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A Flexible Tool for Beam Induced Background Simulations at a Muon Collider

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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^{9-11} muons per bunch are needed. In this context, the Beam Induced Background must be taken into account for its effects on the magnets and on the detector. Several optimizations can be conceived with the aim to mitigate them. 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. First results for the 1.5 TeV machine optics developed by the MAP collaboration are discussed in this paper.

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1. Introduction

In the quest of possible new accelerators allowing to widen our comprehension of the fundamental structure of matter, muon colliders play an important role. Although the idea is not recent, being proposed several decades ago, such a possible machine is seeing today a renewed interest in the scientific community, with its ability to overtake the main limitations of actual colliders. In fact, even if the LHC has still to deliver numerous years of data, it is already now the time to identify possible solutions to carry on the research on fundamental particle physics in the next years. In this context, design studies are being performed on a Future Circular Collider, to be build at CERN, with a circumference of about 100 km and unprecedented energies and luminosities for both hadron and lepton cases.

However, even with respect to such huge and powerful machines, a muon collider would still retain some advantages that make it worth studying. All these advantages arise directly from the very use of muons. In fact, being these particles about 200 times heavier than electrons, a beam of muons will suffer much less of Synchrotron Radiation emission, that is the limit of circular e+ e- colliders, giving the possibility to reach much higher energies. Moreover, the lack of light emission also allows to obtain much smaller energy spread of the beam, resulting in a much higher energy resolution. The advantages of a possible muon collider, however, are not only related to the accelerator, but also to the physics itself. In fact, the coupling with the Higgs boson goes with m^2, meaning that a much higher production of Higgs boson is expected at a muon collider.

However, in spite of these advantages, there are also some critical points that have hindered so far the actual design of a muon collider. First of all, muons decay in few μs, and this means that the whole chain, from generation to acceleration up to the interaction, must be performed very quickly. Moreover, the traditional muon production scheme leads inevitably to large emittance beams. In fact, muons are conventionally produced by colliding protons on target, and then exploiting the π/K decays. Muons are thus produced with a variety of angles and energies, implying the necessity of beam cooling to lower the emittance of the beam. In order to overcome this intrinsic limitation in muon beam emittance, a novel approach has been recently proposed by the LEMMA collaboration, in which muons are directly produced by annihilation of a positron beam in a fixed target, resulting in a much reduced initial emittance, and possibly avoiding the need for cooling. Despite being this an interesting approach, further studies are needed to demonstrate how to address some relevant possible showstopper in this production scheme (e.g. the thermo mechanical stability of muon production targets or the positron source).

2. The Beam Induced Background Issue

Problems and difficulties in a muon collider however are not only related to production and acceleration of muons, but also to the detection of interesting physics. In fact, muons decay all along the machine, giving origin to a pletora of secondary and tertiary particles. Since muon colliders are typically expected to reach energies of the order of tens of TeV, such produced particle could have high energy and multiplicity. This so called “Beam Induced Background“ (BIB) can therefore have a detrimental role for example on magnets quenching, or regarding radiation hazard issues.

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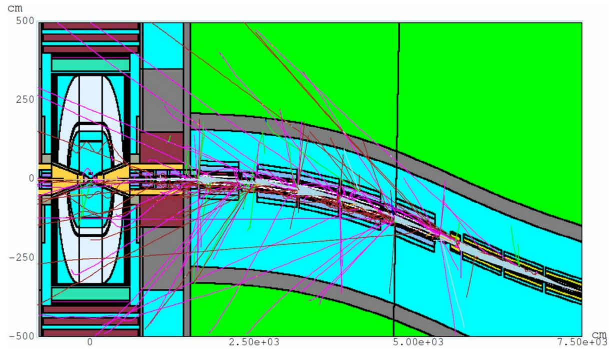

Figure 1: Illustration of the model of the machine and machine-detector interface used in the MARS15 simulation. The shielding nozzles, described in the text, are represented in yellow inside the detector.

However, its most relevant impact is expected on the detector itself, that will have to deal with a massive, continuous flux of a variety of different particles at different energies. Such an issue could therefore impact on the possibility to actually reveal all the interesting physics that is expected to be produced at a high energy muon collider.

3. Monte Carlo simulations of BIB

The possible effects of BIB on detector capabilities is such a crucial aspect that the MAP study [3], the most advanced muon collider study so far, had put a particular effort in the study of the muon collider optics, with the exact aim of mitigating as much as possible its impact. In order to optimize this Machine Detector Interface (MDI) scheme, a Monte Carlo simulation has been used, performed with MARS15 [4, 5], allowing to simulate and track the generation and interaction of secondary and tertiary particles. This study has been performed in particular for the 1.5 TeV Center of Mass energy case, and led to a peculiar design of the MDI Interface, based on the presence of two cone-shaped tungsten shields ("nozzle"), with the role of absorbing the majority of high energy BIB tracks. Such a MDI scheme is represented in Figure 1.

