Preliminary study of constraints, risks and failure scenarios for the High-Luminosity insertions at HL-LHC

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Keywords: HL-LHC

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For the HL-LHC it is planned to basically double the diameter of the triplet quadrupole magnets around the high luminosity insertions of the LHC. The high luminosity experiments ATLAS and CMS would like to keep a small central chamber radius close the interaction point. We present a first study of the possible consequences of these changes for the experimental running conditions based on detailed simulations with tracking. We have started to implement crab cavity failures and discuss first results from these simulations.

Presented at:
5th International Particle Accelerator Conference, Dresden, Germany
Geneva, Switzerland
June, 2014
PRELIMINARY STUDY OF CONSTRAINTS, RISKS AND FAILURE SCENARIOS FOR THE HIGH LUMINOSITY INSERTIONS AT HL-LHC*

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Abstract

For the HL-LHC it is planned to basically double the diameter of the triplet quadrupole magnets around the high luminosity insertions of the LHC. The high luminosity experiments ATLAS and CMS would like to keep a small central chamber radius close the interaction point. We present a first study of the possible consequences of these changes for the experimental running conditions based on detailed simulations with tracking. We have started to implement crab cavity failures and discuss first results from these simulations.

INTRODUCTION

The High-luminosity LHC upgrade program aims at the production of a total integrated luminosity of 3000 fb\(^{-1}\) at the ATLAS (IP1) and CMS (IP5) detectors. Key parameters to increase the luminosity are the beam intensity together with the transverse sizes of the beams at the interaction point. The latter are directly given by the transverse emittances and by the value of the \(\beta\)-functions at the IP. The reduction in \(\beta\)\(^+\) results in smaller beam sizes at the IP, and at the same time in an increase of the beam divergence. This increases the beam sizes in the triplet magnets around the IP and also requires an increase in crossing angle. For HL-LHC the concept is based on a an Achromatic Telescopic Squeezing (ATS) [1] scheme. The main parameters of HL-LHC are given in Table 1 and compared to the present LHC design.

Table 1: Comparison between HL-LHC and LHC nominal parameters

<table>
<thead>
<tr>
<th>LHC nominal</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>7</td>
</tr>
<tr>
<td>(N)</td>
<td>1.15 (10^{11})</td>
</tr>
<tr>
<td>(n_b)</td>
<td>2808</td>
</tr>
<tr>
<td>bunch distance [ns]</td>
<td>25</td>
</tr>
<tr>
<td>(\beta^*) at IP(_{1,5}) [m]</td>
<td>0.55</td>
</tr>
<tr>
<td>(\epsilon_n) [(\mu m, rad)]</td>
<td>3.75</td>
</tr>
<tr>
<td>Crossing angle ((2\theta)) [(\mu rad)]</td>
<td>300</td>
</tr>
<tr>
<td>(\sigma_z) (bunch length) [mm]</td>
<td>75.5</td>
</tr>
<tr>
<td>(L_{\text{virtual}}) (^1) [cm(^{-2}) s(^{-1})]</td>
<td>1.2 (10^{34})</td>
</tr>
</tbody>
</table>

\(^1\) The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the FP 7 Capacities Specific Programme, Grant Agreement 284404.

For HL-LHC the number of bunches \((n_b)\) per beam will be kept the same, as well as the bunch distance: and consequently the collision frequency \(f\). The beams intensity \((N)\) will be increased. Consequently an increase of the crossing angle is needed to avoid parasitic encounters of the 25 ns spaced bunches; with a minimum 12 \(\sigma\) separation. The luminosity is also affected by the Hourglass effect but mainly by the geometrical effect of the crossing angle. Considering no beam offset on the transverse plane, the crossing angle contribution to luminosity is: \(1/\sqrt{1 + (\tan(\theta)\sigma_z/\sigma_{x,y})^2}\). To compensate this luminosity loss - due to the crossing angle increase - crab cavities will be installed before and after the IP to create a local rotation of the bunch along the longitudinal axis.

LAYOUT CHANGES

Key ingredients for the luminosity upgrade in the LHC are new large aperture Nb\(_3\)Sn triplet magnets and crab cavities for the high luminosity interaction regions in the LHC. The required crab cavity voltage depends on the the optical \(\beta\)-functions at the IP and at the cavity location [3]. The inner coil diameter of the triplet magnets will increase from the current 70 mm to 150 mm. In addition, the central beam pipes for ATLAS and CMS are already reduced in the present LHC shutdown to allow for the installation of higher resolution vertex detectors [5].

