Simulation of Machine Background in the LHCb experiment: Methodology and Implementation

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- Particles arriving at the experiment from interaction of beam protons with residual gas or machine elements upstream and downstream of Interaction Point (IP).
  - We exclude the beam gas interactions occurring in the experiment.

- Fluxes are proportional to machine beam current while background from pp collisions scales with luminosity.
  - Relative effect depends on a given operating conditions.

- Contribute to operation condition of the experiment and may affect trigger and measurements.
Origin of Machine Induced Background

- Beam protons collisions with nuclei of residual gas in long straight section (LSS)

- Beam-gas elastic interactions in the arcs

- IR7 Betatron cleaning inefficiency

- IR3 Momentum cleaning inefficiency

- Cross-talk from other IP, i.e. ATLAS

Different probability of reaching an IP depending on where they originate with respect to it

- machine magnetic structure

- aperture restriction
Estimation of Machine Induced Background

- Estimations depend on the combination of the machine operation parameters
  - Machine optics and apertures
  - Residual gas density estimates
  - Collimation system operation
  - Operation scenarios, e.g. filling scheme

- Variations expected during lifetime of LHC
  - Beam current
  - Residual gas densities
  - Collimation efficiency

- Break down of different sources to evaluate relative “weight” and effect. Combine them to have comprehensive view.

- Snap-shot for a given operation condition of the machine and of the experiment to evaluate impact

Interplay between each others

“direct” influence on MIB production
Simulation Procedure

1. **Beam Loss Estimate**
   - Typically multi-turn tracking of protons
   - Gives loss probability and kinematics
   - Interested in losses close to LHCb

2. **Shower Transport**
   - Pick up particles at loss location
   - Transport with FLUKA to interface plane at LHCb

3. **LHCb Simulation**
   - MIB generator in Gauss*
   - Reads in particles from interface plane
   - Generates particles and pass them to transport in detector (Geant4)

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Further processing with any LHCb software

* Gauss Talk N25-3
Loss Estimate on Tertiary Collimators

Tracking of proton around LHC ring with SixTrack\(^{(a)}\) until they hit vacuum pipe or collimators

SixTrack gives tertiary inefficiency. Rate = ineff * N\(_p\) / lifetime

Sixtrack: Primary, secondary, tertiary halo

TCT (V and H)

Boosted hadrons (up to few TeV)

Collimator alignment

pW : FLUKA or DPMJETIII

TCP TCSG

TCP TCSG

TCP TCSG

DPMJETIII lab frame

FLUKA lab frame

\(^{(a)}\) Fast kick-code tracking, thin lenses model of the ring
SixTrack study of $5 \times 10^6$ particles

- E.g. for phase 1 collimation, $\beta^* = 10$ m at IP8, $E_{\text{beam}} = 7$ TeV

Obtain number of p inelastically interacting with tertiary collimators close to LHCb

Scale to a TCT loss rate for a given beam lifetime and number of protons in the machine (e.g. 30 h and $3 \times 10^{14}$ protons)

This gives for beam1 vertical halo on TCTVB an inefficiency of 0.0009 and a proton loss rate of $2.6 \times 10^6$ p/s
Beam gas interaction rate in the machine depends linearly on the beam current, the pressure profile and the p-A cross section.

The distribution of the interactions follows the pressure profile:
- From simulations for LHC nominal energy \((H_2, CO, CO_2, CH_4)\)
- From measurements for current operation conditions \((H_2 \text{ equivalent})\)

To obtain the rate of particles from inelastic beam-gas distribute p-A events in the LSS according to the pressure profile and a nuclear generator (e.g. DPMJET-III, FLUKA) and calculate secondary cascades to the experiment:
- Integrated with shower transport
- Taking p-H2 as 76 mb, \(I=0.582 \text{ A}\) and \(p=1.3 \times 10^{13} \text{ H}_2/\text{m}^3\) we find \(1 \times 10^5 /\text{s}\) inelastic beam-gas interactions in the LHCb left side LSS

SixTrack combined with DPMJET-III to study multi-turn evolution of beam-gas distributions:
- elastic beam-halo on tertiary collimator
Example:

Rates of elastics protons on collimators for nominal settings at 3.5 TeV beam energy with 156 bunches

<table>
<thead>
<tr>
<th>Tertiary Collimator</th>
<th>Beam1 (proton/s)</th>
<th>Beam2 (proton/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>18.0</td>
<td>19.5</td>
</tr>
<tr>
<td>Vertical</td>
<td>14.4</td>
<td>46.0</td>
</tr>
</tbody>
</table>

The distant beam-gas contribution can be estimated from a rescale of the betatron halo as the impinging protons have very similar kinematics.
Shower Transport

