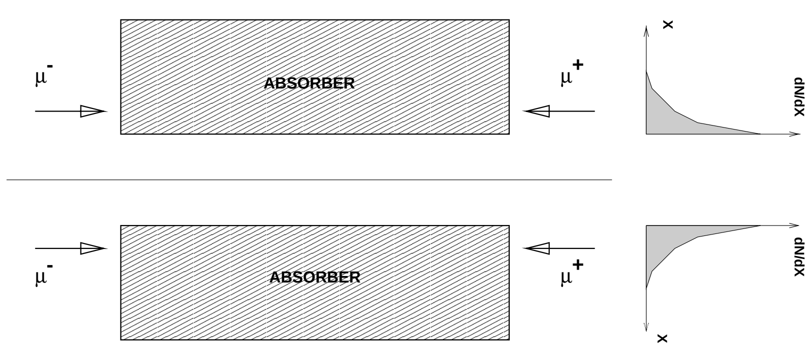

Figure 2: Scraping muon beam halo with a 5-m steel absorber.

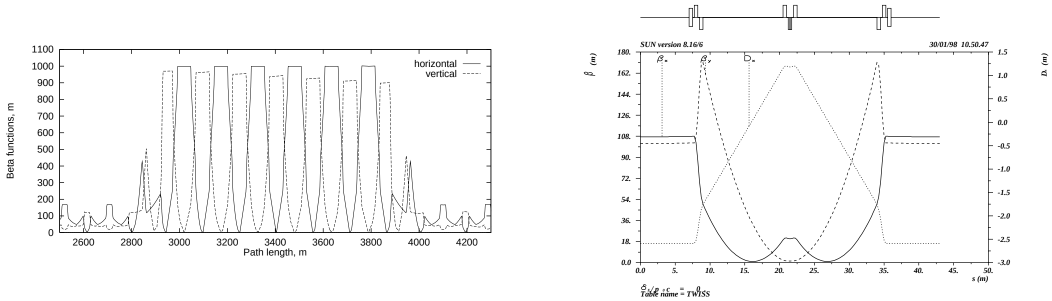

Figure 3: Lattice of the $\mu^+\mu^-$collider utility section: (a) 2×2 TeV with halo extraction; (b) 50×50 GeV with halo collimation.

Three possible layouts were investigated. The first consisted of two horizontal electrostatic deflectors (not shown in Fig. 1) separated by 180° in phase (the second deflector is in the shadow of the first) and using the same Lambertson magnet for extraction. The horizontal deflectors are followed by a vertical one which uses a septum magnet. After vertical scraping, a second horizontal scraping system is inserted, but on the opposite side of the US. The first horizontal deflection scrapes off-momentum muons with momenta greater than the central momentum. The second scrapes muons with lower-than-average momentum. The entire scraping layout has reflection symmetry about the center to make scraping identical for μ^+ and μ^-. This scheme is designed and found to be optimal for a 2×2 TeV $\mu^+\mu^-$collider [4]. Using only one horizontal electrostatic deflector with the Lambertson magnet (Fig. 1) instead of two, gave a calculated efficiency which was several times lower. A final combination consisted of electrostatic deflectors and the Lambertson magnets tangent to the edge of the beam horizontally on both sides in a single high-β region (Fig. 3(a)). Its efficiency was somewhere between the first two layouts. Its advantage, however, is that it is much more compact, occupying only three large high-β regions. Therefore, it is best suited to the compact 50×50 GeV $\mu^+\mu^-$collider.

