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ILCRoot tracker and vertex detector hits response to MARS15 simulated backgrounds in the muon collider[☆]

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Abstract

Results from a simulation of the background for a muon collider, and the hits response of a silicon tracking detector to this background are presented. The background caused by decays of the 750 GeV/c beam μ^+ and μ^- was simulated using the MARS15 program, which included the infrastructure of the beam line elements near the detector and the 10° nozzles that shield the detector from this background. The ILCRoot framework, along with the Geant4 program, was used to simulate the hits response of the tracker and vertex silicon detectors to the muon-decay background remaining after the shielding nozzles. Results include the hit distributions in these detectors, the fractions of type-specific background particles producing these hits and illustrate the use of timing of the hits to suppress the muon beam background.

Keywords: muon collider background, MARS15, ILCRoot, Si vertex and tracking detectors hits simulation

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1. Introduction

The recent results [1] of comprehensive study of interaction region (IR) and machine-detector interface (MDI) designs for 1.5 TeV muon collider demonstrate that the muon beams background can be suppressed more than three orders of magnitude [see details in [2]). The corresponding data were obtained with MARS15 simulation program [3] and available at Fermilab. They represent the list of background particles with their characteristics given at the surface of MDI (two 10° shielding nozzles near the interaction point IP). The MARS15 distributions relating to this paper and describing the absolute yields of different types of background particles and their timing are given below.

The MARS15 output data were used as input for simulation of the detector hits response in the ILCRoot framework [4]. In this paper we present results of ILCRoot simulation of Si vertex and tracking detectors

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hits response to the muon beam background. They include the hits distribution and use of timing for muon beam background rejection in these detectors.

2. The MARS15 modeling results

The major source of the detector background in $\mu^+ \mu^-$ collider is the electrons and positrons from beam muon decays. The decay e^+ and e^- produce high intensity secondary particle fluxes in the beam line components and accelerator tunnel in vicinity of the detector (interaction region IR, Figure 1). For example, for 750 GeV muon beam with intensity of 2x10^{12} per bunch there is about 4x10^5 decays per meter per bunch crossing.

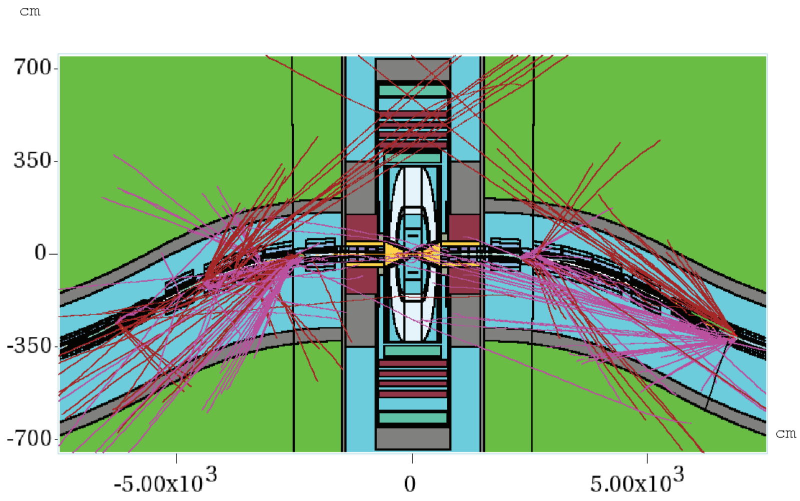

Fig. 1. A MARS15 model of the IR and detector with particle tracks > 1 GeV (mainly muons) for several forced decays of both beams.

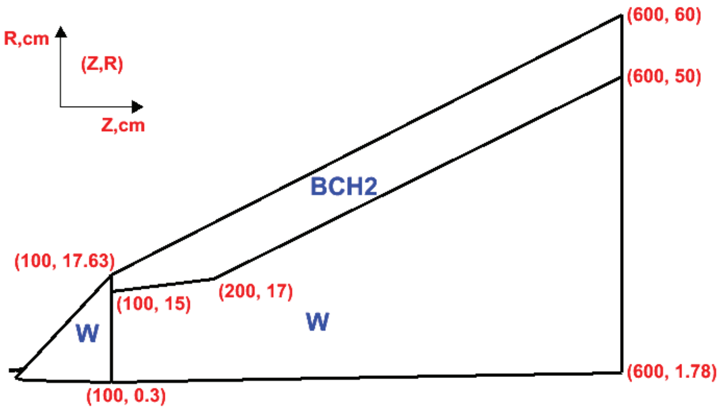

Fig. 2. The MARS15 machine detector interface MDI (nozzle),1/2 RZ view (W - tungsten, BCH2 - borated polyethylene).

