Study of beam-gas interaction at the LHC for the Physics Beyond Collider Fixed-Target study

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Keywords:

Summary

Among several working groups formed in the framework of Physics Beyond Colliders study, launched at CERN in September 2016, there is one investigating some specific fixed-target experiment proposals using beams of the Large Hadron Collider (LHC). This note concerns the study of a high-density unpolarized or polarized gas target to be installed upstream the LHCb detector using storage cells to enhance the target density. This work studies the impact of the interactions of 7 TeV proton beams with such gas targets on the LHC machine in terms of particle losses. The overall compatibility with the planned high-intensity program of the LHC is also discussed.

1 Introduction

The aim of the Physics Beyond Collider program [1, 2] is to investigate possible future experiments to be implemented at CERN’s accelerator complex in order to exploit the vast set of features offered by the Large Hadron Collider (LHC) and High Luminosity LHC (HL-LHC). In this framework, a working group was formed to study the proposals of some specific solid and gaseous fixed-target experiments at LHC [3].

Preliminary studies with internal gas targets have already been performed exploiting SMOG (System for Measuring the Overlap with Gas), a gas injection system installed at the LHCb experiment [4, 5]. Possible improvements of the setup foresee the installation of a cylindrical open-edge storage cell (SC) to be positioned along the LHC pipe around the beam. Both polarized and unpolarized gases could be injected at the center of the cell, assuming an approximately triangle-shaped longitudinal density profile with a central peak at the injection point. This mechanism allows reaching a higher target density while preserving an acceptable vacuum pressure in the beam pipe nearby, as described in [6]. Different gas species, such as H, D, He, Ne, Ar, Kr, N₂, O₂, Xe and isotopes, are considered in the context of this experiment.

The impact of a 7 TeV LHC proton beam on such internal gas targets is expected to
release interaction debris and scattered protons, being deviated from their orbit after losing part of their initial energy in any kind of interaction. These products could in principle dangerously impact sensitive machine elements, e.g. magnets, potentially causing quenches or even damage. It is then necessary to study in detailed simulations the behavior of the debris to check the safety of the experimental setup.

The aim of this work is to study to what extent the scattered protons are expected to impact the machine and where the losses are likely to be located, depending on the target gas species and density. The impact of the local showers on the nearby magnets, in particular the triplet, is not treated and should be studied separately. Beam-target interactions are simulated, separating the elastic and inelastic interaction cases, and the collision products are tracked through the accelerator in order to obtain simulated loss distributions around the ring. Both H and Xe gas target have been studied as extreme cases in terms of atomic weight (all other cases are expected to be in between them). The loss rates, calculated for a given gas target density, are finally compared with the magnet quench limit, in order to determine the maximum acceptable gas density for which the machine is still safe.

2 Simulation setup

2.1 First simulation setup: elastic interactions

Different simulation setups were used to study the impact of elastic and inelastic beam-gas interactions. For what concerns the elastic case, as a first step, a 7 TeV proton pencil beam is forced to elastically interact with a stationary H or Xe gas target thanks to a customized source.f routine implemented in the Monte Carlo code FLUKA [7, 8], and the angular and energy distributions of the scattered protons are dumped after the interaction (see Figure 1).

Secondly, a beam distribution is prepared by randomly sampling coordinates from Gaussian distributions, matched to the transverse phase space at the s-location in the LHC where the interaction takes place. The optical functions obtained with MAD-X [9] were used, for optics version 1.3 of HL-LHC [10]. In this case, the target position was assumed to be at 1.69 m upstream from IP8 in the Beam 1 reference system. To each sampled beam particle, the offsets in angle and energy from a random final-state proton in the FLUKA simulation were added.

On this preliminary distribution, a cut is imposed requiring that the so-obtained particle coordinates are outside of the $5\sigma$ ellipse in either the X-X’ or the Y-Y’ normalized phase space. In such a way, the core is cut and only the beam halo that risks to be lost is retained for the tracking, saving time during the simulation. Initial studies showed that for elastic scattering, the fraction of protons from the core that receive a kick large enough to hit the collimators or aperture is negligible. For the H case, the fraction of discarded particles corresponds to 80.3% of the initial interacting particles, while for Xe it was necessary to cut up to 99.35%, coherently with the different angular distributions in Fig. 1.

