PROCEEDINGS OF SCIENCE

Machine-Detector interface for multi-TeV Muon Collider

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One of the challenges of the multi-TeV muon collider is mitigating the effects of beam-induced background. The primary contribution to this background has been identified as decay products of the muon beams. If not properly managed, these decays arriving at the detector could limit its performance. This paper presents the background sources, the strategies currently identified for mitigation, and ongoing activities in this regard.

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1. The muon collider project in a nutshell

Muon collisions could be the solution for the next high-energy future collider. Muons can be accelerated in a circular collider up to several TeV without significantly suffering from synchrotron radiation. The main parameters of the complex [1] are reported in Figure 1. It can be noticed that a collider circumference of 10 km can host a machine with $\sqrt{s}$ = 10 TeV. The limited dimensions of the collider are needed so that the beams recirculate many times through the interaction point (IP) before luminosity is significantly compromised by muon decay. The limited dimension of the collider means also less civil engineering and the possibility to exploit existing infrastructures like those available at CERN or at Fermilab.

Another characteristic of the muon collider is the increase in luminosity with the center-of-mass energy, as demonstrated in [1]. The combination of high center-of-mass energy and high luminosity makes the muon collider a very appealing option as a future machine. The search for new physics in lepton interactions in the TeV range opens a new scenario where a large variety of signatures can be exploited [1]. The full potential of such a collider in terms of new phenomena needs to be fully assessed. On the contrary, a quite detailed study of Higgs physics has been performed by using a detailed simulation as presented [1, 2], demonstrating that a multi-TeV muon collider is, in fact, an Higgs factory, particularly at the energy frontier. The unstable nature of the muon, with a lifetime

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Total beam power	$P_{-} + P_{+}$	MW	5.3	14	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^{*}_{\perp}$	mm	5	1.5	1.1
IP beam size	$\sigma_{\perp}$	µm	3	0.9	0.6

Figure 1: Preliminary parameter table of muon collider at different center-of-mass energy [1].

of 2.2 μs at rest, drives the design of the facility and poses challenges. All the actions, from muon production to the final beams collision, have to be completed on a time scale compatible with the muon lifetime. Therefore, it is mandatory to accelerate muons to the desired energy quickly.

The muon production chain involves an intense proton beam impinging on a multi-MW target to obtain pions that, in turn, decay into muons. Ionization cooling is used to compress these muons in 6D. The Muon Ionization Cooling Experiment (MICE) [3] has demonstrated an increase in the phase-space density of the beam due to energy loss in absorbers, in agreement with what is expected from simulations. The restoration of momentum in the direction of the beamline must be proven experimentally, even though it is predicted by simulations tuned to the MICE results.

The beam consists of single bunches of μ^+ and μ^-, each about 2×10^{12}. Therefore, their decays produce intense fluxes of particles along the ring. In the interaction region (IR), where there are the straight sections of the ring, such fluxes can affect the detector performance.

2. Background sources and detector shielding

The extensive study of all the components of the beam-induced background sources arriving at the detector is currently in progress for the two reference energies considered so far, $\sqrt{s}$ = 3 and $\sqrt{s}$ = 10 TeV. The fluxes of particles generated by the muon decays constitute the major source of the beam-induced background. High-energy positrons and electrons would arrive directly at the detector, compromising its capabilities if not absorbed.

The Muon Accelerator Program (MAP) collaboration [4], proposed to contain these fluxes by inserting two conical structures made of tungsten around the beam-pipe inside the detector, named nozzles. The external part is coated by BCH_2 to absorb neutrons. Figure 2 (left) illustrates the Interaction Region (IR) for a preliminary configuration at $\sqrt{s}$ = 10 TeV, while the $\sqrt{s}$ = 3 TeV design [5] was developed by MAP. Both cases employ the same nozzle structure depicted in Figure 2 (right), which was optimized by MAP for $\sqrt{s}$ = 1.5 TeV. The study of the nozzles structure and the configuration of the IR at 3 and 10 TeV center-of-mass energy is currently in progress.