As it was shown in the recent study [1] the appropriately designed interaction region and machine-detector interface (including shielding nozzles, Figure 2) can provide the reduction of muon beam background by more than three orders of magnitude for a muon collider with collision energy of 1.5 TeV. These results were obtained with the MARS15 simulation code, the framework for simulation of particle transport and interactions in accelerator, detector and shielding components. The MARS15 model takes into account all the related details of geometry, material distributions and magnetic fields for collider lattice elements in the +-200-m region from IP, as well as machine detector interface (shielding nozzles).

The obtained in MARS15 absolute yields of the background particles crossing the surface of the shielding nozzles on their detector side are shown in Figure 3. The most abundant background consists of photons and neutrons. Table 1 lists the background yields together with kinetic energy thresholds used in MARS15 simulation for different types of particles. There is a total about 2.2x10^8 of background particles per bunch for 750 GeV μ^+ and μ^- beams with each beam intensity of 2x10^{12} per bunch.

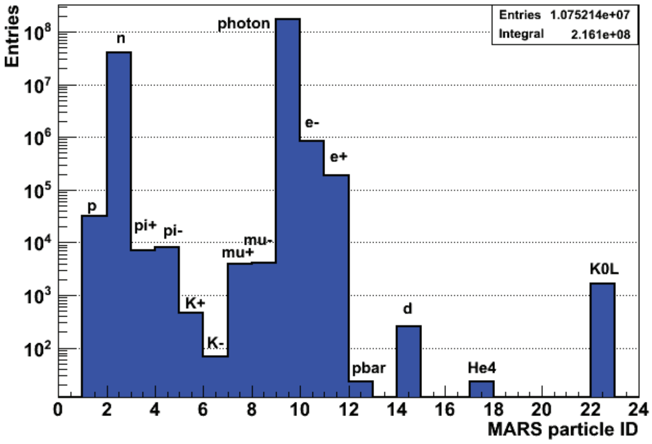

Fig. 3. The MARS15 background particle absolute yields.

Table 1. The MARS15 background yields/bunch on 10° nozzles surface and thresholds Ethr

Particles	γ	n	e	μ
Yield	1.77x10^8	0.40x10^8	1.03x10^6	0.80x10^4
Ethr, MeV	0.2	0.1	0.2	1.0

The MARS15 simulation code provides also the time of flight (TOF) of background particles calculated relatively to the bunch crossing time and given at the moment when particles are crossing the surface of the detector side of the shielding nozzles. Figure 4 illustrates the TOF distribution for different types of background particles. The spread of distribution is rather significant for background neutrons and muons. For example, there is about 20% of neutrons and 36% of muons within the TOF window of 25 ns (starting at 0 ns). This fact suggests that we can use timing in the detector to reduce the number of the readout background hits.

3. Results of the ILCRoot simulation of the hits in vertex and tracker Si detectors

The ILCRoot [4] is the software Infrastructure for Large Colliders based on ROOT [5] and adds-on for muon collider detectors studies. It makes use of the virtual Monte Carlo concept allowing to select and load at run time different Monte Carlo models (Geant3, Geant4, Fluka). In this paper Geant4 [6] was used with the QGSP-BERT-HP physics list for better description of the neutron transport processes. The ILCRoot is integrated for further reconstruction and analysis. The events passed through simulation are digitized and reconstructed (see details in [7]). The latest development of ILCRoot includes:

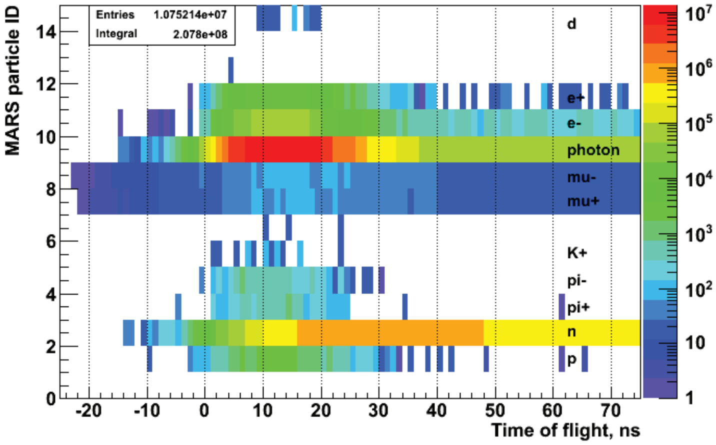

Fig. 4. The MARS15 background particles versus time of flight. The color scale shows absolute yield of different types of particles per 1 ns bin.

