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Machine Detector Interface and Beam-Induced Background Studies for a 10 TeV Muon Collider

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Muon colliders present a unique opportunity to achieve unprecedented center-of-mass energies in lepton collisions. Unlike electrons, muons are not significantly affected by synchrotron radiation, allowing them to be accelerated and collided at higher energies. Additionally, since muons are elementary particles, issues related to partonic effects are eliminated. However, the use of muons introduces several significant challenges. The primary concern addressed in this paper is the impact of muon decay products on the collider's components and the experimental background. We also thoroughly examine other background sources, with a focus on incoherent pair production during bunch crossings. To manage the substantial radiation produced, we propose a shielding strategy for the final focusing elements, detailing its implications on the lattice design. For the detectors, we outline a potential shielding component (nozzle) designed to minimize the background that reaches the experiment.

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1. Introduction

The development of a muon collider presents unique challenges and opportunities for advancing high-energy particle physics [1, 2]. The feasibility of 10 TeV center-of-mass muon collider is presently being studied by the International Muon Collider Collaboration [2]. Central to the success of such a collider is the design of the Machine Detector Interface (MDI), which plays a critical role in guaranteeing optimal conditions for both the detector operation and the integration of the detector with the interaction region [3–7]. A key aspect for the MDI design is the reduction of the beam-induced background (BIB), which is formed by muon decay, beam-beam interactions (incoherent pair production), and beam halo losses on the aperture.

A crucial shielding element for mitigating the decay background in high-energy muon colliders is a conically-shaped nozzle, which was originally conceived during the US-Muon Accelerator Program (MAP) [3, 4, 8]. The nozzle comprises a thick, dense core made of a high-Z metal, which efficiently absorbs electromagnetic showers induced by the muon decay products. Surrounding this core is a cladding of borated polyethylene, which enhances the shielding effectiveness by capturing secondary neutrons. Previous optimizations focused on maximizing the nozzle's performance for collision energies up to 1.5 TeV [3, 4, 9]. First BIB studies for a 10 TeV collider, which still considered the same MAP nozzle design, were presented in our previous papers [5, 7]. In this contribution, we will discuss a first adjustment of the nozzle for 10 TeV, with an optimized multi-layer design to minimize the photon background. In addition, we consider the latest 10 TeV interaction region lattice design, which has undergone a significant evolution in the past years [10], including adjustments aimed to reduce the BIB.

2. Interaction region and MDI design

2.1 Lattice design

The evolution of the optics in the interaction region and final focusing (FF) section has been a critical aspect of the muon collider design, reflecting ongoing efforts to enhance beam control and reduce the background at the IP. Initial optics versions featured a chromaticity correction section placed immediately after a final focus triplet. This configuration faced limitations in controlling the overall chromaticity of the beam [11]. Following versions included a long drift section to improve the chromaticity control by smoothly reducing the β-function. However, while this change significantly improved the Montague's functions, it significantly increased the decay-induced background. As a mitigation measure, a dipole chicane was introduced immediately upstream of the final focus section. This chicane reduces the decay background by steering unwanted decay products from the drift on the aperture before they could reach the final focus region. The latest lattice version including chicane is shown in Fig. 1.

2.2 Adjustment of the MAP nozzle design

The MAP-based nozzle design served as a basis in our previous studies [5], in order to validate the simulation framework and to study the effect of the lattice design on the decay-background. In this paper, we propose a slightly adjusted nozzle design, which features a multi-layered structure, beginning with an INERMET180® core, a high-density tungsten alloy, easier to manufacture

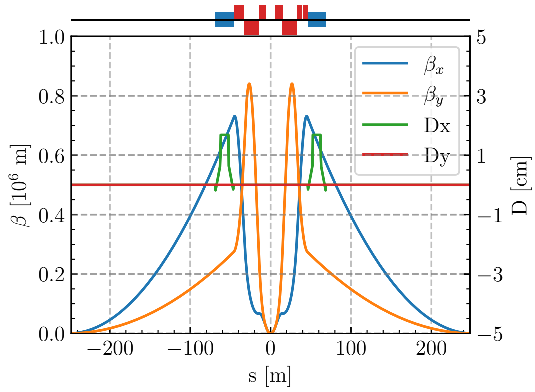

Figure 1: IR lattice and optics functions used in the present studies. Immediately after the final focus there is a set of three dipoles forming a chicane, followed by a long drift.