Despite the relevance of this optimization effort, its results happen to depend dramatically on the considered machine configuration: a "Higgs Factory" muon collider would present a totally different BIB, as well as a 20 TeV machine.

In this context, in parallel with this renewed interest in a possible muon collider, the need arose of a flexible tool to perform BIB simulations, allowing to easily go from the machine optics to the Monte Carlo simulation.

This seamless transition between optics and Monte Carlo simulation is indeed a crucial point since, as demonstrated by the first BIB MAP study, the MDI optimization is expected to be an iterative process, in which each and every change in the machine optics, even hundreds of meters from the Interaction Point, can substantially change the BIB in the detector.

To this aim, we discuss in this paper the identification of a software tool for such simulations, together with its first results in the same 1.5 TeV case.

4. The Tool Identification

The core of the software needed to perform BIB studies is represented by the simulation of primary muons and their decay. This is a task commonly performed by Monte Carlo codes, one of the most used being FLUKA [1]. This is a general purpose Monte Carlo code, that is used in a variety of applications ranging from medical physics to astroparticles. In particular, FLUKA is the golden standard in radio protection and beam shielding studies.

FLUKA does natively support very complicated geometries, thus in principle allowing to accurately reproduce the full accelerator complex in the simulation. The manual construction of such complex geometries however can be both difficult and error prone, but above all is definitely not compatible with that "flexibility" requirement at the base of this particular application. Moreover, a link is needed between the machine to be reconstructed in the Monte Carlo and the one that is designed/modified in the MDI optimization phase, usually performed in tracking codes like MAD-X.

A possibility for such a link between MAD and FLUKA is represented by LineBuilder [2], that is a Python program aimed exactly at automizing the construction of accelerators into FLUKA starting from their optics files. In particular, LineBuilder reads the output of a given tracking program (MAD/MAD-X, SixTrack...) and combines the information in it with a magnetic element database, called Fluka Elements Database (FEDB). This database stores the description, in FLUKA format, of the needed prototypes of magnetic elements, such as dipoles, quadrupoles and sextupoles. The LineBuilder then constructs the final accelerator according to the optics file placing each needed element at the given position. Both magnetic fields and elements materials are accurately reproduced.

A possible choice for this flexible tool for BIB simulations at a Muon Collider can thus be represented by the combination of LineBuilder and FLUKA.

5. The Tool Benchmark

In order to test the viability of the LineBuilder + FLUKA approach, we chose to apply it to reproduce results obtained by the MAP collaboration at 1.5 TeV. The idea is that a positive benchmark on such a well studied configuration could allow for a reliable study also on other ones. In order to perform this benchmark, we used the optics file, in MAD8 format, provided by the MAP collaboration. As a starting point, ‘a la LHC‘ magnetic elements have been implemented in the simulation. Their relevant dimensions, however, such as inner aperture and outer radius have been chosen to reproduce the ones used in the MAP study.

As far as the Interaction Region is concerned, the two tungsten nozzles, the passive elements present around the beam pipe and the outer shell of the detector have been also reproduced. It is indeed to be highlighted that the relevant quantity to consider for this benchmark is the flux of particles that enter the detector. The detailed study of what happens then inside the detector is in fact performed by a separate simulation, that takes care for example also of digitization issues. This detector simulation does need however as input the flux of particles entering it, that is therefore the quantity to be obtained by this FLUKA simulation.

A graphic representation of the muon collider ring reconstructed in FLUKA is shown in Fig. 2.

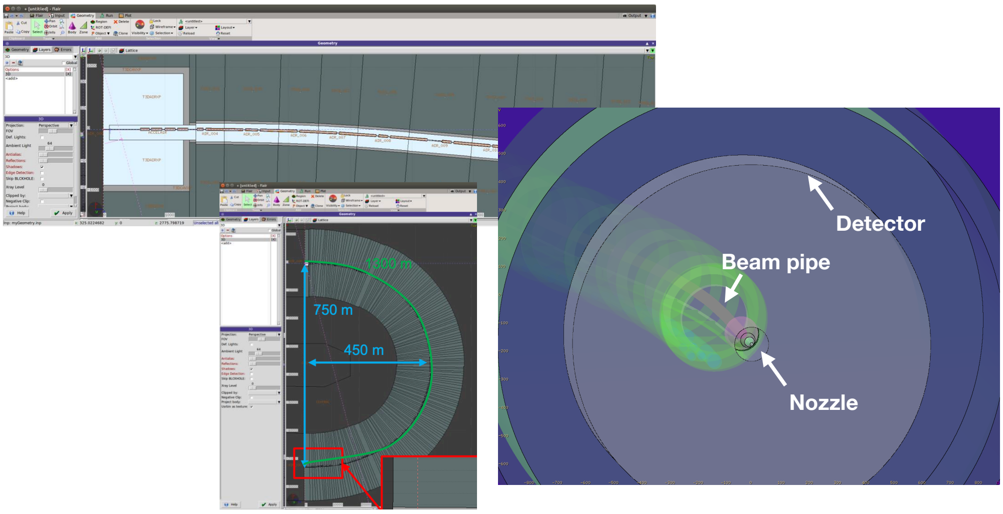

Figure 2: Reconstruction of the 1.5 TeV muon collider ring in FLUKA by means of LineBuilder.

