EFFECTS OF MACHINE INDUCED BACKGROUND ON EXPERIMENTS

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Abstract

This paper discusses the possible effects which background from the LHC machine (MIB) could have on the four main experiments: ALICE, ATLAS, CMS and LHCb. The possible effects are discussed and the needs of further simulation work are indicated. Some unclear issues in the input assumptions to these simulations, as well as other open issues are emphasized. In conclusion, the high-luminosity LHC experiments appear to be quite insensitive to MIB even if it were considerably above presently predicted levels. ALICE and LHCb will be more sensitive, but even for them MIB appears to be an issue only if rates exceed available estimates by an order of magnitude.

INTRODUCTION

By Machine Induced Background (MIB) in the LHC experiments, we refer to particle fluxes caused by interactions of the LHC beam protons, except beam-beam collisions at the IP of the experiment itself.

Broadly MIB can be divided to come from 2 sources, although these are not totally independent:

1. beam-gas interactions and
2. proton halo[1] lost at limiting apertures.

The rate of beam-gas interactions depends on the beam intensity and the residual pressure in the vacuum system[2].

The loss rate of proton halo has a more complicated dependence on beam intensity, efficiency of IR3 and IR7 cleaning insertions and machine optics. But it also has contributions from the luminosity in the experiments and beam-gas rate around the ring.

These sources – more or less distributed around the ring – give rise to hadronic and electromagnetic cascades, but also to formation of high-energy (up to the TeV-range) muons. The latter can penetrate large distances in the surrounding soil and reach the experiments even if their source is far upstream. No shielding in the experimental areas can suppress such muons. Their rate can only be reduced by local absorbers that limit the decay-path for high-energy pions and kaons.

The main purpose of this paper is to review what we know about MIB today, what we do not know and what adverse effects MIB could have on the performance and lifetime of the experiments.

[1]Unless otherwise specified, in this paper the term 'proton halo' will be used for any off-beam protons of 7 TeV. This is a wider definition than used by the machine, where halo is always a multi-turn, slowly evolving component.

[2]This statement applies mainly to muon background. Especially elastic and diffractive protons from beam-gas events will be influenced also by the optics and collimator settings - and thus might fall into item 2 above.

BEAM-GAS INTERACTIONS

For simulation-technical reasons the beam-gas contribution to MIB is often divided into two contributions: events within the UX-areas and events elsewhere in the machine. While the first part can be handled entirely by the simulation software of the collaborations, the second needs specific machine simulations, where the lattice and optics of the LHC are properly reproduced. These simulations then must be interfaced by a suitable way with the detector software. As proposed in Ref, [1], this is best done by defining a virtual plane at the UX/machine boundary, where detector specific simulation software takes over. Distributions on such a plane, shown in this talk, are based on simulation results [2] obtained with the MARS15 simulation package [3].

Beam-gas in UX-areas

According to the most recent LHC pressure maps [4] the NEG-coating of the warm experimental chambers will provide an extremely good vacuum. As shown in Fig. 1 we expect about 10 interactions per meter per second at nominal beam current.

During possible single-beam operation at LHC-startup beam-gas events taking place in the region of the IP might be useful for initial alignment. However, the p_T-spectrum of the secondaries is so soft, that only a few useful tracks per hour can be expected in the tracker acceptance for $I = 3.1\,\mathrm{mA}$.

Beam-gas in LHC-machine

In the Long Straight Section (LSS), adjacent to the interaction points, the residual pressure and hence, the beam-gas interaction rate, varies according to the temperature, being higher in the cold sections, as shown in Fig. 2. In the arc it is assumed that synchrotron radiation increases the pressure to 20 times that of the cold LSS section [5]. Beam-gas interaction points are sampled from the residual pressure map and events are generated with a suitable generator, e.g. DPMJET-III [6]. The produced secondaries then have to be transported through the soil, tunnel or machine optics until they arrive at the interface plane defined at 23 m from the experimental IP.