Realistic Monte-Carlo simulation of beam halo effects is done in three stages. Primary muon interactions with electrostatic deflector wires (or collimator in the

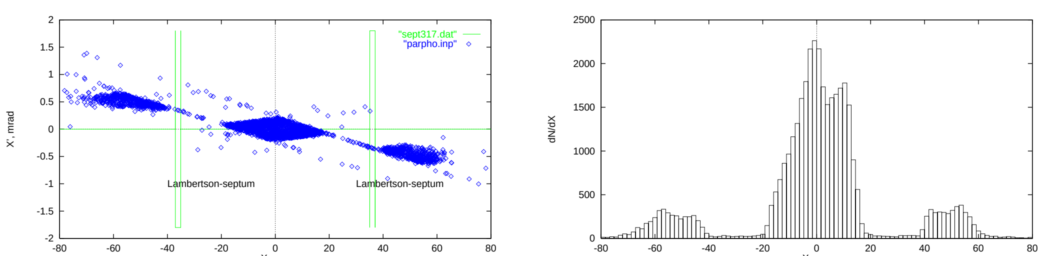

Figure 4: 50 GeV/c muon halo distributions in horizontal plane at the Lambertson magnet entrance in the symmetric scheme.

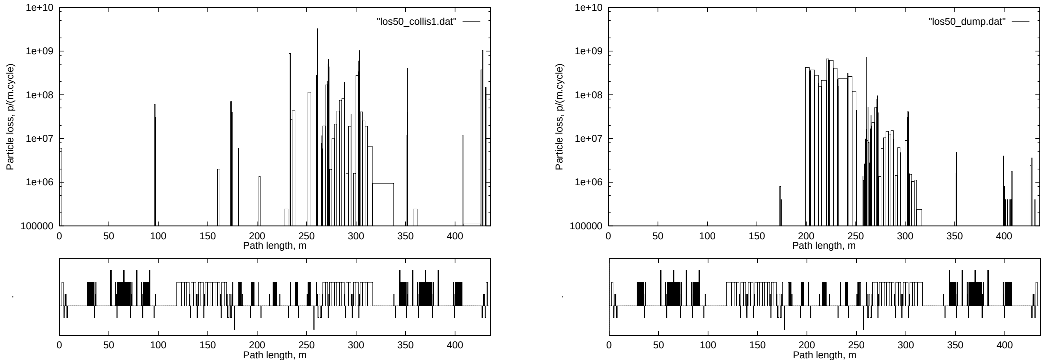

Figure 5: 50 GeV muon beam loss distributions at collisions with halo extraction (left) and halo collimation with the internal absorber (right). 1% of the beam intensity is intercepted.

other approach to scraping which is described in a later section) are simulated using the MARS13(97) code [5]. Multi-turn tracking of muons scattered out of the deflector (or collimator) in the collider lattice and analysis of their loss in the collider elements is done using the STRUCT code [6]. For the third stage, a full hadronic and electromagnetic shower simulation in collider and detector elements is performed after returning to the MARS13(97) code. A 8.5σ aperture is assumed in the arcs (85π and 50π mm-mr normalized rms emittance at 50-GeV and 2-TeV, respectively) and only 5σ in the interaction region (IR). The aperture is enlarged to $>8.5\sigma$ in the scraping section. To protect the IR magnets against irradiation, the aperture of tungsten insertions between the magnets is 4σ as in [7, 8]. Only the halo muons with betatron amplitudes of 2.5 to 4σ and with $\sigma_{\Delta p/p}$=0.0004 are used in these simulations. Deflector septa (wires) are placed at 12.65 mm from the closed orbit to shave both halo and large-amplitude muons and also muons with positive and negative momentum deviations. In the distance from one high-β region to the next, halo muons are sufficiently separated from the circulating beam (Fig. 4) to be cleanly extracted by a Lambertson magnet. Extracting large-amplitude and off-momentum muons decreases dramatically beam loss in the IR. Calculations show that 83% of halo is extracted from the collider over the first few turns. About 30% of beam halo pass through the electrostatic deflector wires. These muons loose on average 0.6% of their energy and are lost at the limiting apertures along the collider, mostly in the first 70 m after the US (see Fig. 5). About 4% of halo muons just get an angular (amplitude) kick without noticeable momentum loss and are lost in the IR resulting in detector background. Assuming the interception of 1% of the circulating beam in the beam cleaning process, 8×10^8 muons are lost in the final focus quadrupoles (just a few meters from the IP) over the first few turns after injection. After that, the scraping system becomes very efficient as beam halos are regenerated by beam-gas and beam-beam scattering, ground motion and resonances. The step size (particle betatron amplitude rise during one turn) at this process is of the order of a few μm. Because of that, disturbed muons will interact first with the electrostatic deflector wires. According to the simulations, 60% of regenerated halo is extracted from the collider, with only 4.6% of the scraped muons passing through the material of the low-β quadrupoles.