These apertures modifications are illustrated by Figure 1. A projection in the vertical plane at IR1 is given. Both colliding beams envelopes (at \(6 \times \sigma_{r ms}\)) are represented along the reference trajectory for the round HL-LHC optics [2]. Simplified sketches of the LHC apertures (before LS1), and the ones foreseen for HL-LHC, are also given.

Figure 1: Illustration of the aperture changes from LHC to HL-LHC at IP1.

Crab cavities will be inserted between D2 and Q4. One consequence is that D2 and the TAN (Target Absorber Neu-
tral) will be shifted closer to the IP. The absorbers TAS (Target Absorber Secondaries) at the entrance of the Q1 magnet and the TAN (Target absorber neutrals) in front of the separation magnet D2 will increase in aperture to accommodate for the increased beam sizes in the triplet region and the crossing angle increase. The main function of the TASs and TANs is to reduce the energy flow from collision debris into the superconducting magnets at the high luminosity interaction regions. In addition, the TAS and TAN absorbers may help to shield the experiments, from accidental beam losses, which could be more exposed due to the apertures increase around the IR.

POSSIBLE FAILURE SCENARIOS

From the LHC operation experience, several possible failure scenario or parasitic effects which could affect the detector operation were identified:

- **Backgrounds**: with the apertures changes, the background due to beam gas scattering, particle showers from the tertiary collimators or IR cross talk have to be evaluated.
- **Missing Beam-Beam deflection**: when only one beam is dumped, orbit perturbations on the remaining beam were observed. It appears to be due to the missing long range beam-beam interactions which is normally compensated by the accelerator settings.
- **Dump procedure failures**: An asynchronous beam dump can induce partial loss of the beam inside the LHC ring. For HL-LHC such accidental scenarios were already studied and presented in [4]. It was shown that heating overloads may be possible on the tertiary collimators close to ATLAS and CMS experiments.
- **UFOs**: Unidentified falling objects are micrometers size dust particles which can interact with the beam everywhere along the ring for several turns. They may induce very fast losses even in the detector chambers.
- **Crab cavities failures**: The failure of crab cavity or their control system may induce perturbation or a transversal kick on the beam orbits and substantial beam losses.

This failure scenarios list is non-exhaustive and here we just focus on the last two points: UFOs and crab cavity failures.

CONSIDERATIONS ON UFOS

It has been shown and observed that UFOs had a major impact on the LHC availability during the first run period [6]. It may also be a major performance limitation after LS1 with the energy increase and operation with 25 ns bunch spacing. Losses due to UFOs are localised in unusual locations: mainly in the injection kicker magnets and in the arcs. Nevertheless, a non negligible part of identified UFOs that caused beam dumps were triggered by the experiments. For the HL-LHC these doubts on the possible increase of triggers due to UFOs remains.

Figure 2 shows the trajectories of off-momentum particles, which could be generated by collision with dust particles.

We here assumed that Beam 1, at 7 TeV, hits a UFO in an area close to D2; just before the IP5. In this scenario there is a chance to produce off-momentum (w.r.t the beam momentum) scattered protons. With the aperture changes, some scattered particles may now interact directly with the detector chamber (for example: off-momentum particle by 30 %). In the current LHC configuration these particles would end up in the triplets shielding or in the TAS.

We are planning more detailed simulations, which should allow for quantitative estimates of the risks for damage in the detector region. These studies are performed in close collaboration with the LHC experiments in the framework of machine-detector interface (Work package 8) for the high luminosity LHC upgrade. For ATLAS, studies using a GEANT4 model are ongoing to evaluate the possible impact of scattered or secondary particles generated by UFO. In the mean time, the LHC second run period should bring more statics on the UFOs “availability impact” as well as the new mitigation strategies [6].