The residual pressure variations are reflected in Fig. 3, where for high-energy muons observed at the interface plane, the coordinates of the initial proton-gas scattering are shown, weighted by the observed muon weight. The

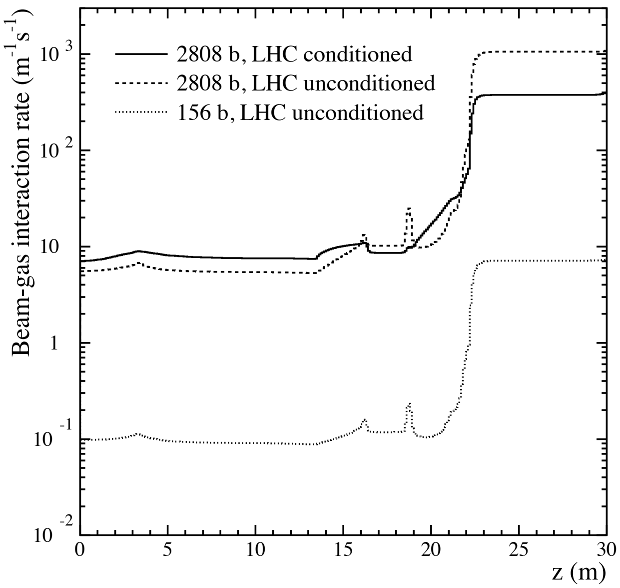

Figure 1: Beam-gas interaction density in the CMS experimental beam-pipe.

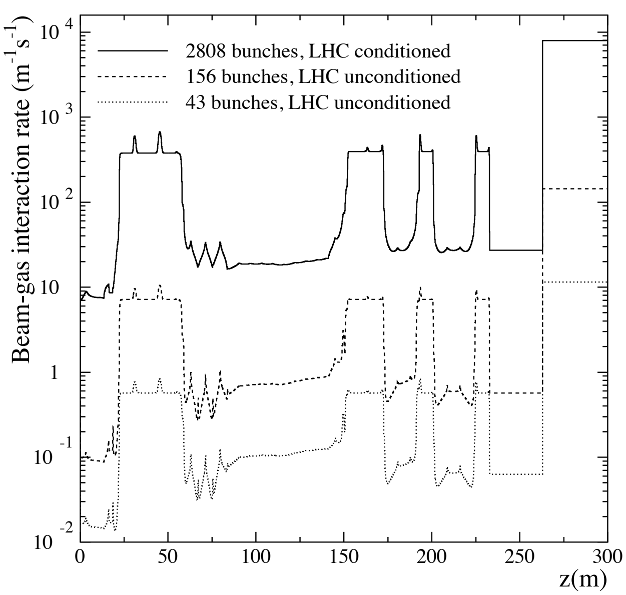

Figure 2: Beam-gas interaction density in LSS and LHC arc.

figure illustrates that the muon flux entering the cavern has non-negligible large-distance contributions from the arc.

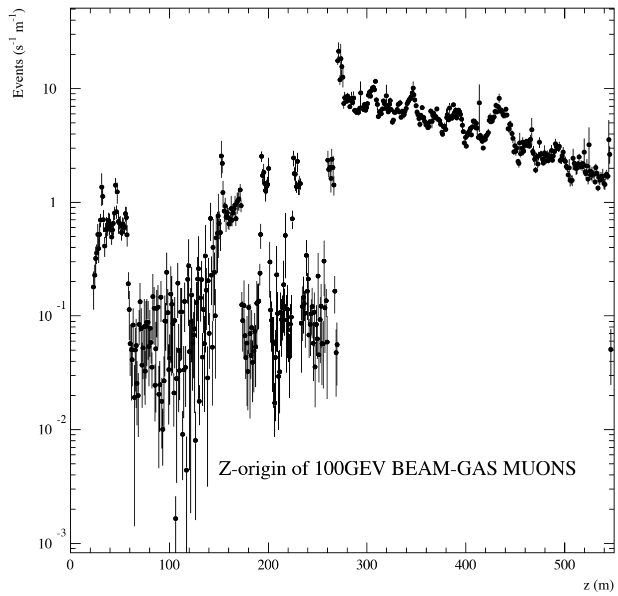

Figure 3: Coordinates of intial proton-gas collisions for E>100 GeV muons observed at the z=23 m interface plane [2].

INTERACTIONS OF PROTON HALO

With its intense high-energy proton beams the LHC requires an extremely efficient cleaning system in order to prevent quenches of the superconducting magnets. This will be provided by two separate cleaning insertions: betatron cleaning at IR7 and momentum cleaning at IR3. The efficiency in the nominal machine has to be >99.9%. In order to protect the inner triplets of the experimental insertions additional tertiary collimators (TCT) have been introduced. These are set such that they remove the tertiary proton halo[3] that would otherwise impinge on the triplet. The main role of the TCT, however, is to protect the triplet in case of accidental beam losses.

