NUMERICAL ANALYSIS OF MACHINE BACKGROUND IN THE LHCb EXPERIMENT FOR THE EARLY AND NOMINAL OPERATION OF LHC*

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Abstract

We consider the formation of machine background induced by proton losses in the long straight section of the LHCb experiment at LHC. Both sources showering from the tertiary collimators located in the LHCb insertion region as well as local beam-gas interaction are taken into account. We present the procedure for, and results of, numerical studies of such background for various conditions. The expected impact on the experiment and signal characteristics are also discussed.

THE LHCb EXPERIMENT

The LHCb experiment [1] at LHC is designed to investigate CP-violation and rare decays, mainly in the b-meson sector. It is a single arm spectrometer in the direction of the clockwise beam (beam 1), and is resultingly more sensitive to machine induced background coming from this beam compared to the other. Unlike ATLAS and CMS, LHCb aims for an average rate of one proton-proton interaction per bunch crossing. In order to attain this during high intensity runs, LHCb can operate with a larger $\beta*$ than ATLAS and CMS, which can affect the relative amount of background in the experiment.

MACHINE INDUCED BACKGROUND SOURCES AT LHC RELEVANT TO LHCb

Machine induced background (MIB) is defined as particles arriving at the experimental caverns as a result of beam proton interactions with the gas residue in the vacuum chamber or with the aperture material of the machine. The following MIB sources are relevant to the LHCb experiment [2], though only the first three will be discussed in this document:

- Betatron cleaning inefficiency at IR7
- LHC-wide proton-gas elastic interactions
- Local proton-gas interactions
- Momentum Cleaning Inefficiency at IR3
- Elastic and Diffractive Interactions at ATLAS

On both sides of LHCb there are tertiary collimators (TCT) designed to protect the local quadrupoles and consequently also the experiment itself. Most MIB sources result in halo buildup where beam protons, due to various processes, are slightly off-momentum and off-center with respect to the beam centroid. These can strike the TCTs and produce a secondary particle shower into the experiment. All the listed sources, except the local beam-gas give raise to particle flux into the cavern due to such interactions. The local beam-gas source on the other hand is caused by interactions with gas-residue in the long straight section (LSS) close to the experiment and as such give a direct background.

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ESTIMATION OF MIB SOURCES

Estimation of proton losses are performed individually for the various MIB sources, with the division between the experiment and the machine at an interface plane. For the MIB arising from betatron halo losses, the rate of betatron halo loss on the TCTs is calculated from a multi-turn Sixtrack simulation [3], which calculates the fraction of a beam lost on each collimator in the ring. This simulation includes the beam optics, a machine aperture model, a collimation scheme and either a pure vertical, horizontal or skew beam halo. The proton loss rate and loss distribution on the TCTs is then computed in terms of the total proton fill and the betatron beam lifetime. The loss rates at 7 TeV are shown in table 1 for the LHCb TCTs for beam 1.

Table 1: The proton loss rate on the tertiary collimators of LHCb for beam 1 for a beam lifetime of 30 hours. The rates are computed for nominal optics at 7 TeV and $\beta*$ of 10 m.

Halo type	TCTVB	TCTH
Vertical	2.57×10^6 p/s	0.10×10^6 p/s
Horizontal	7.23×10^3 p/s	0.51×10^6 p/s

Beam-gas interactions in the LHC result in several sources of machine-induced background. Elastic beam-gas events in the arcs either give a beam emittance increase, or a rate of loss on the next aperture restriction for larger amplitude particles. If this loss occurs on a TCT of LHCb, a background particle flux is produced with similar characteristics to the betatron halo contribution. The rates of losses on TCTV and TCTH estimated for 100 hours lifetime and 1/3 nominal current are 5.97×10^5 and 8.32×10^5 p/s respectively, hence of the same order of those originating from betatron halo inefficiency. Inelastic beam-gas events in the LSS give a direct background contribution to LHCb. The source is calculated by distributing proton-H2 inelastic interactions along the LSS according to a pressure profile obtained from simulation or measurements of the vacuum conditions [4]. The proton-H2 interactions are computed with DPMJET [5], and the total rate of inelastic interactions in the LSS calculated from the integral of the pressure profile.