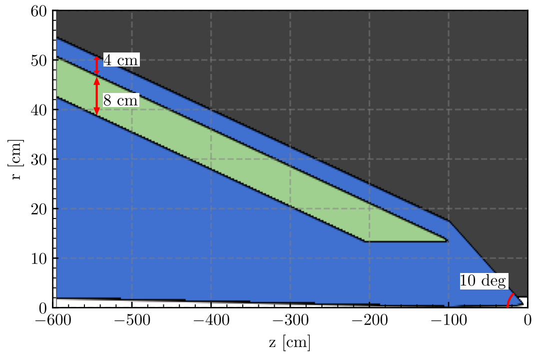

Figure 2: Nozzle design adopted for the BIB simulations. The two material considered are INERMET180® (in blue) and boron polyethylene (in green).

compared to the pure tungsten used in earlier designs, with a density of 18 g/cm^3. This core serves as the primary barrier against radiation, absorbing high-energy particles produced during muon decays. A layer of borated polyethylene, specifically designed to moderate and capture neutrons, encases the core. The outermost layer of the nozzle is once again made of INERMET180®, which absorbs characteristic gamma rays emitted after neutron capture. This cladding reduces the low energy photon background by a factor 2. The geometric layout of the elements is shown in Figure 2.

3. Beam induced backgrounds

A unique type of background, characteristic of muon colliders, is the one generated by the muon decays. The generated $e^{\pm}$ travel with the beam and are lost on the beam aperture, producing intense particle showers which the nozzle aims to shield. Originating from the beamline, this background can be discriminated from actual physics events with directional cuts and partially with appropriate timing cuts. Despite these mitigation techniques, muon decay isexpected to be the dominant source of background in muon colliders and the whole MDI design needs to suppress it by orders of magnitude to guarantee a suitable experimental environment.

Other sources of backgrounds are also in common with electron-positron colliders, such as incoherent pair production, where single muons of the two beams interacts via real or virtual photons generating $e^{\pm}$ pairs, or coherent pair production, where one muon interacts with the electromagnetic field generated by the other beam. Incoherent pairs are estimated to yield a much larger background contribution than coherent pair production. Finally, another source of background are the secondaries produced by the muon halo losses on the beam aperture. Muons are difficult to collimate and therefore other halo suppression techniques must be studied in order to reduce halo losses in the final focus region. In this paper, we focus only on the background induced by decay and incoherent pair production, while the contribution of halo losses is subject of ongoing studies.

3.1 Decay-induced background

To assess the decay-induced background, we conducted a high-statistics FLUKA [12, 13] simulation. The muon decay position and secondary particle direction was sampled from a matched beam-phase space distribution. The produced secondary particles are propagated until they reach the detector volume, modelled as an all-absorbing volume, where they are scored and killed. For all particles but neutrons, the assumed energy threshold was 100 keV, while neutrons were simulated down to thermal energies. In the following, we discuss the total number of secondary particles entering the detector per bunch crossing and per single bunch with a nominal bunch population of 1.8×10^{12} muons.

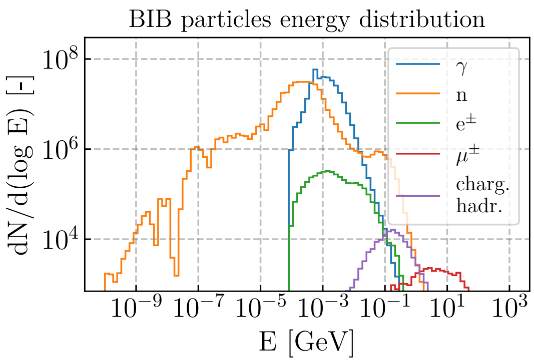

Figure 3: Energy distribution of secondary particles entering the detector as a consequence of muon decay.

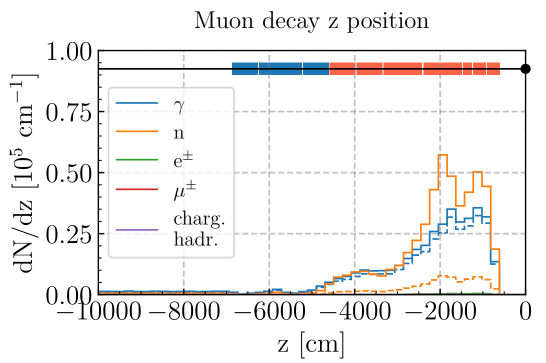

Figure 4: Number of secondary particles entering the detector per position of muon decay. The dashed lines are the particles withing the [-5, 15] ns time cut with respect to the bunch crossing.

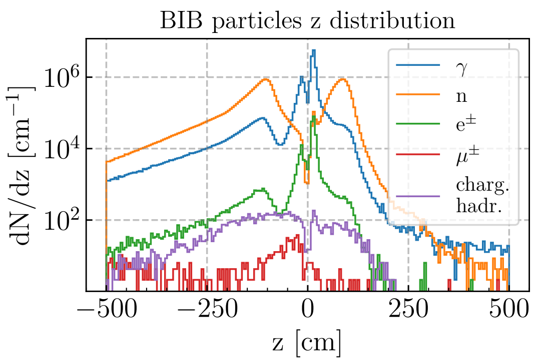

Figure 5: Distribution of the entry position of secondary particles in the detector volume.