Sitting at 150 m from the IP the TCT is an important source of MIB for the experiments. Ideally – from the point of view of the experiments – it should intercept only protons that would otherwise be lost on the triplet. If the presence of the TCT increases losses in the LSS significantly with respect to the unprotected triplet, it will have adverse consequences on the experimental conditions. In available simulations [2] all halo-losses take place on the TCT. Thus a plot similar to Fig. 3 just shows a single sharp peak at the TCT location.

It is predicted [7] that in the nominal machine with a 20 h beam-lifetime about 2×10^6 protons per second are lost on the 'worst side' TCT[4].

[3] Primary and secondary halo will be intercepted in IR7.

[4] The losses on the TCT are highly asymmetric depending on the location with respect to the cleaning insertions.

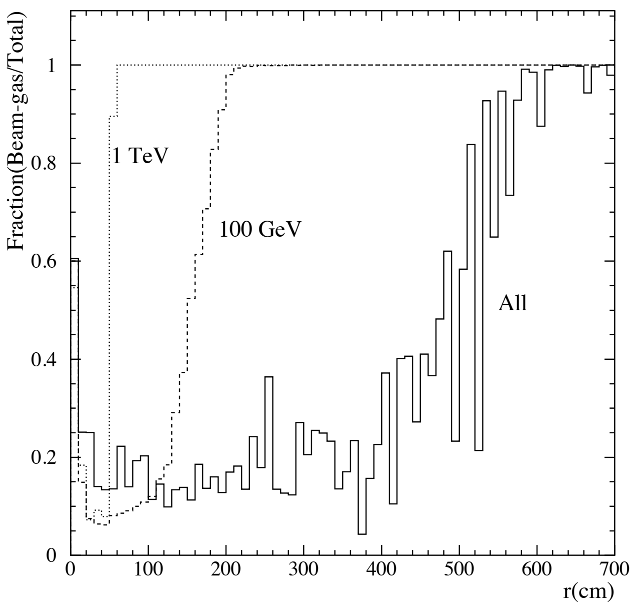

Figure 4: Relative importance of beam-gas scattering to muon background with different energy cuts. The complement to unity comes from proton-halo losses on the TCT.

However, there have been studies [8] predicting that secondaries from elastic beam-gas scattering in the LHC can impinge on the TCT before reaching the IR7 collimators. The rates have been estimated to be about one order of magnitude higher than the losses of normal halo, i.e. in the 10^7 p/s range.

While the muons from beam-gas events, being emitted tangentially from the arc, reach to large radii with an asymmetric distribution those from the halo-interactions on the TCT stay closer to the beam line and are rather symmetrically distributed in azimuth. The relative importance of the two components as a function of radius and muon energy is shown in Fig. 4. It can be seen that close to the beam-line the halo-losses dominate by about an order of magnitude. The radial region of this dominance, however, decreases with increasing muon energy.

CUMULATIVE RADIATION LOAD

The high-luminosity detectors, ATLAS and CMS, have been designed to operate in the hostile radiation environment created by the pp-interactions at LHC. In order to achieve this, the experiments are heavily shielded and radiation hardness of detector technologies has been a central design criterion. In particular, it should be pointed out, that in both high-luminosity experiments the whole beam-line between the detecor and the end-wall of the cavern is hermetically enclosed in massive shielding which also seals the tunnel entry.

The TAS, initially introduced to protect the triplet from collision products, also serves the purpose to stop MIB close to the beamline and to provide a last defense against accidental beam losses. In fact there is no viable way to steer a 7 TeV beam past the TAS such that it could hit the experimental vacuum chamber.

This does not apply to the two low-luminosity experiments. These do not have a TAS and also the forward shielding of both ALICE and LHCb is significantly thinner and less hermetic than of the high-luminosity experiments.

In CMS the attenuation provided by the shielding, together with the large distance, cause that the radiation load on the inner pixel detector, due to one proton lost on the TCT, is about 5 orders of magnitude lower than that from one pp-collision at the IP. Assuming that each of the high-luminosity experiments would integrate $500\,\mathrm{fb}^{-1}$ in 10 years (5×10^{16} pp-interactions), there would be some 2×10^{14} protons lost on the TCT over the same time. Thus the radiation load of 10 years worth of TCT losses would be equivalent to roughly 10 s of normal high-luminosity operation. Similar arguments show that the losses from beam gas in the machine and the UX are of the same order of magnitude. Thus MIB is totally negligible for cumulative damage in the high-luminosity experiments.