The lost protons, either from halo interactions with the collimator or an inelastic beam-gas interaction, initiate a hadronic cascade which results in the production of a MIB flux towards the experimental cavern.

PROTON INITIATED HADRONIC CASCADES TOWARDS THE LHCb EXPERIMENTAL CAVERN

The hadronic and electromagnetic (EM) showers initiated by the lost protons are calculated using FLUKA [6]. A geometrical model of the LSS of LHCb was constructed, comprising of tunnel, beam pipe, all accelerator elements and the tunnel shielding [7, 8]. The magnetic fields were included through explicit field maps for the final triplet elements and idealized fields for the rest.

The cascades initiated by either proton loss on the TCTs or a beam-gas interaction in the LSS are followed to the interface planes located at the boundaries between the LHC tunnel and the experimental cavern. The showers were propagated with a 20 MeV cut on kinetic energy for charged hadrons, electromagnetic particles and muons, whilst allowing neutrons down to thermal energies. The multiplicity of the EM cascade was controlled with a leading particle bias on the cascade below 1 GeV.

Table 2: The beam 1 LHCb background fluxes for the TCTs, expressed in terms of per proton lost. The rates (per second) can be obtained using table 1. The rates are computed for nominal optics at 7 TeV and β* of 10 m.

Collimator	muon rate [/p]	CH rate [/p]
TCTVB	0.16	0.06
TCTH	0.15	0.15

The betatron halo particle rates for 7 TeV and beam 1 can be seen in table 2, while the full set of results for both beams can be found in [7]. The LSS beam-gas inelastic interactions at 7 TeV also initiate showers to the LHCb interface planes. The proton-gas inelastic interactions generally produce multi-TeV shower products at large angles, of which some are lost locally and some cascade towards the IP and produce the inelastic beam-gas background. For the early machine pressure profile and 1/3 nominal current, the resulting beam 1 LHCb LSS beam-gas MIB rate is 0.17 MHz of charged hadrons and muons flux 0.02 MHz of muons.

At 3.5 TeV, the betatron halo and LSS beam-gas calculations have been performed using the 3.5 TeV optics, collimation scheme and a pressure map dominated by the static vacuum pressure, as described in [4]. The showers from the TCTH into the LHCb cavern generate 0.02 charged hadrons and 0.07 muons above 20 MeV per lost proton, and the absolute rate is under study. The LSS inelastic beam-gas at 3.5 TeV generates 3.33 charged hadrons and 0.24 muons into the cavern from beam 1 for a 20×10^9 protons beam. Estimates of local and distant beam gas losses for 3.5 TeV can be found in [9]. MIB fluxes and phase space distributions for the various cases can be found at [10].

SIMULATION OF MACHINE INDUCED BACKGROUND PARTICLE SHOWERS IN LHCb

In order to ascertain the impact of various MIB sources on LHCb these particles must be imported and simulated in the standard software of the experiment.

The simulation application Gauss [11] is divided into two phases, generation of the initial particles and simulation of their transport through the LHCb detector. In order to simulate the MIB sources a dedicated algorithm has been implemented for the generation phase. This generator imports the files created from the MIB particle shower transport and, using a randomization procedure, generate events consistent with the estimates. In addition to giving the particles the correct kinematic properties and generation probabilities, the generator takes care of correlations between the particles. That is, if for example a certain proton loss at the TCTs resulted in several particles arriving at the interface plane, all of them are generated as a single event in Gauss. The simulation of particle transport and of the physics processes they undergo when traveling through the LHCb experimental setup is based on the Geant4 toolkit [12]. All particles are treated in exactly the same fashion irrespective of their generation procedure.

The digitization application, Boole, simulates the subdetectors responses and their digitization transforming the data in the same format as the experiment electronics and the DAQ system provide. From this point on real data and Monte Carlo data follow the same path through reconstruction and analysis procedures.