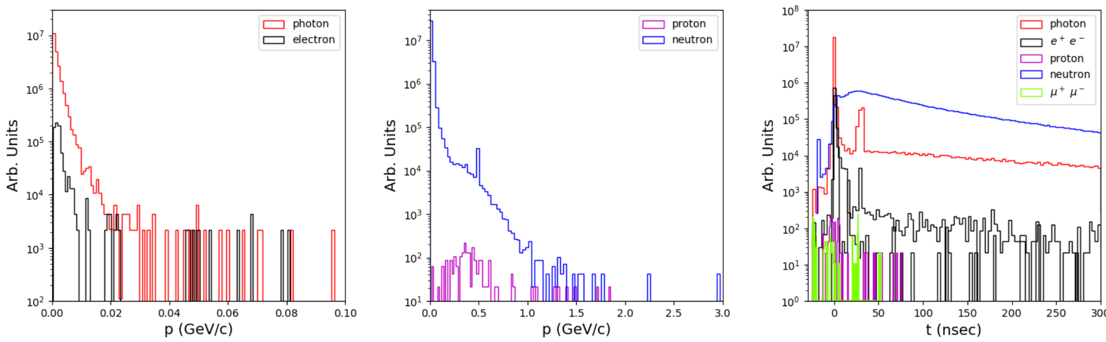

Figure 3: Result of the BIB simulations in the 1.5 TeV case: momenta of produced particles (first and second plot) and time of entering in the detector (last plot)

The primary particle is a muon with 750 GeV energy fired from the opposite Interaction Point. In order to have a reasonable statistics the muon decay can be biased in the simulation.

To obtain these quantities of interest, the scoring is thus performed by simply saving on a dump file information on tracks entering the detector shell, either from the tungsten nozzle or from the "world" volume. In particular, these quantities are registered: *particle, energy, position, momentum, direction, time, position of the muon decay, and first interaction point of decay secondary*.

In Fig. 3 results in terms of momentum and time distributions of particles entering the detector are shown.

6. Conclusions

The renewed interest in a muon collidier as a possible future machine for frontier particle physics calls for several new studies. Among these, the contribution of Beam Induced Background, i.e. the background due to primary muon decays, into the detector has a preminent role.

In this context, a tool is needed to study this BIB and optimize the MDI to mitigate its impact, allowing a flexible and scalable approach, when for example changing the beam energy or the machine/MDI design.

In this paper we presented the possible use of LineBuilder in association with FLUKA to perform such simulations, and its first results in a case (1.5 TeV) that has already been studied in detail by the MAP collaboration, chosen as a benchmark for the proposed tool.

First results suggest that this tool has the capabilities needed to perform such task with the required flexibility. A detailed comparison of the results with those obtained by the MAP collaboration, once their geometry is reconstructed with the needed level of detail, will provide the needed benchmark of its accuracy, necessary to proceed with the BIB study in other machine configurations. Moreover, a comparison of BIB in the 126 GeV [6, 7] and 1.5 TeV cases will be performed, with the aim of identifying possible scaling lows that would allow to draw some hints on BIB impact on higher energy cases even before having the actual optics of such machines.

References

[1] A. Ferrari, P.R. Sala, A. Fassò, J. Ranft, FLUKA: A Multi Particle Transport Code. Geneva, Switzerland: CERN; 2005. Technical Report CERN-2005-10, INFN/ TC05/11, SLAC-R-773

[2] *The FLUKA Linebuilder and element database: tools for building complex models of accelerator beam lines* Proceedings of IPAC2012, New Orleans, Louisiana, USA WEPPD071

[3] Muon Accelerator Program, https://map.fnal.gov

[4] N.V. Mokhov and C.C. James, *The MARS code system user's guide version 15(2016)*, Fermilab-FN-1058-APC (2018) [DOI:10.2172/1462233]

[5] Y.I. Alexahin et al., *Muon Collider Interaction Region Design*, FERMILAB-11-370-APC

[6] N. Bartosik *et al.*, Preliminary Report on the Study of Beam-Induced Background Effects at a Muon Collider, arXiv:1905.03725

[7] N. Bartosik *et al.*, Detector and Physics Performance at a Muon Collider, 2020 JINST 15 P05001

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