Beam Halo Collimation

An alternative scheme is to collimate the halo using a solid absorber (Fig. 2). Our studies [4] showed that no absorber, ordinary or magnetized, will suffice for beam cleaning at 2 TeV; in fact the disturbed muons are often lost in the IR. At 50 GeV, on the other hand, collimating muon halos with a 5-m long steel absorber (Fig. 2) in a simple compact US (Fig. 3(b)) does an excellent job. As Fig. 6 shows, muons loose a significant fraction of their energy in such an absorber (8% on average) and have broad angular and spatial distributions. Therefore, almost all of these muons are lost in the first 50-100 m downstream of the absorber as shown in Fig. 5, with only 0.07% of the scraped muons reaching the low-β quadrupoles in the IR. This is 60 times better than with the halo extraction scheme. At the same time, the peak beam loss in SC magnets downstream of the US is six times higher compared to the halo extraction (Fig. 5). Without halo scraping, a full 1% of the beam is lost in the IR, i.e., the collimation system reduces beam loss in the IR by almost a factor of 1500. One percent of the steady-state beam loss on the collimators results in a total of 1.4×10^7 muons lost in the low-β quadrupoles during the cycle. Halo collimation has a further advantage in that the lattice required (Fig. 3(b)) is shorter and simpler compared to Fig. 3(a). It could, in fact, be placed in the matching sections on either side of the IP leaving the US for injection and extraction and reducing the overall accelerator circumference.

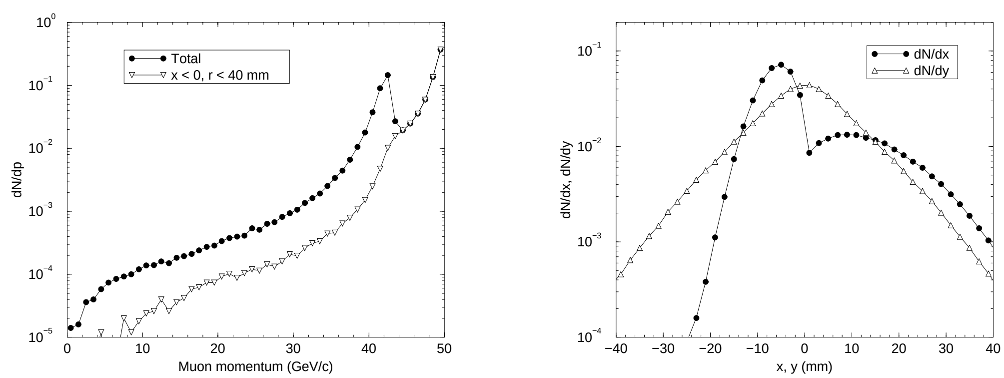

Figure 6: Muon leakage from a 5-m steel half-absorber for 50 GeV/c muon beam: (a) Momentum spectrum; (b) Space distributions.