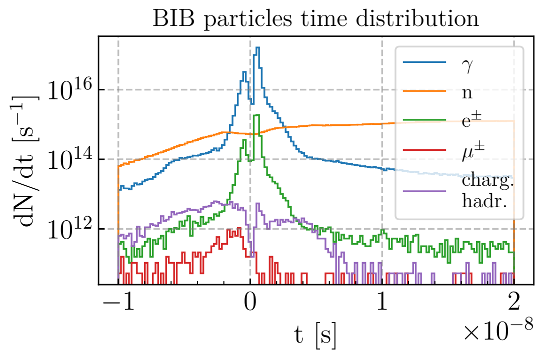

Figure 6: Time distribution with respect to the bunch crossing of secondary particles when they enter in the detector volume.

Figure 3 presents the decay-induced background spectra for secondary electrons/positrons, photons, neutrons, muons, and charged hadrons. The characteristic shapes of the spectra do not depend on the lattice design choice, but they are the results of the cascade development in the nozzle. In Figure 4, the multiplicity of background particles per position of the muon decay is reported. The effect of the chicane can be clearly seen: all the muon decays occurring before the dipole elements yield only a little contribution to the decay-induced BIB, while most of the secondaries are actually coming from muons decaying in the final focus magnets.

Finally, the position and time of entry in the detectors are plotted in Figs. 5 and 6. The photons, electrons and positrons enter in the detector very close to the IP and mostly in time with the bunch crossing. Instead, most of the neutrons arrive mostly out of time.

3.2 Incoherent pair production

The simulation of incoherent pairs is based on the Guinea-Pig code [14]. With a recent improvement of the code, the muon interactions can be explicitly simulated, taking in account beam-beam effects in the propagation of secondary pairs.

Differently from the background coming from the muon decay, which is transformed into a much softer spectrum by the nozzles, some of the incoherent pairs can be lost directly on the central vacuum chamber, i.e. without being intercepted by the nozzles, and can therefore induce a harder background. They are also produced in time with the bunch crossing, and in the proximity of the IP. Therefore, directional and timing information would not suffice to discriminate those particles by the ones generated by muon collisions. The following propagation of secondary pairs into the interaction region geometry is done with FLUKA.

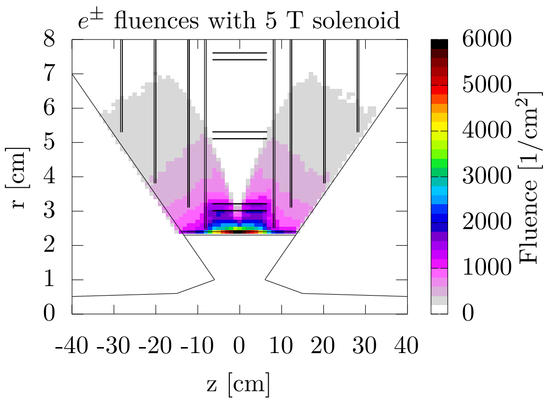

Figure 7: Fluences of pairs in the detector volume. The first tracker layer is assumed at 3 cm from the interaction point.

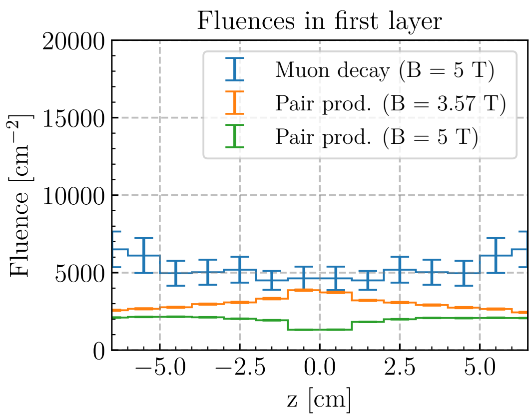

Figure 8: Comparison of the fluences of background particles from muon decay or incoherent pair production. Employing higher magnetic field strongly reduces the secondaries in the first tracker layers.

The trajectories of incoherent pairs are affected by the detector solenoid. Figure 7 shows the resulting fluence in the inner tracker, where the $e^{\pm}$ are bent towards the outer surface of the nozzle elements. However, the magnetic field mitigates the resulting background only partially, as seen in Fig. 8. Incoherent pair production can hence yield an important contribution to the background in the tracker, which has to be considered in addition to the background coming from the muon decay.

4. Conclusions

In this paper, we explored two different sources of background for a 10 TeV muon collider. In particular, we presented the background contribution from muon decay considering the latest lattice and nozzle design studied within the International Muon Collider Collaboration. Secondly, we performed an updated Guinea-Pig simulation to assess the background by incoherent pair production in case of different solenoid strengths. The comparison between this background and the decay-induced one yield similar fluences in the first tracker layers, proving the importance of incoherent pairs for the detector design.

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