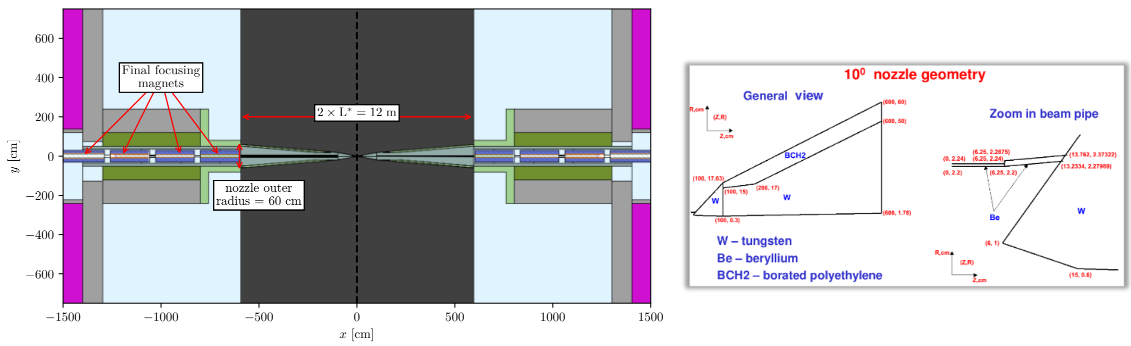

Figure 2: Left: IR of the 10 TeV center-of-mass energy, the x axis represents the beam direction. The outer shape of the detector is a cylinder with a radius of 6 m. The space between the outer shape and the nozzles is considered as a perfect particle absorber. Right: MAP nozzle design [6].

In addition to the muon decay, an other potential source of background is incoherent e^+e^- pair production [7]. The MAP collaboration evaluated its contribution in the detector region for beams of 750 GeV [8] and found it to be nearly negligible. As the production cross section of this process increases with the beam energy, its impact at $\sqrt{s}$ = 10 TeV needs to be assessed. Electrons and positrons are produced synchronously with the beam collisions, mainly along the beam line, and the effect on the detector can be mitigated by its solenoidal magnetic field.

Beam losses, while unavoidable, are currently not considered as a potential source of background in the detector region. The design of the collimation system upstream of the IP should be able to keep them at a level much lower than other sources.

3. Beam-induced background characterization

The nozzles absorb the high energy particles produced by the muon decays and generate intense fluxes of electromagnetic showers and hadronic particles, mainly neutrons with a minor contribution from charged hadrons. The cladding material stops the neutrons but then produces photons that arrive in the internal layer of the calorimeter [9]. Muons are produced in the Bethe-Heitler process [10] and can come from a large distance with respect to other particles therefore requiring a dedicated production; likely their contribution is much less than that of other particles.

The detector performance evaluated at $\sqrt{s}$ = 3 TeV [9] has been assessed with the beam-induced background generated by the MAP collaboration for 1.5 TeV centre-of-mass energy using the MARS15 code [11]. A new procedure [12], which exploits the FLUKA [13] package, has been setup and a data sample of beam-induced background was generated. A comparison with the results obtained with the MARS15 code demonstrates a very good agreement, providing robustness to these predictions [12].

The study of the beam-induced background at $\sqrt{s}$ = 3 and 10 TeV has just began. The data samples have been generated using the IR configuration previously mentioned, with the $\sqrt{s}$ = 1.5 TeV nozzles structure being the only one available so far and a magnetic field in the detector region of 3.57 Tesla. Figure 3 (left) shows the arrival time on the detector with respect to the collision time of the muon decay background particles. The distributions, similar for both center-of-mass energies, show a sizeable contribution outside the time window of [-1, 15] ns. This time range is considered appropriated to mimic a data taking window. Figure 3 (right) displays the energy distribution of the same two data sets in the defined time window. It can be noticed that the distributions at the two

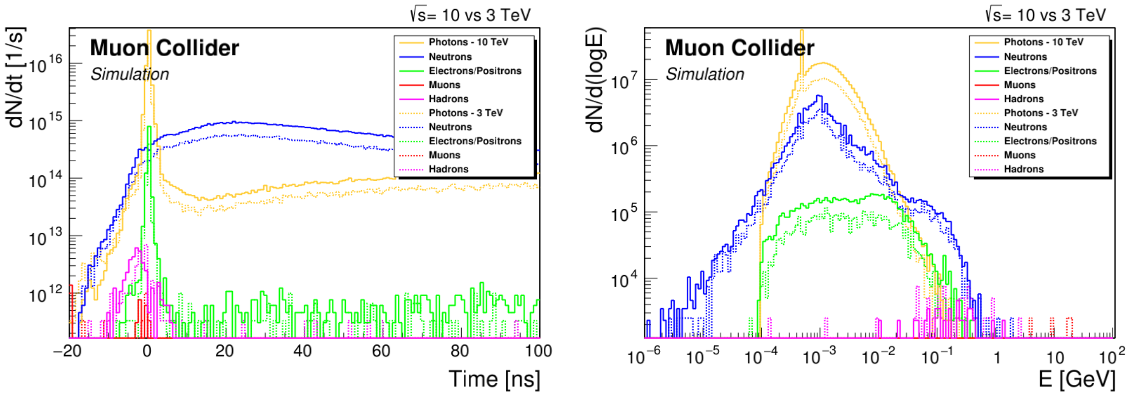

Figure 3: Left: Distribution of the arrival time of particles arriving at the detector for $\sqrt{s}$ = 3 TeV (dashed line) and $\sqrt{s}$ = 10 TeV (solid line). Different colors represent different particle types. Right: Energy distribution of the same particles in the same conditions but in the time window [-1 15] ns.

center-of-mass energies have a similar shape, also comparable to $\sqrt{s}$ = 1.5 TeV [12]. Given the wide energy range considered, this brings to the conclusion that the characteristics of this beam-induced background are determined by the nozzles configurations. The number of particles that arrives at the detector at $\sqrt{s}$ = 10 TeV is higher by factors that depend on the particles types, energy and arrival time with respect to that at $\sqrt{s}$ = 3 TeV. This behaviour is anticipated given the two different center-of mass energies and the different IR configurations.