The beam sampled in this way is finally used as initial distribution to track up to a total of 6 million particles with the SIXTRACK code including a collimation routine [11, 12, 13, 14]. Each particle undergoes a thin-lens element-by-element tracking through the HL-LHC lattice
Figure 1: **Top:** Distribution of the scattering angle with respect to the initial direction of 7 TeV protons after facing elastic interactions with H (blue) and Xe (red) target, as simulated with FLUKA. **Bottom:** Simulated energy distribution of elastically scattered protons after hitting H (blue) or Xe (red) target. Both histograms are normalised to the total number of incident protons.

Figure 2: **Top:** Distribution of the scattering angle with respect to the initial direction of 7 TeV protons after facing inelastic interactions with H (blue) and Xe (red) target, as simulated with FLUKA. **Bottom:** Simulated energy distribution of inelastically scattered protons after hitting H (blue) or Xe (red) target. The histograms only include the protons that did not disintegrate in the interaction (55% of the initial beam for H and 48% for Xe) and are normalised to the total number of incident protons.
for up to 200 turns, starting from the target position. Losses on collimators or on the aperture are recorded as outputs of the simulation and are later analyzed as described in Sec. 3.

Since the elastic scattering contribution was expected to be less significant than the inelastic one, only Beam 1 was tracked and only one target longitudinal position was considered within this routine.

2.2 Second simulation setup: inelastic interactions

The beam-gas inelastic scattering contribution was studied using an extension of the FLUKA-SixTrack coupling code [15, 16, 17]. When using the coupling, particles are tracked throughout the lattice by SixTrack and when they reach certain labeled sections (i.e. collimators or the target region), they are transferred to FLUKA, which simulates their interaction with the machine elements that are modeled using a 3D geometry. Surviving protons are passed back to SixTrack for further tracking.

This setup is endowed with a beam-target interaction feature, forcing the inelastic interaction of each primary particle with a customizable target during the first beam passage across the defined interaction region. The geometry for the beam-gas interaction region, implemented in FLUKA, was given by a dummy pipe with longitudinal length larger than a bunch length and the radius much larger than a bunch radius, filled with either H or Xe and centered at the target position. The interaction was forced to take place within a 20 cm-long portion of this pipe. Two positions of the centre of the target were studied (-3.0 m and -1.5 m upstream of IP8 in the Beam 1 reference system) to check for any dependence of the loss patterns on the target location.

The tracking was set to start at the entrance of the pipe, and a Gaussian beam was given as the initial particle distribution, sampled to have a matched beam at the tracking starting point, using the optical functions. The energy threshold for tracking was set to 1 TeV, while no energy or rigidity cuts were imposed in the particle exchange between FLUKA and SixTrack. Losses on collimators and on the aperture were recorded and later analyzed as described in Sec. 3. Inelastic interactions were studied using this simulation setup for both Beam 1 and Beam 2, and for Xe and H targets.

The scattering angle and energy distribution of the protons surviving the inelastic interaction were dumped and are shown in Figure 2 for comparison with the elastic case. It is noticed that both the energy and the angular deviations of final-state protons cover much wider ranges than in the elastic case.

3 Loss maps plotting and normalization

The beam losses that were obtained with the two simulation methods were analyzed by plotting the loss distributions at a given location along the HL-LHC circumference: the loss maps are expressed in W/m. In order to allow meaningful comparisons, it was necessary to normalize the loss spikes with respect to the specific beam-gas interaction rate $R$, which was calculated from:

$$ R \text{ [1/s]} = \text{cross section [cm}^2\text{]} \times \rho_{\text{gas}} \text{ [1/cm}^2\text{]} \times \text{beam current [1/s]}, $$

(1)
where $\rho_{\text{gas}}$ is the target areal density and the beam current was calculated as:

$$
\text{beam current [1/s]} = \frac{N_b \times n_b \times v_{\text{beam}} [\text{m/s}]}{\text{LHC circumference [m]}},
$$

with $N_b$ the number of protons per bunch, $n_b$ the number of bunches per beam, and $v_{\text{beam}}$ the beam speed.

The normalization procedure of the loss spikes was slightly different for the elastic and the inelastic scattering case. For the elastic case the local number of particles lost is divided by the total number of simulated interactions (we recall that the tracked particles only correspond to a small fraction of the total simulated interacting particles, as explained in Section 2.1, so the original number of events has to be restored from the number of tracked particles); the so-obtained local losses per proton-gas interaction event, is multiplied by the elastic interaction rate from Eq. (1) and by the initial energy of primary protons ($7.0 \times 1.6022 \times 10^{-7}$ J). Finally, every bin content of the resulting histogram is divided by its width: in such a way the power lost per meter [W/m] is plotted.

