Muon Collider: Machine Detector Interface Studies

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Abstract

Muon collisions can represent the new frontier for the investigation of physics beyond the standard model since they can reach multi-TeV center of mass energies. One of the main issues is the beam-induced background caused by the muon decays that can limit the collider functionalities and the detector performance if not mitigated properly. This letter proposes to study the Machine Detector Interface (MDI) at $\sqrt{s} = 1.5$ TeV and $\sqrt{s} = 3.0$ TeV by using the MAP accelerator design and a new software framework. These results will be the groundwork for future studies on the optimization of the MDI and detector at $\sqrt{s} = 10$ TeV or higher, to minimize the impact of the beam-induced background on the physics reach.

Status of the art

Muon beams at a Muon Collider (MC) are expected to have the order of $2 \cdot 10^{12}$ muons per bunch to reach the desired instantaneous luminosity. The number of particles produced by the muon decays along the ring is very large, for example two beams of 750 GeV of energy generate about $4.28 \cdot 10^5$ decays per meter of the lattice in a single pass.

The primary products of these decays are energetic electrons and neutrinos. Then, the electrons emit synchrotron photons in the presence of the high magnetic field of the accelerator ring magnets. Electrons and photons, in turn, produce electromagnetic showers by hitting the beam pipe and the Interaction Region (IR) elements, hadrons via photo-nuclear interactions and muons via the Bethe-Heitler process. These particles can generate additional showers and particles by interacting with the detector components.

In the IR design, the dipoles close to the interaction point (IP) and tungsten masks in each interconnect region (needed to protect magnets) help reducing beam-induced background (BIB) particle fluxes in the detector by a substantial factor. The tungsten nozzles in the 6 to 600 cm region from the IP (as proposed in the very early days of MC [1] and optimized later [2]), assisted by the detector solenoid field, trap most of the decay electrons created close to the IP as well as most of incoherent e^+e^- pairs generated in the IP. With sophisticated tungsten, iron, concrete and borated polyethylene shielding in the MDI region [3], the total reduction of background loads by more than three orders of magnitude can be achieved. Detector background rejection criteria were studied in [4], [5] and [6]. Note that all the beam induced deleterious effects in the MC and their mitigation – radiation loads and peak energy deposition in superconducting magnets, MDI design and background particle loads on detectors and neutrino-induced hazard for TeV-range MC [7] – were studied over many years with the continuously upgraded MARS Monte Carlo [8].

During the last year, a software framework and the relevant code to produce the beam-induced background starting from the MAP IR and MDI design has been developed [9], and it is being currently validated by reproducing the previous results published by the MAP collaboration. The Fluka Line Builder is used to automatically build the accelerator geometry starting from the machine optics. Then, with the Fluka Monte Carlo code, muon beams and their products are generated and tracked to relevant regions. Finally, the density of particles on the nominal detector volume is produced. The same simulation framework will be used also to estimate the neutrino fluxes along the ring and at the IR to study neutrino interaction with the matter and the environment.

Proposed activities

The MAP collaboration has already made available the IR lattice description for $\sqrt{s} = 1.5$ TeV and they are planning to recover the files for $\sqrt{s} = 3.0$ TeV as part of the Snowmass activities. With these two IR descriptions and by using the new software framework, we propose the following activities:

- Reproduce the beam-induced background studies inside the nominal detector volume by using the IR and the MDI designed by MAP at $\sqrt{s} = 1.5$ TeV. The results will be compared with the published ones to benchmark the code.
- Study the MDI at $\sqrt{s} = 3.0$ TeV by using the MAP IR design with the following steps:
    1. evaluate the BIB characteristics with no detector shielding in order to identify the origin of the background and to be able to understand how one can mitigate it with improved machine design.;
    2. assess the backgrounds inside the nominal detector volume by assuming the $\sqrt{s} = 1.5$ TeV detector nozzles and shielding;
    3. optimize the nozzles and the shielding by using AI advanced software methods and by iterating the evaluation of the BIB inside the detector volume at $\sqrt{s} = 3.0$ TeV. New detector technologies will help to mitigate the effects of the BIB, see the LoI "Muon Collider experiment: requirements for new detector R&D and reconstruction tools ".

Outcome

- Detailed comparison between the BIB studies performed by MAP and those obtained with the new software framework at the center of mass energy of 1.5 TeV.
- BIB characteristics and behaviors at $\sqrt{s} = 1.5$ TeV and $\sqrt{s} = 3.0$ TeV. These studies will lay the foundation for a new collider and detector design that minimizes the impact of background at other center of mass energies like the 10 TeV or more.
- Information on the requirements for high center of mass energy detector to mitigate BIB.

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