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MONTE CARLO DRIVEN MDI OPTIMIZATION AT A MUON COLLIDER

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Abstract

A Muon Collider represents a very interesting possibility for a future machine to explore the energy frontier in particle physics. However, to reach the needed luminosity, beam intensities of the order of 10^9–10^{12} muons per bunch are needed. In this context, the Beam-Induced Background must be taken into account for its effects on magnets and detector. Several mitigation strategies can however be conceived. In this view, it is of crucial importance to develop a flexible tool that allows to easily reconstruct the machine geometry in a Monte Carlo code, allowing to simulate in detail the interaction of muon decay products in the machine, while being able to change the machine optics itself to find the best configuration. In this contribution, a possible approach to such a purpose is presented, based on FLUKA for the Monte Carlo simulation and on LineBuilder for the geometry reconstruction. Results based on the 1.5 TeV machine optics developed by the MAP collaboration are discussed, as well as a first approach to possible mitigation strategies.

INTRODUCTION

First proposed in the late ‘60s [1, 2] and then studied in detail by the Muon Accelerator Program (MAP) [3], the idea of a Muon Collider (MC) is receiving today a renewed interest by the scientific community.

Besides the remarkable advantages represented by an MC, conceptual and technological challenges have hindered so far the design of such a machine. A peculiarity of MCs is that muons decay all along the machine, resulting in a continuous flux of secondary and tertiary particles reaching the detector, the so called “Beam-Induced Background” (BIB), that is able to jeopardize the data taking if not properly dealt with since the initial stages of the collider concept. The MAP collaboration studied in detail MC optics, interaction region (IR) and Machine-Detector Interface (MDI) [4], with the aim of mitigating as much as possible BIB effects. A specific design of the MDI, based on the presence of two cone-shaped tungsten shields called “nozzles”, leads to a massive reduction of BIB in the detector, as demonstrated by simulations performed with the MARS15 [5–7] Monte Carlo code. A complete design of the whole machine and MDI at the centre of mass (CM) energies of 125 GeV, 1.5 and 3 TeV has been performed by MAP collaboration, including a preliminary study at 6 TeV [8–11].

As demonstrated by MAP results, the amount of BIB impacting the detector depends on the CM energy and on the instantaneous luminosity, key figures of the IR design.

A seamless transition between optics and Monte Carlo simulations is indeed a crucial point. In fact, as demonstrated by the first BIB MAP study [6], the MDI optimization is expected to be an iterative process, in which each and every change performed in the machine optics, even hundreds of meters away from the IP, can substantially change the BIB in the detector.

In this paper a flexible and powerful approach to BIB simulation is presented, based on the combination of LineBuilder and FLUKA; results for the 1.5 TeV CM energy case are shown.

SIMULATION OF 1.5 TeV BIB

Simulation Setup

The BIB studies consist in the simulation of primary muons decay and the interaction of their decay products with machine and detector components. To this aim we choose the Monte Carlo multi-particle transport code FLUKA [12, 13].

The possibility to model in the FLUKA geometry the lattice and optics optimized with MAD-X [14] is offered by the FLUKA LineBuilder [15] (LB), a Python program for automatically assembling complex FLUKA geometries of accelerators based on machine optics. The output of a code for lattice design (e.g. MAD/MAD-X) is used to assemble the beam line geometry with the accelerator elements modelled in the Fluka Elements Database (FEDB). Hence, the accelerator geometry is built according to the optics, placing each needed element stored in the FEDB at the correct position with the correct orientation and magnetic fields.

In this work, we present BIB results computed with FLUKA for the 1.5 TeV CM energy machine configuration, assembled with the LB. The choice of this case has a two-fold motivation: first, this IR configuration is one of the most studied and optimized by the MAP collaboration; secondly, a BIB sample generated with MARS15 Monte Carlo is available, giving thus the opportunity to use it as reference for benchmarking.