LHCb is also designed for high radiation doses and despite weaker shielding around the beamline, MIB is not expected to be an issue for cumulative radiation damage.

ALICE, however, will take data only at very low luminosities, not exceeding $3 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in pp-mode. Together with weak forward shielding this implies that MIB contributes a significant fraction of the total radiation exposure.

It should be remarked, however, that hot spots, either spatially (MIB focused by quadrupole fields) or in time (accidents of significant spikes in background) could lead to local damage or instantaneous single failures that might accumulate over time to reach levels that compromise detector performance.

EFFECTS OF MIB ON TRIGGER

ATLAS and CMS

The total predicted rate of MIB muons – radial distributions are shown in Fig. 5 – entering the experimental caverns is comparable to the L1 trigger rate of the order of 100 kHz. However, both high-luminosity experiments require already at L1 that a triggered muon points to the IP. Even if this pointing is done with fairly wide tolerances, it still reduces the geometric acceptance for MIN-muons dramatically. Therefore the rate is negligible compared to the L1 bandwidth. Random hits by the MIB might in theory lead to accidental IP-pointing, but at full luminosity the rate of such hits will be dominated by the pp-created neutron background in the UX areas [1], which is well understood.

At the High Level Trigger (HLT) level information from the Tracker is included in the muon reconstruction, ensur-

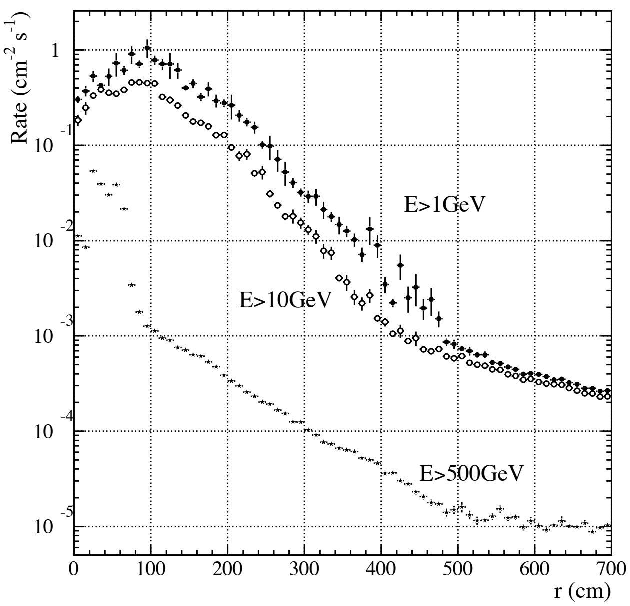

Figure 5: Radial distribution of muons at the z=23 m interface plane. Beam-gas and proton-halo losses (on TCT) are included [2].

ing that all triggered muons originate form the IP.

A high-energy (E >100 GeV) muon traversing calorimeter material can undergo a radiative energy loss, which results in local deposition of a significant fraction of the muon energy. Such losses might lead to fake missing E_T (MET) triggers. The rate of such events can be roughly estimated to be of the order of 1 Hz, which is many orders of magnitude below the L1 bandwidth. However, it is not clear to what extent HLT is able to filter out such events, especially if they happen to overlap with a real event at the IP. Given about 2 orders of magnitude with respect to the HLT bandwidth this is unlikely to become a problem, but it should not be completely ignored as a potential issue.

In both cases, however, timing might help to reduce the rate. Most often the fake MIB-induced trigger will lie outside the expected time window for a particular detector. For instance the possible fake-MET triggers are likely to be in-time only in the downstream endcap calorimeters.

LHCb

In the L0μ trigger of LHCb MIB overlapping with a Minimum Bias event can occupy few percent of the bandwidth [9]. This value is based on losses at the TCT at the 10^6-level. This trigger rate can be reduced by shielding in the tunnel close to the VELO detector. At present part of this shielding has been staged.

ALICE

The ALICE triggers have very small rejection rates, of the order of 1000 and are based on event characteristics (high multiplicity) that are not expected to be sensitive to MIB. In addition the L0 interaction trigger will efficienctly discriminate beam-background.

