Machine-induced Background in the Near-beam Detectors (IR1/IR5)

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Summary

A set of simulations is done for the near-beam detectors located in IR1 and IR5 of the LHC to estimate the machine-generated background components resulting from the momentum cleaning inefficiency and beam-gas interactions.

1. Introduction

The near-beam detectors are considered by the ATLAS and CMS experiments for measurements of the elastic and/or diffractive processes in $pp$-collisions at LHC. These detectors must operate at very small distances from the circulating beam. Some components of the beam halo can be observable at these distances.

The transverse halo of the beam consists mostly of on-momentum protons with large and increasing with time betatron amplitudes. The longitudinal halo consists of the off-momentum protons losing their energy due to synchrotron radiation. To intercept both the halo components the collimation system of LHC consists of the two parts.

The betatron cleaning insertion IR7 houses the betatron collimators and the momentum cleaning insertion in IR3 houses the momentum collimators. The two-stage collimation scheme assumes that the primary halo hits the primary collimators first. Then out scattered protons (so called secondary halo) either come back to the primary collimator after a number of full turns in the machine or they hit the secondary collimators. Protons scattered at the secondary collimators populate the tertiary halo. The tertiary collimators protect the inner triplets in the experimental insertions. Thus proton losses are concentrated at the collimators to prevent radiation induced quenches of the superconducting magnets both in the arcs and insertions.

Moreover the betatron collimators limit the transverse size of the primary halo while the momentum collimators limit the smallest proton momentum in the primary halo. Obviously the near-beam detectors must be outside these limits. But even in that case the secondary/tertiary halo can contribute to the background.

The other important contributions to the machine-induced background can result from the nuclear interactions of the beam protons with the nuclei of residual gas. The majority of beam-gas interactions occur in the arcs and dispersion suppressors far from the near-beam detectors.

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Elastically scattered protons and the most energetic protons produced in the inelastic interactions will not be lost close to the beam-gas interaction point. They will travel for long distances from the interaction point or even make full turns in the machine forming a sort of a short-term halo. Other products of inelastic interactions upstream of the detector but not too far from it will be also able to reach the detector. Both the “distant” and “local” beam-gas interactions are considered in this note.

2. ATLAS ALFA at high-$\beta^*$

ATLAS ALFA (Absolute Luminosity for ATLAS) detectors have to measure elastic scattering at very small angles in order to get a handle on the absolute luminosity at the interaction point of ATLAS [1]. The Roman Pots with their detectors will be installed on both sides of the IP1. The Roman Pot technique will make it possible to approach the beam to distances in the millimeter range. For the position sensitive detectors scintillation fibers have been chosen. The special high $\beta^*$ optics ($\beta^* = 2630$ m in IP1) will be used in combination with rather few bunches of low intensity. The other requirement is the reduced beam emittance of $1\,\mu\text{m}\cdot\text{rad}$ instead of the nominal one ($3.75\,\mu\text{m}\cdot\text{rad}$). The resulting luminosities will be in the range of $10^{27}\,\text{cm}^{-2}\cdot\text{s}^{-1}$ to $10^{28}\,\text{cm}^{-2}\cdot\text{s}^{-1}$. Roman Pots will be placed between Q6 and Q7 in the LHC lattice, located near 240 meters away from the IP1.

2.1. Momentum cleaning and distant beam-gas interactions

The simulations of the momentum cleaning are described in [2]. Here we do very similar simulations with the same code STRUCT [3] to estimate the secondary/tertiary halo shape at the detector location. The LHC lattice and optics version 6.5 with the special high $\beta^*$ optics in IR1 (courtesy of H. Burkhardt) is used as the input. We must note here that the reduced emittance requires adjusting the transverse positions of the momentum collimators in IR3. The baseline setting for the primary collimator is $15\sigma_x$, where $\sigma_x$ is the horizontal $\text{rms}$ size of the beam at the primary collimator, for the normalized emittance of $3.75\,\mu\text{m}\cdot\text{rad}$. Leaving the same margin of $\sim 7\sigma$ for the betatron oscillations we come to the new collimator setting of $21\sigma_x$ for the normalized emittance of $1.0\,\mu\text{m}\cdot\text{rad}$.