CRAB CAVITIES FAILURE SCENARIOS

**Principle**

As previously explained, Crab cavities (CCs) will be installed upstream and downstream IP1 and IP5 to increase the luminosity. In the present HL-LHC optics scheme, triplets of crab cavities will be used to apply a transverse kick which depends on the longitudinal position ($z$) of the particle within the bunch. it can be express as:

$$\Delta_{pt} = \frac{q}{E} V_0 \sin \left( \frac{\omega_0 z}{c} + \Phi_x \right)$$  \hspace{1cm} (1)

with $q$ the particle charge, $E$ its energy, $\omega_0$ the CC angular resonance frequency, $\Phi_x$ the synchronous phase and $V_0$ the voltage amplitude which depends on the $\beta$-functions and the crossing angle [7]. In normal operation $\Phi_x = 0$: particles at the centre of the bunch are not affected by the cavity field. But if an RF failure occurs and $\Phi_x \neq 0$ then the bunch may be kicked from its nominal orbit. And if the voltage...
quickly drops down, the crabbing (or uncrabbing) effect is not complete but still fully compensated by the cavities on the other side of the IP : this also induces perturbation on the beam.

**Failures simulations**

Beam based tests during the first LHC run period showed that the transverse particle distribution in the LHC is far from an ideal Gaussian distribution. Highly overpopulated tails containing up to 4.5 % of the beam beyond 4σ (measured beam size) from the beam centre were observed [8]. This corresponds to a stored energy of about ∼15 MJ for nominal operation. In a fast failure scenario, one has to ensure that these particles are intercepted by the collimation system and not lost in sensitive area.

In this context extensive tracking simulations [10] [11] have been carried out with a modified version of the SixTrack code; which includes the HL–LHC collimation system [9]. For these simulations two types of scenarios have been considered :

- Voltage failure : the voltage of a CC drops down to 0V and the synchronous phase remain 0.
- Phase failure : the phase moves from 0° to 90° and the cavity voltage remain at its nominal value.

Several dynamics for the voltage, or the phase, variation have been considered. Here we will just comment on the worst case scenarios when the voltage (respectively the phase) drops to 0V (respectively 90°) in one beam turn (∼ 100 μs). Our simulations showed that even 10 turns after such a drastic failure, most of the core of the beam is not lost. To increase the statistics we therefore choose to only simulate particles beyond 3σ in the transverse phase space. In the longitudinal phase space, all the positions are considered and the beam is matched in the RF bucket according the HL–LHC nominal parameters.

As an example of failures studies, Figure 3 shows the repartition of the losses on beam 1, after a phase failure of the first CC located upstream IP5. These losses are recorded for 10 turns after the failure. For this typical scenario one can see that most of the particles are absorbed by the collimation system in IR7. The detector regions are almost not affected, with very few absorbed particles in the tertiary collimators. In addition, no losses occurred in the detectors apertures.

More statistics can be found in [10], and all the results of these preliminary studies confirm that the detector should be protected by the collimation system. Still, advanced simulations with simultaneous cavities failures have to be carried out with a more realistic model of the CC. It is also necessary to fully ensure that no safety threshold will be reached (magnet quench, collimators limits). Nevertheless, it is important to notify that the simulated scenarios were quite pessimistic. Indeed, when a failure occurs we assume that 10 turns are needed to dump the beam. This is more than three times longer than the nominal procedure at LHC. In addition, it is also envisaged to mitigate the failure, by decreasing the voltage in all the CCs once the failure is detected. Some preliminary simulations gave very optimistic results showing it is possible to decrease the losses from ∼ 75 % up to ∼ 95 %; depending on the type of failure [10].

**CONCLUSION**

We discussed the first tracking simulations in HL–LHC for crab cavity failure scenarios. With rather pessimistic assumption, the results tend to show that for this type of failure the experiments will remain protected by the collimators and the beam dump procedure. Still, more work is in progress to improve the model and evaluate with more accuracy the deposited energy in the collimators. We also presented basic considerations on UFOs which could finally represents a more critical danger for the experiments. The risk study is in progress, in particular for ATLAS with GEANT4 model developments. In the mean time, The next LHC run should bring substantial informations about the UFOs risks around the interaction regions.

**ACKNOWLEDGMENT**

The authors would like to thank T. Baer, J. Barranco Garcia, R. Bruce, R. Calaga, F. Cerutti, R. De Maria, B. Di Girolamo, L. Lari, A. Lechner, A. Marsili, S. Redaelli, A. Sbrizzi and M. Zerlauth for their comments, help and constructive discussions.

**REFERENCES**