BACKGROUND TO PHYSICS

SUSY searches

SUSY events will typically be characterized by jet activity associated with missing E_T (MET). As discussed in the context of the trigger, an energetic muon has a small chance to deposit a very large energy in a calorimeter. If such a fake energy deposition happens to overlap with a hard QCD event at the IP, it can resemble a SUSY event with large MET. Although such an overlap will be very rare, the rate might still be comparable to the rate of real SUSY events. Offline handles probably can be devised to recognize such cases, but depending on the rate, it is a potentially significant pollution of the data sample.

Luminosity measurement

Several techniques have been studied and implemented by the collaborations to perform the luminosity measurement. Except for TOTEM, which is specially designed for this purpose, most luminosity monitors do not have pointing capability and therefore will not be able to tell if a track originates from the IP-region. For all such systems the accuracy of the luminosity determination will be influenced by the uncertainty in the MIB-contribution to the measurement.

In particular, collisions of satellite bunches with the nominal bunch might be an issue in this respect. Such collisions will not happen at nominal crossing angle, but in early running, with head-on collisions, satellite bunches could collide at 37.5 cm from the IP with normal bunches. The relative luminosity would correspond to the relative population of the satellite bunch. Thus, if the latter is too high, it could introduce a bias in the early luminosity determination.

Forward physics

Forward physics studies looking at rapidity gaps can obviously suffer from MIB filling the gap. Without tracking and IP-pointing capability these effects are irrecoverable. In addition MIB is likely to influence the studies of forward energy flow, but exclusive MIB simulation samples are needed to quantify these effects.

EARLY OPERATION

When LHC starts up the experiments will use the initial low luminosity to explore the behaviour of their triggers. Therefore, the trigger thresholds will be much lower at start-up than at the nominal LHC. This will make them significantly more sensitive to background, including MIB.

While the LHC, from the point of view of not quenching magnets, could operate with less efficient cleaning at low beam intensity, it should be remembered that this could compromise the early trigger studies of the experiments by introducing an excess background trigger rate.

It should be emphasized that essentially all simulations so far have considered only the nominal machine. At lower luminosity the relative importance of MIB – even for same cleaning efficiency and vacuum quality – will be higher alone by the fact that MIB is mostly related to beam intensity and not luminosity.

DETECTOR ALIGNMENT

All experiments recognize that MIB-muons could be useful for alignment of the detectors. In particular, energetic muons, being parallel to the beam-line, could be a useful means to inter-align the endcap detectors on each side of the detector. However, a prerequisite of using MIB for this purpose is a capability to trigger on it. Studies in this direction with existing hardware are in progress in both ATLAS and CMS.

Should the LHC start up with a prolonged period of single beam, then MIB (and cosmic muons) will be the only means to align the detectors. MIB will arrive at the IP in time with the bunches and thus will be a suitable reference to time-in detectors and triggers. Despite these possibilities to use MIB beneficially, it is clear that the experiments would prefer to get background-free collisions from the start on.

MEASURING THE BACKGROUND

In order to control its effects, even if small, the experiments need to measure the MIB.

Ideally this should be done in conditions as similar as possible to the normal collider operation. Especially at higher luminosities it is possible that due to the absence of beam-beam effects a measurement performed during single-beam operation would not be representative.

ALICE and LHCb will always have some periods of non-colliding beam since the abort and injection gaps in the LHC beams meet only at the two high-luminosity insertions. The latter, therefore, will never see single beam in normal operation.

One proposal to accomplish the MIB measurements is to have some non-colliding bunches in the beam structure. In order to ensure that only MIB gets measured, enough time must be allowed for products of the last pp-collisions to disappear and detectors to terminate signal collection. The exact times for this still need to be specified, but are likely to be of the order of a few hundred ns. If bunches would be removed from a bunch following an injection gap[5], the detector would be 'clean' already when the next bunch-train arrives and the non-colliding time could be halved, thus saving some luminosity.

Such special conditions will not be required in every fill, but only from time to time to monitor the conditions and initially to establish the first background measurement.

Obviously it is up to the LHC experts to decide what is technically the best possibility to provide the most representative non-colliding conditions with a minimal price in luminosity for physics.