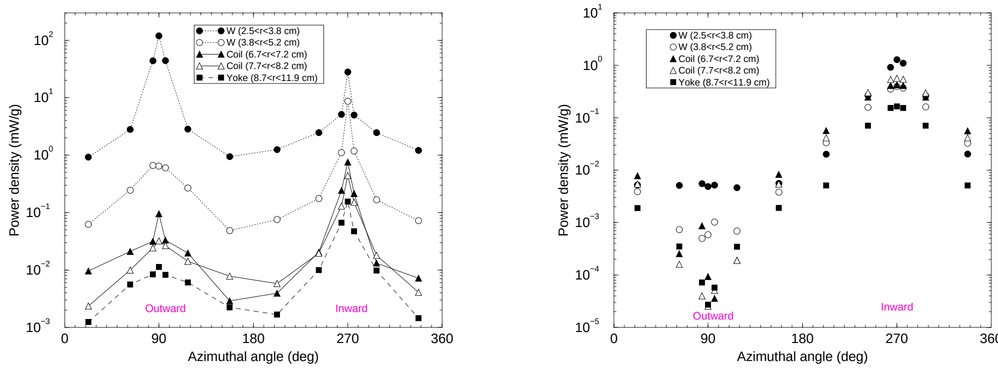

Figure 7: Azimuthal distributions of power density in the ring SC dipoles for 50 GeV/c muon beam: (a) Beam decays; (b) Scraping with the absorber.

Effect on SC Magnets and Detector

As shown in [1, 7, 8], to protect the SC coils of a 2×2 TeV $\mu^+\mu^-$collider from the excessive heat load due to unavoidable muon decays, a tungsten absorber (liner) of up to 6 cm thick is required inside the SC magnets. Our new calculations for a 50 GeV machine with 3.3×10^{12} μ/bunch at 15 Hz, show that such a liner should be 3 to 4 cm thick. The power density distribution in the SC magnet components is strongly non-uniform azimuthally (Fig. 7), so an alternative design would be with cold or warm iron and SC coils completely separated on the mid-plane [1]. If one takes the liner approach, then a 3-4 cm thick tungsten absorber protects the SC magnets at 50 GeV even where the beam loss peaks, which is just downstream of the US. Opposite to the decay-induced heat load, the power density from scraping peaks on the one, in-

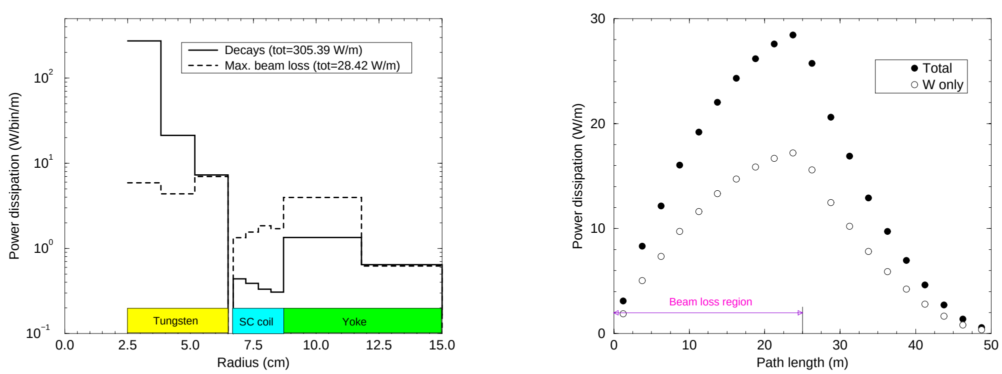

Figure 8: Power dissipation in the ring SC dipoles for 50 GeV/c muon beam: (a) Radial distribution for beam decays and beam halo; (b) Longitudinal distribution for beam halo.

ner, side of the magnet aperture relative to the ring center (Fig. 7), and more power is dissipated deeper in the magnet body (Fig. 8(a)). As Fig. 8(b) shows, at 50 GeV halo muons are absorbed in the lattice elements within about 30 m after the beam loss region. With a collimator-based scraping system, this occurs within a 100 m region downstream the US. Another words, with such a system on the opposite side of the ring from the IR, halo-induced detector backgrounds are not an issue in the 50×50 GeV $\mu^+\mu^-$collider.

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