For the inelastic case, since the protons surviving the initial impact with the target show a wide energy range, the local lost energy is considered instead of the particle counts, and it is divided by the total energy lost along the circumference. Protons that do not survive the inelastic interaction, and hence are not tracked, are considered to be lost locally at the storage cell and therefore also accounted for in the normalization. In this case there is no need to restore an original interaction number, since the whole beam is tracked. The histogram obtained is multiplied by the inelastic interaction rate (from Eq. 1) and the initial primary proton energy, and divided by the bin widths, to obtain local losses in W/m.

To assess whether the cold losses are safe, we compare them to the quench limit. We conservatively assume the same limit of 5 mW/cm$^3$ that was used during the LHC design, which corresponds to about $7.8 \times 10^6$ p/m/s [18]. Multiplying by the beam energy, it corresponds to 8.75 W/m. In the cases where the cold losses were seen to exceed this limit, the maximum allowed gas density was calculated by re-scaling the losses in order to obtain the highest loss at that level. It is known today that this quench limit is well on the conservative side, and quench limits measured with beam are a factor of a few higher [19]. Nevertheless, we use it in order to have a safety margin and ensure that the presented results stay on the pessimistic side, in particular since the full shower is not simulated, which introduces an uncertainty.

The parameters for HL-LHC version 1.3 used within the present work are listed in Table 1, while Table 2 collects the gas densities considered, the cross sections assumed and the resulting interaction rates calculated with Eq. (1). These numbers are shown together with the proton-proton elastic and inelastic cross section and the event rate at IP8 (calculated from p-p cross section in the same table and an assumed luminosity of $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at IP8).
Table 1: Parameters assumed for the calculations. Machine and beam parameters are taken as for HL-LHC, version 1.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC circumference [m]</td>
<td>26658.8832</td>
</tr>
<tr>
<td>primary proton energy [TeV]</td>
<td>7.0</td>
</tr>
<tr>
<td>$\varepsilon_n$ [µm]</td>
<td>2.5</td>
</tr>
<tr>
<td>$N_b$</td>
<td>$2.2 \times 10^{11}$</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2760</td>
</tr>
<tr>
<td>Beam current [1/s]</td>
<td>$6.83 \times 10^{18}$</td>
</tr>
<tr>
<td>Luminosity at IP8 [cm$^{-2}$s$^{-1}$]</td>
<td>$2 \times 10^{44}$</td>
</tr>
<tr>
<td>IP8 s position (from IP1) [m]</td>
<td>23315.3790</td>
</tr>
<tr>
<td>Internal spectrometer angle at IR8 [µrad]</td>
<td>-135</td>
</tr>
<tr>
<td>External crossing angle at IR8 [µrad]</td>
<td>-250</td>
</tr>
<tr>
<td>Cold magnet quench limit [W/m]</td>
<td>8.748</td>
</tr>
</tbody>
</table>

Table 2: Assumed elastic and inelastic cross section and calculated interaction rate for 7 TeV protons on a H or Xe target at given density, shown together with the cross sections and event rates for 7 TeV proton-proton collisions at IP8 for comparison. A proton-proton luminosity of $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ is assumed.

<table>
<thead>
<tr>
<th></th>
<th>p-H</th>
<th>p-Xe</th>
<th>p-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas density [atoms/cm$^2$]</td>
<td>$1.0 \times 10^{14}$</td>
<td>$1.0 \times 10^{14}$</td>
<td>-</td>
</tr>
<tr>
<td>Elastic Cross Section [mb]</td>
<td>9.0</td>
<td>1000</td>
<td>24</td>
</tr>
<tr>
<td>Elastic Interaction Rate [MHz]</td>
<td>6.1</td>
<td>683</td>
<td>48</td>
</tr>
<tr>
<td>Inelastic Cross Section [mb]</td>
<td>38</td>
<td>1408</td>
<td>80</td>
</tr>
<tr>
<td>Inelastic Interaction Rate [MHz]</td>
<td>26</td>
<td>962</td>
<td>160</td>
</tr>
</tbody>
</table>

4 Results

4.1 Elastic interactions

In Fig. 3a (H) and 3b (Xe) the loss maps for elastic interactions are presented. The power lost per meter is plotted over the longitudinal coordinate $s$, starting from IP1. All loss maps have been normalized considering parameters and interaction rates as in Tables 1 and 2.