SIMULATION NEEDS

The first complete studies of MIB in the experiments date back to 1996 [1]. Since then further studies have been performed by various groups for all experiments. Unfortunately the present picture is rather confusing, probably mostly due to different assumptions used in the simulations over the years, but also because most simulations have considered only one source of MIB at a time. Thus, no up-to-date, complete and commonly agreed simulations are available at the moment.

By now a fairly consistent picture of the loss sources is available from the vacuum and collimation groups. It would be highly desirable to repeat the MIB simulations for all experiments using consistent and agreed input. However, past experience has shown that these MIB simulations are very complex and sensitive to small variations. Therefore independent simulations by more than one group would be appreciated in order to be able to cross-check the results and to estimate uncertainties.

A special issue is that up to now all MIB estimates have been based on biased Monte Carlo[6]. The biasing has been mandatory in order to obtain even close to sufficient statistics in reasonable CPU time. The biasing, however, results in a spread of statistical weights of the particles arriving at the interface plane. While this makes their use in non-biased MC codes (e.g. Geant4) difficult, even more problematic is that a biased simulation is intrinsically incapable of reproducing any correlations. The latter would be needed to reliably study the effects on trigger and physics. It is probably not possible to do all forthcoming simulations in non-biased mode, but some smaller non-weighted sample files would be useful in order to get an idea of the correlations.

OPEN ISSUES & QUESTIONS

While the contributions from inelastic beam-gas scattering and from proton-halo losses on the TCT appear to be rather well understood, there remain several issues that need further clarification or call for detailed simulation studies:

[5] The abort gap is used for detector timing and its length should not be modified.

[6] Biasing in this context does not mean that the results would be biased. The biasing applies only to the statistics, i.e. the particle population is artificially increased in regions of phase space that are of interest - and correspondingly reduced elsewhere.

- The effect of elastic scattering in the arcs appears contradictory. Can the scattered protons be lost on the TCT before they are intercepted by the cleaning insertions. If so, what would be the rate? A related specific issue is, if diffractive or elastic protons from ATLAS – operating at 4 orders of magnitude higher luminosity than neighboring ALICE – might have an influence on the latter.
- It has been predicted [7] that the losses on the TCT can momentarily increase by about 2 orders of magnitude. It remains to be clarified what the origin of these spikes is, how often they occur and under which conditions.
- While no mechanism has been identified that could steer 7 TeV protons past the TAS on the ATLAS/CMS experiments, it has been pointed out that for protons with energies E <5 TeV it is possible to impinge on the experimental beam pipe. The rate of these should be quantified since their effect might be significant with respect to other background.
- The present pressure maps do not include the TCT or other elements with potentially increased outgasing due to the radiation-load [10]. In these the pressure could be significantly higher than elsewhere. This calls for some quantification.

The issue of total losses on the TCT, e.g. item 1 above, appears to be of crucial importance and at the moment the the spread of values is an order of magnitude. A consistent (e.g. wrt beam-lifetimes) and commonly agreed number should be worked out urgently.

In general, it would be important to agree on a consistent set of assumptions to be used as input values for all forthcoming MIB-simulations.

SUMMARY

Both high-luminosity experiments, ATLAS and CMS, are designed for such high radiation loads that MIB – at predicted levels – appears totally negligible in this respect. The same is true, albeit to a slightly lesser extent, for LHCb. ALICE, however, is designed for much lower radiation exposure and is not as heavily shielded. If MIB increases above presently predicted levels, its first adverse consequence most likely will be excess radiation damage in ALICE.

Concerning effects on the trigger, the only potential issue identified so far in ATLAS/CMS is the possibility of fake missing E_T due to radiative losses of very energetic muons. However, present estimates do not indicate that this would reach rates that could come close to constituting a real problem. In LHCb MIB, overlapping with a MinBias event, can fill a non-negligible fraction of the L0 bandwidth according to present estimates (order of 10^6 protons lost on TCT per second). A significant increase of this loss rate might severely compromise LHCb trigger efficiency.

It should be noted that the experiments will start data-taking with triggers wide open, i.e. with very low thresholds. Thus they will be initially much more sensitive to background effects. In view of this, it is desirable that MIB is minimized as much as reasonably possible already from the beginning of LHC operation, even if machine protection considerations would not yet impose full cleaning efficiency.

All experiments will utilize MIB to some degree for their detector alignment. It will certainly be a useful tool to inter-align endcap detectors. Should LHC start up with a prolonged period of single beam, MIB can be used to time in trigger and detectors already prior to collisions.

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