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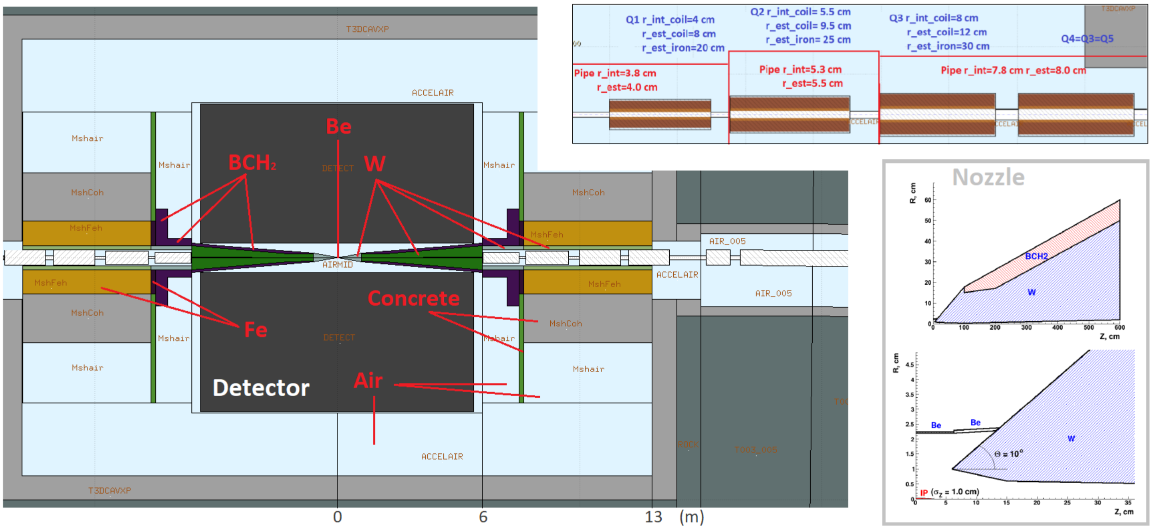

Figure 1: MC interaction region. The passive elements, the nozzles and the pipe around the interaction point are constituted by iron (Fe), borated polyethylene (BCH_2), berillium (Be), tungsten (W) and concrete. The detector volume is a 11.28 m long cylinder of 6.3 m outer radius with an inner hole of 60 cm radius. The bunker is a 9 m radius and 26 m long cylinder. Top right: IR quadrupoles specifications. Bottom right: detailed description of the nozzle from [7].

The optics file provided by the MAP collaboration has been used. Families of accelerator elements have been defined in FEDB based on information contained in this file and in MAP publications [4, 5]. The IR, characterised by the presence of two tungsten nozzles around the Interaction Point (IP), is represented in Fig. 1.

Only the external shell of the detector has been considered in this simulation setup. In fact, the quantity of interest for this study is the flux of particles that enters the detector; the detailed study of what happens inside the detector is then performed by a separate simulation [16].

Only half of the machine is modelled, considering its symmetry and the μ^+/μ^- simmetry. A realistic (i.e. taking into account emittance and energy spread) primary muon beam at 750 GeV energy is simulated starting from the point opposite to the IP considered for the flux estimation; therefore, it travels half ring reaching the IP from the right side looking at the machine from up. In order to have a reasonable statistics, the decay probability of muons is increased in the section of the ring next to the IP, and a weight is assigned to the decay products to compensate this bias. Decay products are further transported in the geometry, with accurate description of electromagnetic and hadronic processes. Hadrons (mostly neutrons) are generated through electronuclear and photonuclear interactions.

Comparison Between FLUKA and MARS Results

The results we obtained are benchmarked against those provided by the MAP collaboration.

Table 1 reports the total number of particles produced by the primary muons' decay that enter the detector hall, divided by particle type.

The major contributors to BIB are photons, neutrons and electrons/positrons, as confirmed by both simulation programs. The kinetic energy and time distribution of all particle types have similar shapes. The observed discrepancies on the total number of particles types are within a factor of 3. Several studies have been performed to understand these differences without finding a unique cause. The most probable reason is that the two simulations are not using exactly the same IR configuration and geometry. To better understand the history of particles that are entering the detector, information regarding first interaction region has been extracted from the simulation. In particular, Fig. 2 top-left reports regions where the first interactions corresponding to the BIB particles entering the detector occur. The majority of them happens in the right nozzle, but a not negligible number happens also on the left nozzle. The pie on the right of Fig. 2 represents the elements from which the BIB particles exit just before entering the detector. Many elements are present, but the left nozzle is the second most relevant element. The sketch at the bottom displays the elements names with the primary beam arriving from the right. These three graphs together demonstrate that the first interactions occur mainly in the right inner part of the nozzle that, together with the

Table 1: Results for a 2×10^{12} μ^- Beam. Number of BIB Particles Obtained by Using MARS15 and FLUKA Programs. Muon Decays Within 25 m from the IP are Analysed. For Each Particle Type the Threshold Energy is Also Reported

Particle (E_{th}, MeV)	**MARS15**	**FLUKA**
Photon (0.2)	$8.3\ 10^7$	$4.3\ 10^7$
Neutron (0.1)	$2.4\ 10^7$	$5.4\ 10^7$
Electron/positron (0.2)	$7.2\ 10^5$	$2.2\ 10^6$
Ch. Hadron (1)	$3.1\ 10^4$	$1.5\ 10^4$
Muon (1)	$1.5\ 10^3$	$1.2\ 10^3$