- an interface to MARS15 output data with possibility to generate particle multiplicity according to the weight assigned to background particle by MARS15;

- merging detector hits produced by MARS15 background particles with the hits from physics event.

The results presented here are based on the ILCRoot simulation of the small part of the full statistics background particles data provided by MARS15. The simulation was also limited to the hit level only (see the ”hit” definition in Geant4 [6]) and did not include the front-end electronics response.

3.1. Detector layout

In this work the geometry of the ILCRoot detector included the vertex and tracker Si subsystems as the only sensitive detectors. The other detectors such as muon spectrometer, electromagnetic and hadron calorimeters were used as material in interactions with background particles without hit simulation. Other non active components were the shielding nozzles, detector magnet coil, walls and beam-line magnet quadrupoles next to the detector. The detector magnetic field was 3.5 Tesla.

The vertex and tracker Si pixel detector layouts are based on the SiD ILC concept [8]. The sensitive thickness of all pixels in vertex and tracker detectors was set to be 100 microns. The vertex subsystem comprises of five barrel layers and eight end-cap disks. It occupies space close to the beam pipe with radii 3-17 cm and length of 36 cm in Z-direction. The tracker has five barrel layers and fourteen end-cap disks. The sizes of the tracker are 20-120 cm in radial direction and 330 cm in Z-direction.

In addition to the SiD ILC concept, Si pixel forward tracker detector with six end-cap disks was used to cover and improve tracking in forward θ region with high hit occupancy. More details about the vertex and tracking detectors layout can be found in [7].

3.2. The vertex and tracker hits for MARS15 simulated muon beam background

The distributions of the hits in their R (radial position) and Z (position along the beam) coordinates are shown in Figure 5, Figure 6 and Figure 7 for hits from photons, neutrons and e+e- correspondingly. All barrel and end-cap layers are clearly seen for the tracker and vertex detector (Figure 5). The fine structure in R is caused by layout of the barrels in vertex and tracker detectors: they are assembled from the ladders. Picture for neutrons (Figure 6) shows that vertex detector is illuminated less than layers in tracker detector. For e-e+ (Figure 7) most of the hits are observed in the first layers of the vertex detector due to magnetic field of 3.5 Tesla.

Table 2 summarizes the fractions of background photons, neutrons and e+e- making hits in the sensitive volumes of tracker and vertex detectors. Note that the denominators for these ratios include also the particles

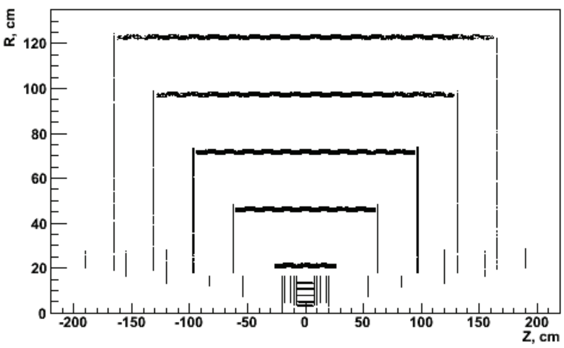

Fig. 5. The R and Z coordinates of the hits for background photons

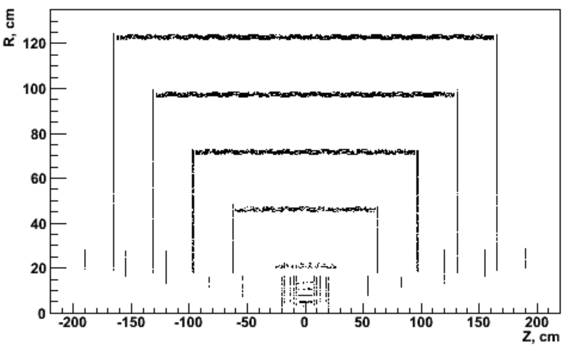

Fig. 6. The R and Z coordinates of the hits for background neutrons

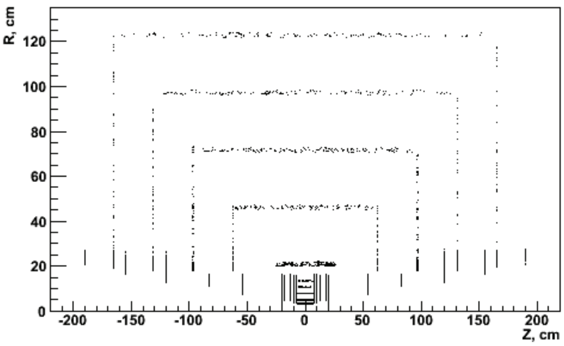

Fig. 7. The R and Z coordinates of the hits for background e+ and e-

Table 2. MARS15 background particles making hits in vertex and tracker detectors

Particles	γ	n	e
Fractions of particles	~2.8%	~4.2%	~43%
Number of particles	~5.0x10^6	~1.7x10^6	~0.4x10^6