Momentum cleaning simulation starts from the impact of the primary halo proton at the primary collimator. The turn by turn tracking is being done until the proton is absorbed in one of the collimator jaws or reaches the other limiting aperture. Every pass through the detector plane is recorded as a “background hit”.

Simulation of the distant beam-gas is pretty much similar except for the beginning. Here the source is distributed along all the arcs and dispersion suppressors. The simulation starts at some initial point of the ring with selection of the coordinates and angles of the proton from the beam phase space. The path length to the beam-gas interaction is selected randomly from the uniform distribution and the beam proton is tracked to the point of interaction. Interactions in the long straight sections are neglected to avoid double counts with the local beam-gas simulations. Assuming that the gas composition in the arcs and dispersion suppressors is dominated by hydrogen we simulate $pp$-interactions only. If the interaction is elastic or there is an energetic proton (energy loss less than 1%) in the final state of inelastic interaction then tracking is continued. Otherwise the proton is counted as lost at the point of interaction.

The simulations were performed for the Beam 1 only because the high-beta optics for the Beam 2 was not finished at that time. The hit maps i.e. the files containing all the hit records at 240 m are the main results given to the ATLAS ALFA community for the further studies. Here
we show the vertical shape of the momentum halo and the vertical distribution of the impacts due to distant beam-gas interactions in Figure 1.

Figure 1 The vertical distribution of the background hits at 240 m from IP1 from the secondary/tertiary halo produced by the momentum cleaning system (solid histogram normalized per 1 cleaning event) and from the distant beam-gas interactions (dashed histogram normalized per 1 beam-gas interaction in the arcs and dispersion suppressors). The vertical coordinate $Y$ is measured in units of the vertical $rms$ size of the beam at 240 m.

2.2. Local beam-gas interactions

The geometrical model of the beam-line has been developed to provide the input for numerous cascade simulations in the long straight section LSS1. This model describes 3D geometry and magnetic fields of all the lattice elements starting from MQM.B7 left up to MQM.B7 right, beam pipes, beam screens, collimators/absorbers etc. The elements sequence corresponds to the LHC lattice version 6.500 and the magnetic fields are defined by the optics version. Here the high-beta optics version 6.5 is used.

The residual gas distribution along the straight section is used to define the source term for simulations. The density of the residual gas molecules has been calculated using the data published in [4]. We used the case of 43 bunches with $1.15 \cdot 10^{11}$ protons per bunch after machine conditioning. Photonic desorption (PSD) is the main mechanism of the gas molecules desorption at cryogenic temperatures for beam current below 20% from nominal value. Number of the PSD photons is proportional to the beam current. To estimate residual gas density corresponding to our case - the $10^{10}$ protons per bunch - the partial gas density for cold parts of the LSS1 was reduced proportionally to the beam current reduction. After such scaling the average H$_2$ equivalent density has been decreased from $4.2 \cdot 10^{11}$ to $3.4 \cdot 10^{11}$ mol/m$^3$. Averaged (over all the warm and cold parts) nuclear composition of the residual gas is presented in the Table 1.

Table 1: Estimated nuclear composition of the residual gas in LSS1 for the case of 43 bunches, each of $10^{10}$ protons.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>atomic part</th>
<th>weight part</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.925</td>
<td>0.500</td>
</tr>
<tr>
<td>C</td>
<td>0.069</td>
<td>0.448</td>
</tr>
<tr>
<td>O</td>
<td>0.006</td>
<td>0.052</td>
</tr>
</tbody>
</table>

- 3 -
The gas density of $3.4 \cdot 10^{11}$ mol/m$^3$ results in the rate of 3 inelastic interactions of beam protons (43 bunches with $10^{10}$ protons per bunch) with residual gas nuclei per second in one half of LSS1. This rate is used for the absolute normalization of the simulation results.