ESTIMATED IMPACT OF MACHINE INDUCED BACKGROUND ON THE LHCb EXPERIMENT

By utilizing the applications and algorithms described in the previous section, MIB simulation files are produced. These can be compared to the simulations of proton-proton (Minimum Bias or MB) interactions as well as real data in order to ascertain the viability of our estimates and ultimately to explain various features of the data. When a populated bunch from one beam crosses an empty bunch from the other, the resulting signal is a pure MIB signal as no proton-proton interaction can be present. This can be used as direct verification of the background estimates. A good understanding of the MIB signal characteristics is useful to discriminate and reduce its contribution to pp collisions. In this section two detector response features are considered, particle time of arrival and detector multiplicities.

Time of Arrival

Machine induced background typically arrives on time with the originating proton bunch and intermingle with the particles from collisions at the interaction point (IP) with the protons in the bunch coming from the opposite direction. However this is only true for particles traveling away from the IP, while as the bunch travels towards the IP it is only accompanied by MIB.

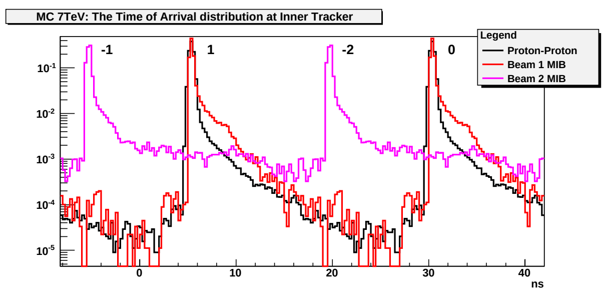

Figure 1: Particle hit timing in one of the LHCb trackers. Proton-proton interaction particles and MIB from beam 1 arrive at the same time, while beam 2 MIB is offset. Interactions are set to occur in all bunch crossings for the purpose of the plot. The peaks are marked with their related bunch number where bunch 0 crossed the IP at time zero.

The LHC has a nominal bunch separation of 25 ns, corresponding to about 7.5 m. This means that the bunches meet each other at every 3.75 m. When MIB from the two beams arrive at these locations they are undistinguishable from each other. In other regions between these locations the timing of the detectors signals would allow to discriminate the MIB originating from the two beams. An example of such a region is shown in Figure 1 for one of the trackers located at about 9.5 m from the IP. One can clearly see that the signal from beam 1 MIB is on-time with the proton-proton signal, while beam 2 MIB is separated by about 10 ns. Due to the single arm design of LHCb the visibility of beam 2 MIB by the spectrometer is highly reduced. The different timing feature of MIB from the two beams can be exploited by special background sensors that have been appropriately positioned upstreams of the LHCb detector.

Detector Multiplicities

As can be seen from figure 2 the particle hit multiplicity distribution of the vertex locator, situated around the interaction point, show different characteristics depending of whether the particles are due to simulated MB interactions or MIB, in this case from beam-gas interactions. Though, as can be seen from the histograms, this also depends on the beam energy in question. In general MIB results in a long tail at higher multiplicities which is not present in the MB events. It can be argued that this is due to the fact that the MIB particle showers have had a longer distance to develop compared to the MB events.

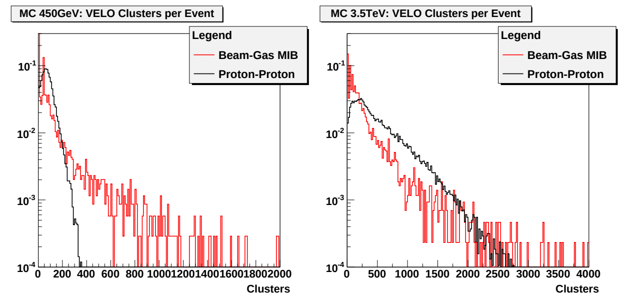

Figure 2: Simulated vertex locator multiplicities. The black line shows the multiplicities due to MB events, while the red is the equivalent for MIB. On the left are the results for 450 GeV beam and on the right for 3.5 TeV.

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