The optimization of the IR configuration and the nozzles dimensions, shape, and materials for the 3 and 10 TeV center-of mass energies is currently in progress. To find the most appropriate figures of merit, the regions that contribute most to the background in the detector are being studied. Figure 4 shows the distribution of the origin in $R - z$ of the hits belonging to the first layer of the tracker, where z is the beam line and R the direction transverse to it. For each hit, the particle that generates it and then its "mother" is searched and distinguished if primary, i.e., coming from IR or nozzles or secondary, i.e., from a subsequent interaction in the detector or other object's material. Then, the origin of the "mother" particle is plotted in $R - z$.

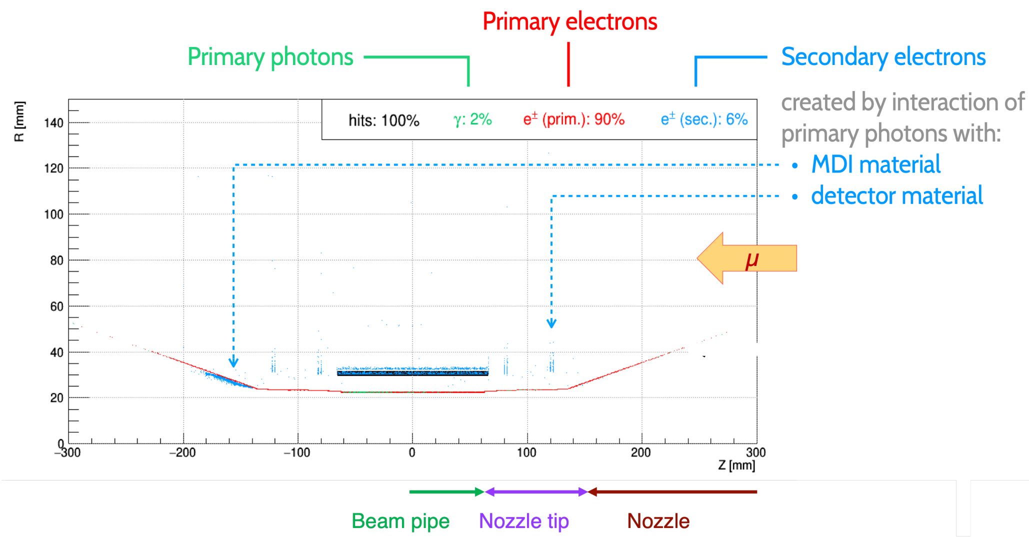

Figure 4: Origin of beam-induced background hits in the first layer of the tracker. Particles coming from the IR including nozzles are labeled as primary while those originating in other material are called secondary. One muon beam coming from the direction of the peach-coloured arrow is used. The different location of the machine-detector interface elements is described on the bottom of the figure. A symmetrical configuration can be assumed for the other muon beam.

The major part of the hits are from primary $e^{\pm}$ coming from the nozzles. It is possible to see the nozzles actual shape in red. The second contributor is again $e^{\pm}$ but secondary. Positrons and electrons originate from the silicon tracker detector in the forward/backward region and from the nozzle on the other side of the beam direction, which acts as a production target. The smallest fraction, around 2%, of these beam background hits is induced by primary photons. A similar study is in progress for the internal layer of the electromagnetic calorimeter. In this case, the goal is to understand if changing the nozzle shape and the material will make it possible to mitigate the flux of photons.

These studies will be repeated by changing the IR configuration, including the nozzles. This process will help avoid hot spots on the detector and mitigate the fluxes in the most critical parts of the detector.

4. Outlook

The primary source of beam-induced background arriving at the detector has been studied using the MARS15 and FLUKA simulation codes at $\sqrt{s} = 1.5$ TeV. Although the studies at the center-of-mass energies of 3 and 10 TeV are in their initial phases, it is evident that the beam-induced background due to muon decays is influenced by the configuration of the nozzles. Therefore, optimizing the nozzles is crucial for experimental activities. Achieving an optimal design involves understanding the spatial distribution of background sources in the IR. The next steps include incorporating contributions from incoherent pair production at high energy and optimizing the nozzles using machine learning techniques.

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