Beam protons interact with the residual gas nuclei along the trajectory of the beam. These interactions form the initial source of this kind of the background. Products of the primary interactions can pass all the way to the detector inside the beam pipe, or they can hit the beam pipe or the beam screen and initiate nuclear-electromagnetic cascades. Products of these cascades can hit sensitive elements of the detector along with the secondary particles from primary interactions. Particles are recorded at the plane of the luminosity monitor (~240 m from IP1) inside the vacuum chamber of the Beam 1.

Simulation of the cascades in the long straight section LSS1 is done with MARS/IHEP program package [5]. Beam-gas interactions in the right half of the LSS1 were considered as a source of background on the right luminosity monitor.

Figure 2 The vertical distribution of the charged particles hits at 240 m from beam-gas interactions in LSS1. Solid histogram corresponds to charged hadrons, upper dashed histogram – to electrons, lower – to muons.

One can see in the Fig.3 that local beam-gas background is negligible at distances less than 13 mm compared to the distant beam-gas, but is dominating at larger distances.

Different components of hadronic background are shown on Fig.4. Charged pions are dominating. Two holes on the wings of proton distribution were caused by the shadowing of protons by the beam screen inside vacuum chamber. There is no such effect for pions because they are generated mostly in close beam-gas interactions and secondary cascades starting in beam screen and vacuum chamber material. Protons are collected in many distant initial interactions and therefore are partly collimated by the beam screen. There is practically no deposition of pions produced in the left half of LSS1 into right RP240. At the same time the left half gives 20 % - 50 % addition to proton distribution generated in the right part of the LSS1.
Figure 3  The vertical distribution of the background hits at 240 m from local beam-gas interactions (dashed histogram – charged hadrons component) compare to the distant beam-gas (solid histogram - protons) background. Last one was normalized per 1000 h beam lifetime.

Figure 4  The vertical distribution of the background hits at 240 m from local beam-gas interactions (dashed histogram – protons, solid – $\pi^+$, dash-dotted – $\pi^-$).

3. CMS RP220

CMS/TOTEM Roman Pot detectors [6] will be located at 220 m from IP5. Diffractive protons with a momentum loss larger than 2% will be detected by the RP stations. The minimum distance of a detector to the beam on one hand and constraints imposed by the beam pipe and beam screen size on the other hand will determine the proton acceptance of a RP station. The detectors are assumed to be fully efficient at a distance from the beam which is proportional to
the beam size \((10\sigma_{xy}(s))\) plus a constant \((\sim 0.5 \text{ mm})\) which takes into account the distance from the edge of the sensitive detector area to the bottom of the RP window,

3.1. Distant beam-gas interactions

The simulations were done in the same way as described in 2.1 but for the nominal collision optics version 6.5 and for the baseline settings of all the collimators. The hits were recorded at both 220 m and 420 m from the IP. The horizontal and vertical hit distributions are shown in Figures 5 and 6 respectively.

![Figure 5](image1.png)  
**Figure 5** The horizontal distribution of the background hits at 220 m from IP5 from the distant beam-gas interactions (normalized per 1 beam-gas interaction in the arcs and dispersion suppressors). The central part \((|x| < 7 \sigma_x; |y| < 7 \sigma_y)\) of the distribution is not shown.

![Figure 6](image2.png)  
**Figure 6** The vertical distribution of the background hits at 220 m from IP5 from the secondary halo produced by the distant beam-gas interactions (normalized per 1 beam-gas interaction in the arcs and dispersion suppressors). The central part \((|x| < 7 \sigma_x; |y| < 7 \sigma_y)\) of the distribution is not shown.
3.3. Local beam-gas interactions

The geometry setup of the LSS5 is similar to LSS1 (see Sec.2.2) but not the same. The nominal collision optics version 6.500 of IR5 is used. The residual gas density distribution along the LSS5 was taken from [4] (data in Fig.4f - CMS after machine conditioning, nominal bunch intensity and 2808 bunches). The gas composition averaged over the LSS5 is equal to 0.26, 0.26 and 0.48 weight parts for H, C and O nuclei respectively. The corresponding interaction rate is equal to $3.6 \times 10^4$ inelastic interactions of beam protons with residual gas nuclei per second in one half of LSS5.