For comparison, we show in Fig. 4 a regular betatron cleaning loss map for a 12 min beam lifetime, which was obtained by tracking an annular beam halo impacting on the primary collimators in IR7 using the simulation method described in Ref. [13] for HL-LHC beam parameters. This plot represents the loss pattern for the most critical scenario of betatron losses that the collimation system has been designed to handle. During such irregular lifetime drops to 12 minutes, beam-target interaction loss maps, which instead are obtained simulating the whole beam for 200 turns, are to be considered as superimposed to such a regular loss map.

As expected, the elastic contribution is negligible with respect to the losses in Fig.4, and all the cold losses are orders of magnitude below the expected magnet quench limit, so these losses are not expected to be problematic. Notice that since only elastic events
are considered, all protons survive the scattering and no particle losses are recorded within the target itself. For the case of elastic interactions, the vast majority of lost protons have impacted first on the primary betatron collimators in IR7, meaning that the global pattern is similar to the betatron cleaning loss map.

### 4.2 Inelastic interactions

For what concerns the results of beam-gas inelastic interactions, simulations were performed for both H and Xe, considering a target position of either -1.5 m or -3.0 m from IP8 (in the Beam 1 reference system).

Loss maps are shown for a H target in Fig. 5 and Fig. 7 and for a Xe target in Fig. 6 and Fig. 8. Bottom plots zoom into the region extending from the target to a few hundred meters downstream, where the main losses are concentrated, and the lattice of the region is plotted on top (blue rectangles correspond to bending magnets, red to quadrupoles, yellow to sextupoles, light grey to multipoles, purple and pink to horizontal and vertical orbit correctors, and black lines to collimators). Notice the presence of the highest magenta bar at IR8 corresponding to the target itself: most of the protons are either lost during the inelastic interaction simulated by FLUKA and never exit the target region, or have too low energy to be tracked by SixTrack.

Differently from the elastic case, one can notice that the power absorbed in the momentum cleaning region (IR3) is now comparable to the betatron cleaning one (IR7). This is due to the broad energy range covered by the protons produced in the inelastic interaction, as shown in Fig. 2.

For both H and Xe targets, the highest losses in Beam 1 are recorded at s = 23553.4 m in cell 6 right of IR8, where a horizontal orbit corrector (MCBCH.6R8.B1) is located. The losses resulting from the proton-Xe interactions are more than one order of magnitude worse than the H case. Moreover, they exceed the cold magnet quench limit, since
Figure 4: Beam loss distribution around the LHC for Beam 1, 12 min lifetime, assuming the beam parameters of Table 1 and a horizontal halo. No interaction with gas targets is included. The maximum cold loss is found to be 20 W/m at $s = 23708.2$ m. Bin width set to 10 cm.

The highest cold loss reaches 72 W/m. This value was used to calculate the maximum gas areal density allowed to keep all the losses lower than the quench limit, obtaining $\rho_{\text{MAX}} = 1.21 \times 10^{13} \approx 10^{13}$ atoms/cm$^2$.

However, this value is possibly pessimistic, since the highest losses from inelastic interactions are recorded for Beam 1 on an orbit corrector, for which the quench limit is not well known, but likely higher than for the more sensitive main dipoles. The quadrupole just downstream is likely to intercept a large fraction of the shower, but this magnet is known to have about a factor 2 higher quench limit [19]. Almost as high losses are seen on the separation dipole D1, for which the quench limit is also not well known. Future dedicated energy deposition studies of the most critical impacted region, as well as quench limit studies on the different magnet types, could be used to improve the estimate on the maximum safe gas density. This was done for the proton-proton collisions in Ref. [20], where it is shown that, with the new TAS and TAN absorbers that will be installed, the triplet will withstand a proton-proton luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, which gives rise to an event rate just below the one from p-Xe interactions with a target density of $10^{14}$ atoms/cm$^2$.

For both gas species and beams, very similar losses are found for the two target positions. Differences of only up to a few percent are found, and we conclude that the losses do not depend strongly on the target position within the studied range.

The simulation results for the H target and Xe target in Beam 2 are shown in Fig. 7–8. In these figures, the beam travels from right to left. The absolute position of the target in the ring is always the same, which means that Beam 2 faces the target downstream of the LHCb detector. Notice that the main losses are now located on the opposite side of the target, as expected from the opposite beam direction, and look mostly symmetric with respect to the pattern from Beam 1.

All the maximum cold losses recorded for the simulations of beam-gas inelastic interactions are summarized in Table 3.
Table 3: Maximum cold losses recorded for simulations of inelastic interaction of a 7 TeV proton beam on the gas target.