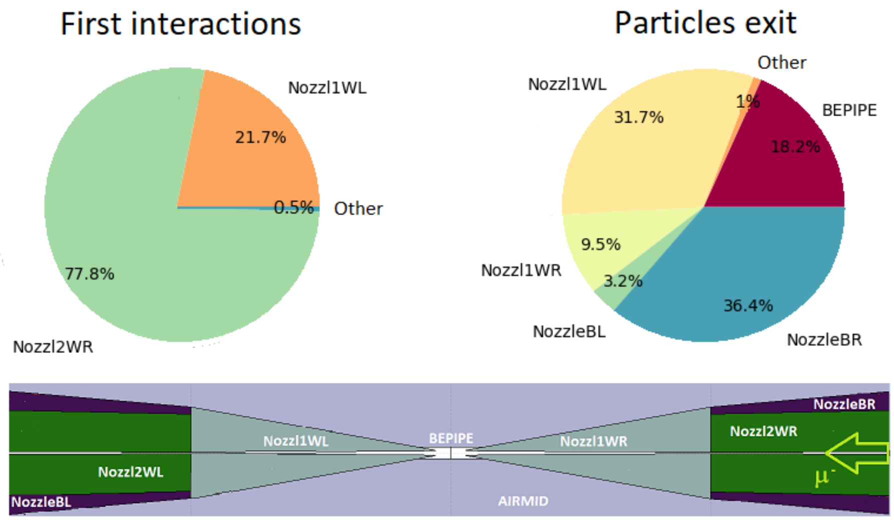

Figure 2: Pie graphs of the IR elements where the first interaction occur after the primary muon decay (left) and from which BIB particles exit the IR to enter the detector (right). Bottom: sketch of the IR with relevant regions names.

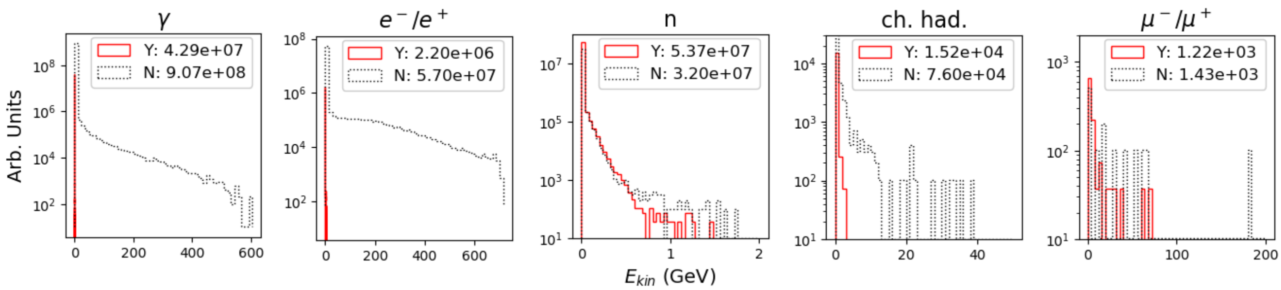

Figure 3: Energy spectra by particle type with nozzle (“Y”, solid red line) and without nozzle (“N”, dotted black line).

right tip, acts as a “funnel”, and on the opposite nozzle tip, that operates as a “target”, from where 31.7% of BIB exits to enter the detector.

BIB Characteristics Without the Nozzle Absorber

In order to envisage some possible new mitigation strategy, the characteristics of the BIB without the nozzle have to be understood. The comparison between the “with nozzle” (Y) and “without nozzle” (N) cases is reported in Fig. 3. As expected, a major increase in particle fluxes is observed when removing the nozzle for photons and e^+e^-. A milder increase is observed for charged hadrons and muon flux. On the contrary, the nozzle insertion yields an increase in the neutron flux. Besides fluxes, the most important thing to highlight is the energy spectrum of the particles, which is very similar to that of the particles produced in the muons primary interaction. This huge amount of high energy BIB particles would completely jeopardise the physics measurements, as expected.

CONCLUSION

Among the challenges presented by a MC, a prominent role is played by the BIB, as illustrated in this paper. A massive reduction of the BIB can be obtained by means of a careful optimisation of the MDI, for which an advanced approach to simulations is presented in this contribution, based on the combination of LineBuilder and FLUKA. Such a software combination allows a seamless link between the code used for lattice and optics design (e.g. MAD-X) of the Muon Collider and the Monte Carlo simulation used to assess the BIB impact on the detector. Results for the 1.5 TeV CM energy case have been shown, also compared to those obtained by the MARS15 simulations. A good agreement has been found, and the residual differences are most probably due to lack of details in the machine model (i.e. passive absorbing materials between magnetic elements). Results suggest that this tool has the required characteristics in terms of flexibility and accuracy, and can thus be fundamental to perform the MDI optimization needed in a MC.

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