Simulation of the cascades in the LSS5 structure was done with MARS/IHEP program package. Beam-gas interactions in the entire LSS5 were considered as a source of background on the right RP220. The horizontal and vertical profiles of the local beam-gas background rates are illustrated in Figure 7 in comparison with those resulting from distant beam-gas interactions. In vertical plane local beam-gas background is dominating at distances greater than 9 mm from the beam orbit and it is negligible compared to the distant beam-gas protons at smaller distances.

![Figure 7](image-url) The horizontal (left) and vertical (right) distributions of the background hits at 220 m from local beam-gas interactions (dashed histogram – charged hadrons component) compared to the distant beam-gas protons (solid histogram). Distant beam-gas was normalized per 100 h beam lifetime.

4. FP420 in IR1 and IR5

FP420 is a proposed magnetic spectrometer, consisting of detectors installed at ±420 m from the interaction point (IP1 or/and IP5) [6]. The FP420 detector consists of a system of moveable sensors which measure the spatial position as well as the arrival time of the outgoing protons at several points in a 10 m region near 420 m. The FP420 spectrometer is expected to operate with the standard high-luminosity optics.

The goal of FP420 is measurement of the off-momentum protons produced in $pp$-interactions in the IP. The location at ~420 m from the IP is physically possible because of the so-called missing dipole in the LHC lattice. The relatively high horizontal dispersion $D_x$ at this location converts the momentum offset $\delta = 1 - p/p_0$ to the horizontal displacement $\Delta x = -D_x \cdot \delta$ with respect to the closed orbit.
At the same time the minimum distance of approach to the beam orbit will be limited by the primary momentum halo. The primary momentum collimators cut the primary halo at $\delta \equiv \delta_{\text{cut}} = -x_{\text{col}} / D_x(s_{\text{col}})$, where $x_{\text{col}}$ corresponds to the edge of the collimator jaw ($\delta = \delta_{\text{cut}}$ when the horizontal betatron amplitude is equal to zero). The horizontal shape of the secondary/tertiary momentum halo is shown in Figures 8 and 9.

![Figure 8](image1.png)

**Figure 8** The horizontal distribution of the background hits at 420 m from IP1 from the secondary/tertiary halo produced by the momentum cleaning system (normalized per 1 cleaning event).

![Figure 9](image2.png)

**Figure 9** The horizontal distribution of the background hits at 420 m from IP5 from the secondary/tertiary halo produced by the momentum cleaning system (normalized per 1 cleaning event).

The locations of the peaks there correspond approximately to the edge of the primary halo which occupies the entire region $x > -\delta_{\text{cut}} \cdot D_x(420 \text{ m}) \approx x_{\text{peak}}$. Not only the peak position but the shape of the distributions is different for Beam 1 and Beam 2 because the optics of Beam 1 and Beam 2 is not identical. On the other hand the horizontal density of the halo $dN/dx(x)$
decreases quickly at $x < x_{\text{peak}}$ confirming the high efficiency of the both collimation systems. We must remind here that the betatron collimators in IR7 take an active part in the momentum cleaning process as it is shown in [2].

The contribution of the distant beam-gas interactions to the background hits at FP420 is shown in Figures 10 and 11. The slope of these distributions is not as sharp as in the case of the momentum halo. Therefore the distant beam-gas component can contribute to the background at larger distances from the beam orbit.

![Figure 10](image1.png)

**Figure 10** The horizontal distribution of the background hits at 420 m from IP1 from the distant beam-gas interactions (normalized per 1 beam-gas interaction in the arcs and dispersion suppressors).

![Figure 11](image2.png)

**Figure 11** The horizontal distribution of the background hits at 420 m from IP5 from the distant beam-gas interactions (normalized per 1 beam-gas interaction in the arcs and dispersion suppressors).
5. Conclusion

The results of the presented set of simulations are being used by the ATLAS and CMS forward physics community. They help to optimize the near-beam detectors positioning with respect to the beam orbit. Also these results help to estimate the possible contribution of the presented components to the machine induced background. The source intensities i.e. the momentum cleaning rate and the absolute rate of beam-gas interactions even if used in the illustrations are the external factors but not the results of the present study.

References