- The LHCb simulation covers -2m to +20m around IP8
- Losses given at TCTs (-74m & -118m) or inside vacuum pipe for ± 270m of LSS
  - Distant/Global: Transport from TCT to Cavern
  - Local: Transport from interaction to Cavern
- Showers need to be transported to an interface plane close to LHCb
  - Agreed at -2.1m and 19.9m to cover all detectors
  - Model interactions with material between primary interaction and interface plane
  - Result is stored and LHCb simulation SW (Gauss) can sample results and proceed

Origin of particles arriving at interface plane for 450 GeV beam1-gas interactions in LSS
Two separate geometrical layouts for LSS upstream and downstream of LHCb

- Up to Q7 (at 270m)
- Include Injection Elements for beam 2 downstream of LHCb

Use appropriate LSS for showers from losses of related incoming beam

Cascade simulation in FLUKA

- 20 MeV cut on charged hadrons and muons
- Leading particle bias for the E.M. cascades
MIB source at interface plane

- MIB source given at interface plane
  - Flat text files, one file per setting & source
  - Event based → Particle correlations
  - Information included to allow analysis and simple rescaling of the source

- MIB particle information
  - Proton loss information (i.e. position, atom, timing, ...)
  - Shower particle information (i.e. PDG id, position, direction, energy, timing, ...)
  - Particles correlations (identifier of originatin proton loss)

- ROOT file translation and rescaling
  - Flat text files, one file per setting & source
  - Event based → Particle correlations
  - Information included to allow analysis and simple rescaling of the source

Particle entry format
- LossId: Loss identifier
- LossT0: Loss LHC clock offset
- LossZ: Loss location
- LossA: Loss interaction atom
- LossW: Loss weight (Likelihood)

- PartFid: Particle ID
- PartX: Particle location @ interface plane
- PartZ: Particle location @ interface plane
- PartO: Particle origin
- PartDx: Particle direction cosine @ interface plane
- PartDy: Particle direction cosine @ interface plane
- PartEk: Particle kinetic energy @ interface plane
- PartDt: Particle time offset from LHC clock @ interface plane
- PartW: Particle weight (Likelihood)
Examples of MIB from Beam1

XY distribution

- Zooming in see shape of shield
- Can see clearly shape of tunnel

Radial distributions at interface plane

- 450 GeV
- 3.5 TeV

- LSS
- TCT Halo

Similar distributions for LSS at different beam energies

MIB from halo at larger radii than that from LSS

Most particles peaked at small radii
Muon flatter
Benefits of timing information in MIB sources

- Correctly simulate the arrival of MIB particles at various detector components
- Needed for realistic trigger and reconstruction effects
- Simulation of fast (40MHz) detectors for distinction between beam1 and beam2-MIB

Benefits of event based MIB sources

- Gives the correct correlation between MIB particles
- Multiplicity variations $\rightarrow$ realistic particle showers
- Needed for realistic trigger and reconstruction effects
- Many events with single particles $\rightarrow$ well behaved
- Few events with large showers $\rightarrow$ trigger interference?
Setup for Generation

- Sources can be simulated independently or together
- Stand-alone or with beam-beam interactions events
- Manipulation of probabilities, position, timing, …

Particle generation step

- Find number of MIB events
- Randomly select event
- Randomly generate particles from event
- Hand over to standard LHCb simulation (Gauss)

Further Processing:

- Simulation of tracking in detector in Gauss (GEANT4)
- Digitization (Boole), Reconstruction (Brunel), Analysis (DaVinci) as for any other MC data
How does the detector sees MIB?

**Time of Arrival**

**Beam1 MIB**
- On-time with interaction
- Could interfere with trigger and reconstruction
- Can be separated from interaction by detectors upstream

**Beam2 MIB**
- Off-time with interaction
- Can be separated from interaction by detectors downstream
Example at the end of the processing

Very useful in understanding data taken early with activity trigger an open collimators (→ only beam gas)

Now more complex situation: physics trigger
collimators closer to beam
How does the detector sees MIB?

Look at bunch crossings where beam1 does not encounter beam2 in LHCb.

Identify differences between MIB and beam gas in detector and devise selection to extract only MIB events so to compare with predictions.

Linear combinations for the different distributions give consistent fractions of MIB particles.
Can process MIB through digitization and reconstruction and look at event display to understand better its characteristics
Beam losses at various energies with a given operation conditions processed all the way

Results of shower transport can be rescaled for different sources with similar effect (elastic and cleaning inefficiency on TCTs)

Any step in the chain can be modified and improved independently from the others

Definition of MIB source file format has been essential