coming from a surface of the shielding nozzles far from vertex and tracker detectors and therefore they are missing the layouts of these detectors. Taking into account the absolute yields of the background particles (see Table 1) we can estimate the absolute number of background particles making hits in the vertex and tracker detectors (Table 2). As we can see most of the hits are produced by photons. These results are based on small statistics samples and therefore they are preliminary. Also the layout of these detectors does not have cooling elements.

3.3. The timing of the hits

The time of flight for muon collider background particles coming to the detector has significant spread with respect to the bunch crossing time, especially for neutrons. This well known fact suggests that it can be used for suppression of background registered by detector.

The ILCRoot output for hits provides time of flight (TOF) of hits calculated relative to the muon collider bunch crossing time and including the time of flight of background particles and the time of their propagation in the detector. Figure 8 shows the fraction of hits produced within the time window of TOF versus the width of this time window. The time window starts at the bunch crossing time.

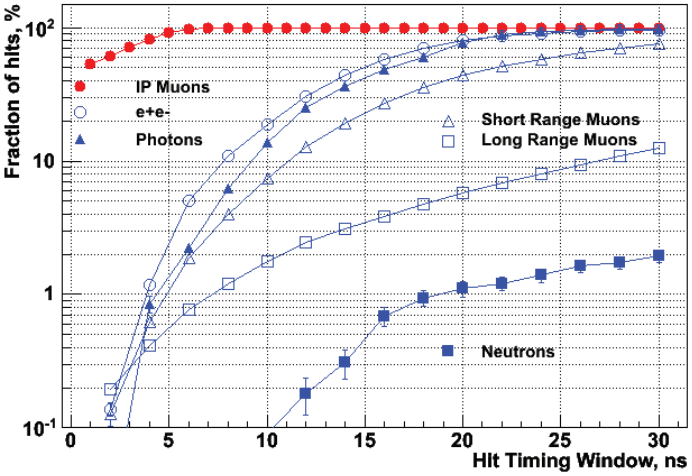

Fig. 8. Fractions of hits within timing window versus the width of window. The red points are for the hits from IP muons, the rest of the points give fractions for the hits from background particles.

The IP muons were simulated in the interaction point IP to represent physics events. The "long range" muons have as their source the beam muon decays simulated in MARS15 at distances from interaction point 25 m $\leq | Z | \leq$ 189 m, "short range" muons (and the rest of background particles) - at distance -1 m $\leq Z \leq$25 m for μ^- beam and -25 m $\leq Z \leq$1 m for μ^+ beam.

As can be seen from Figure 8 that, for example, for the 7-ns time window, the efficiency of IP muon hits is on plateau at 100% while the fraction of background neutron hits is less than 0.1%. We can expect even better background rejection if we can narrow the timing window by choosing its start at the time when IP photon arrives at the same point where the hit from background particle (or IP track) took place. It will require the high precision time tuning of the corresponding delays in the front-end electronics.

The observed significant reduction in number of neutron hits registered in a few nanosecond interval is caused by the fact that low energy neutrons having large elastic cross section are bouncing in the detector multiple times before to interact with detector material and produce the hits. The possible contribution from the tails from previous bunches to an occupancy of the hits in timing window of several nanosecond is negligible because of 10 μs long time between the beam bunch crossings in the muon collider.

4. Conclusion

The recent development in the design of interaction region and machine-detector interface of the 1.5 TeV muon collider demonstrated possibility of suppression of muon beam background by more than three orders of magnitude. The ILCRoot simulation of the vertex and tracking detector hits response to the MARS15 background showed that the use of timing criteria can provide further significant reduction of the occupancy of observed hits produced by background neutrons.

The current plans are to run ILCRoot simulation for the full statistics muon collider background calculated in the MARS15 model. The background rejection due to timing can be improved if the hit timing is calculated with respect to the time of flight of the IP photon having hit with the same coordinate as hit from background particle.

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