SIMULATION OF BEAM-GAS SCATTERING IN THE LHC

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Abstract

We report on background studies for the LHC with detailed simulations. The simulations now include generation of beam-gas scattering in combination with multiturn tracking of protons. Low beta optics and available aperture files for this configuration make it possible to generate loss maps according to the pressure distribution in the LHC.

INTRODUCTION

The study we describe is part of a more general study to understand and optimize the experimental conditions in the LHC [1]. The LHC will soon start to run and produce proton-proton collisions which will be observed by four large experiments, installed at the four interaction regions IP1 (ATLAS), IP2 (ALICE), IP5 (CMS) and IP8 (LHCb) of the LHC. The LHC is designed for a high nominal luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This is a rather ambitious goal and will likely require several years of stepwise commissioning. In particular, it is planned to increase the single bunch intensity from a few 10^{10} protons per bunch to the nominal 1.15×10^{11} protons per bunch, to increase the collision energy from initially about $5\,\mathrm{TeV}$ to the nominal $7\,\mathrm{TeV}$ per beam, to decrease the transverse beam sizes at the interaction by decreasing β^*, and to increase the number of bunches circulating and colliding in the LHC. It is planned to start initial operation with $43 - 156$ bunches, which would allow sufficiently large bunch spacing to eliminate any parasitic beam encounters in the $\pm 58\,\mathrm{m}$ common beam pipe around each interaction region. At every stage, we will try to understand and minimize the machine induced backgrounds to be able to predict conditions for the next steps.

The LHC is equipped with a three stage collimation system [2], which is primarily designed to keep the flux of particle losses on the cold parts of the LHC machine below the quench level. The performance of the collimation system is simulated by following up secondary particles which first hit the primary collimators at small impact parameters. These primary halo losses are further reduced by secondary and tertiary collimators. A small fraction of these losses will impact on the tertiary collimators placed in the straight sections around the experiments and result in a small fraction of secondary particles which can reach the experimental detectors.

To allow to predict the total flux of beam induced machine backgrounds into the experiments, we have to consider any direct losses of the circulating protons as a result of the scattering of the protons with particles of the rest-gas in the beam pipe.

EVENT GENERATION

The collisions between the high energy protons and the residual gas are not implemented directly into the tracking tool. An interface is developed so that the collision events can be simulated prior to the tracking using DPMJET [3] as the event generator. The output format from DPMJET is simple and flexible, including a particle ID, energy and angles with respect to the angle of the incoming proton. It will be a straight forward task to replace or compare DPMJET with other event generators if that would be a request or a necessity at any point in time.

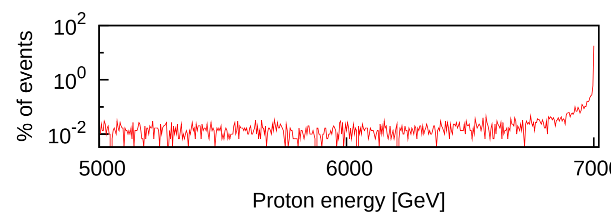

Figure 1: Percentage of events generating a proton with a given energy, from the scattering of $7\,\mathrm{TeV}$ protons with H atoms at rest. The elastic peak is observed for proton energy close to $7\,\mathrm{TeV}$.

So far, we simulate proton collisions with a H atom, and the H_2 equivalent pressure distribution (normalized by cross section ratios) is used in the simulations. A histogram of the energy distribution can be seen in Fig. 1. Recent discussions have emphasized that one in the future should simulate the collisions with all types of residual gas due to the different ratios of energy distribution and ratios of residuals. This inclusion is part of the future plans for this project.

PROTON TRACKING

The event generation is followed by tracking of protons around the LHC ring using SixTrack [4]. This kick-code tracking tool provides a fast tracking including collimation, providing multiturn tracking and the ability to study halo generation from beam-gas. The proton tracks are subsequently used in an aperture code, determining aperture losses. In order to track protons after the beam-gas event, it

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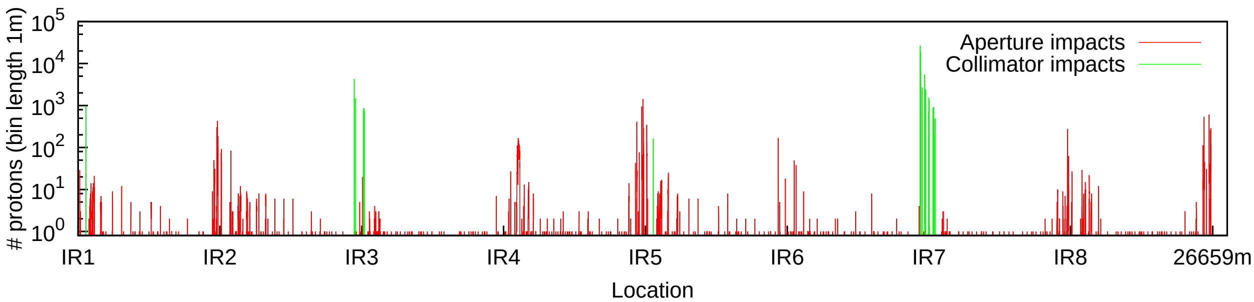

Figure 2: In about 22% of the scattering events, a proton with more than 90% of initial beam energy is generated. The loss locations of those protons are shown here. In addition, 78% of the events are generating locally lost particles only, and are not a part of this plot.

is required they are not very much off-momentum due to a reduced Hamiltonian. The exact limitations regarding off-momentum particles are under investigation, and results so far indicates that at least a few percent off momentum will not be a problem. In other words, since the dispersion limitation in the arcs is expected to be less than one percent, the code seems to be fitting for our purpose. What remains is the tracking of all residues in the long straight sections (LSS) and to compare tracking of protons with different tracking tools for the highly off-momentum particles over shorter terms.