<table>
<thead>
<tr>
<th>Target position from IP8 [m]:</th>
<th>Beam 1</th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td>-3.0</td>
<td>-3.0</td>
</tr>
<tr>
<td>H target max cold loss [W/m]:</td>
<td>4.1</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Xe target max cold loss [W/m]:</td>
<td>72</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>72</td>
</tr>
</tbody>
</table>

(a) H target at -1.5 m from IP8. Max cold loss: 4.1 W/m at s = 23553.4 m.

(b) H target at -3.0 m from IP8. Max cold loss: 4.1 W/m at s = 23553.4 m.

Figure 5: Beam loss distribution around the LHC, Beam 1 inelastic interactions with H target. Bottom plots show details of IR8. Bin width set to 10 cm.
Lossmap 7TeV beam, Xe target at -1.5 m from IP8, INELASTIC, Beam 1

Lossmap 7TeV beam, Xe target at -3.0 m from IP8, INELASTIC, Beam 1

(a) Xe target at -1.5 m from IP8.
Max cold loss: 72 W/m at s = 23553.4 m.

(b) Xe target at -3.0 m from IP8.
Max cold loss: 72 W/m at s = 23553.4 m.

Figure 6: Beam loss distribution around the LHC, Beam 1 inelastic interactions with Xe target. Bottom plots show details of IR8. Bin width set to 10 cm.
(a) H target at -1.5 m from IP8. Max cold loss: 2.6 W/m at s = 23150.0 m.
(b) H target at -3.0 m from IP8. Max cold loss: 2.6 W/m at s = 23150.0 m.

Figure 7: Beam loss distribution around the LHC, Beam 2 inelastic interactions with H target. Bottom plots show details of IR8. Bin width set to 10 cm.
(a) Xe target at -1.5 m from IP8. Max cold loss: 70 W/m at s = 23150.0 m.
(b) Xe target at -3.0 m from IP8. Max cold loss: 72 W/m at s = 23150.0 m.

Figure 8: Beam loss distribution around the LHC, Beam 2 inelastic interactions with Xe target. Bottom plots show details of IR8. Bin width set to 10 cm.
5 Conclusions

Simulations have been presented of the losses of scattered protons on the LHC magnets and collimators, produced by the interaction debris resulting from a 7 TeV beam impact on a fixed gas target upstream of IP8 in the Beam 1 reference system.

Elastic and inelastic beam-gas interactions were studied separately using the simulation methods presented in section 2.1 and 2.2. Both H and Xe targets were studied as limiting cases—all gas species of interest for the experiment have a mass in between. Elastic interaction simulations were performed for Beam 1, with the target located at -1.69 m from the IP. Inelastic simulations were performed for both Beam 1 and 2, with the target located at -1.5 m and -3.0 m from the IP. The dependence of losses on the longitudinal target position between 1.5 m and 3 m from IP8 was found to be very small.

For both species, the losses resulting from elastic interactions hit predominantly the betatron collimation system, and the leakage to the cold magnets is orders of magnitude below the assumed quench limit.

For inelastic interactions, the impact of the beam on an H target with areal density $\rho_{\text{gas}} = 1.0 \times 10^{14}$ atoms/cm$^2$ can be considered safe with respect to the magnet quench limit. This cannot be said for a Xe target of such a density. The highest losses on cold magnets were recorded for the case of Beam 1 hitting the target at -1.5 m from IP8 i.e., 72 W/m at S= 23553.4 m at a horizontal orbit corrector (MCBCH.6R8.B1). The maximum Xe density necessary to maintain all the losses below the LHC design quench limit is calculated to be $\rho_{\text{MAX}} \approx 10^{13}$ atoms/cm$^2$. This estimate is likely pessimistic and could be further refined through dedicated energy deposition and quench studies of the most impacted magnets.

In addition to the global view of the LHC ring presented in this note, the local energy deposition on the elements closest to the LHCb experiment should be studied. It is hoped that the additional protection that will be added in the future to cope with the proton-proton luminosity debris in High Luminosity-LHC (HL-LHC) [21] could be effective also in intercepting the local beam-gas debris, nevertheless, detailed simulations should be carried out to conclude, similarly to what has been done for standard proton-proton operation [20]. Future studies should also be done to assess potential radiation damage at the most impacted elements as well as possible effects on emittance blowup and luminosity lifetime from the beam-gas interactions.

References


MAD-X program. [http://cern.ch/mad/](http://cern.ch/mad/).