Beam-gas scattering is normalized so that all particles in the simulation is scattered once during the first turn of tracking, according to given pressure distributions around the ring. Multiple beam-gas scattering is not considered since the probability of this to happen should be insignificant. For each type of parent atom, a separate tracking simulation will be ran. The output is then afterwards normalized according to

$$P(z) = \mathrm{lossMap}(z) \cdot \sigma_{\mathrm{tot}} \cdot \frac{n_{\text{p in ring}}}{n_{\text{p in sim}}} \cdot \frac{c}{r_{\mathrm{LHC}}} \cdot \oint p(z)dz.$$

In this equation, $\mathrm{lossMap}(z)$ is the losses at position z around the ring (according to the given pressure map), σ_{tot} is the total cross section for a beam-gas interaction (elastic and inelastic), $n_{\text{p in ring}}$ is the total number of protons stored in the LHC ring, $n_{\text{p in sim}}$ is the number of simulated events, $\frac{c}{r_{\mathrm{LHC}}}$ is the speed of light divided by the circumference of LHC which mounts to about 11 200 turns per second. Finally, $p(z)$ is the partial pressure distribution for the given parent atom.

The pressure distribution has been simulated by the vacuum group at CERN [5], and seems to correspond well with measurements (static pressure only as we have not had a high energy beam inside LHC yet). The plan is to include a full simulation with the partial pressure for at least four different gas residuals (H_2, CH_4, CO and CO_2). In the example shown below the simulated pressure distribution is not implemented. The implementation of a pressure distribution is ready, and will be included in future simulations.

Summarizing $P(z)$ for all residual gases that are included in the simulation, one then has the losses per second at location z. The output includes all particles generated, but only protons within a given off-momentum limit is tracked after the beam-gas event. The other particles are still part of the output, directly written to file from their position inside the beampipe. The same is true for particles coming out from a given event other than the high energy proton. They will be written to file at the location where the scattering event took place. The principle is that all particles are tracked as far as possible with our tool, but not further.

OUTPUT AND SIMULATION EXAMPLE

The output from the tracking includes particle type, 6D coordinates and current condition. This can be that the particle is still inside the beampipe or that it hit some aperture or a collimator. The output also includes the type of the parent atom in the scattering process and the event id so that one can keep track of what came out of a given event.

The output can be used as input for loss studies in the LSS. Similar studies has been performed in the past [6]. What is new here is the halo generation from the elastic scattering with the realistic residual gas pressure map, followed by multiturn tracking with the full LHC ring considered. The simulation does not give priority to any of the IRs, but is instead developed as a general tool where the losses in a given region can be extracted for detailed studies afterwards.

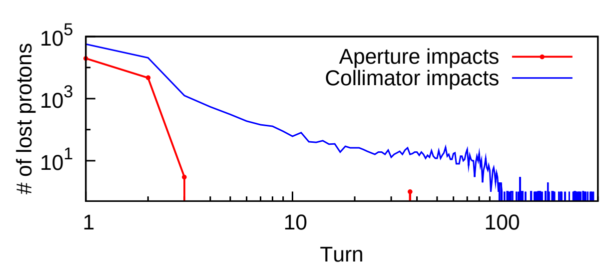

Figure 3: The spread of lost protons as a function of number of turns since the beam-gas event. After about 100 turns, there seems to be little to no losses anymore. Losses on aperture drops much faster, within the first few turns.

As an example run, 500 000 protons underwent a beam-gas scattering on a H atom and were subsequently tracked for 300 turns. For this example, the pressure were set constant around the entire ring. The off-momentum acceptance in the code is not yet well known, but was here set to 10%, which includes a proton from about 22% of the scattering events. 10% is at least an order of magnitude larger than the momentum acceptance in the arcs. The result can be seen in Fig. 2 and Fig. 3. The losses on aperture drops to zero within the first few turns, and the losses on the collimators drops by about three orders of magnitude in the same amount of turns.

If one wants to combine these data with data from the collimation studies [7], one should remember that there could a double count when considering the losses on the collimators. This is probably more present for protons surviving many turns before impact with the collimators. The losses on the collimators fall off more slowly after the first few turns before they more or less disappear after about 100 turns. Only one beam is simulated (clockwise rotation around the ring). Independent studies [8] have shown that for the clockwise beam the background is worse for CMS (IR5), whilst for the other beam the background is worse for ATLAS (IR1). This lossmap seems to be in agreement with such a statement, as we see more losses around IR5. The code is parallelized (hardcoded), so the simulation may run in a few hours on a large server.

The idea is that the simulation can be ran more or less automatically on a server when one has a new pressure profile to study (e.g. a pressure bump). Another possibility would be to run a very large simulation with a constant pressure map and map on the pressure profile to this simulation afterwards.

SUMMARY

The project presented is a work in progress. The output data are expected to be ready well in time before the LHC startup this fall. Amongst the first users of this code are probably LHCb and ALICE where the output provided from these beam halo simulations will then be used to estimate the background flux towards the detectors. ATLAS and CMS in collaboration with Fermilab use different tools for similar studies and from what has been seen until now the simulations seems to be consistent.

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