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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 tracking simulations. 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 beam emittances and by the value of the β-functions at the IP (β^*).

Table 1: HL-LHC and LHC Nominal Parameters

	LHC nomi.	**HL-LHC**
Energy [TeV]	7	7
N	$1.15\ 10^{11}$	$2.2\ 10^{11}$
n_b	2808	2808
bunch distance [ns]	25	25
β^* at $\text{IP}_{1,5}$ [m]	0.55	0.15
ϵ_n [μm rad]	3.75	2.5
Crossing angle (2θ) [μrad]	300	590
σ_z (bunch lenght) [mm]	75.5	75.5
$L_{virtual}$ [1] [$\text{cm}^{-2}\ \text{s}^{-1}$]	$1.2\ 10^{34}$	$2.2\ 10^{35}$

The reduction in β^* 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 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. For HL-LHC the number of bunches (n_b) per beam will remain the same, as well as the bunch distance: and consequently the collision frequency. The number of particles per bunch (N) will be increased while β^* will be decreased. An increase of the crossing angle is consequently needed to avoid parasitic encounters of the 25 ns spaced bunches; with a minimum 12 σ 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 separation 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_3Sn triplet magnets and crab cavities for the high luminosity interaction regions in the LHC. The required crab cavity voltage depends on the β-functions at the IP and at the cavity location [2]. 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 [3].

These apertures modifications are illustrated in Figure 1. A projection in the vertical plane at IP1 is given. Both colliding beams envelopes (at 6σ) are represented along the reference trajectory for the round HL-LHC optics [4]. Simplified sketches of the LHC apertures (before LS1), and the ones foreseen for HL-LHC, are also given.

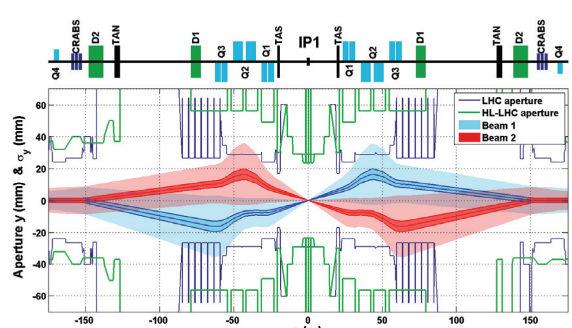

Figure 1: Illustration of the aperture changes from LHC to HL-LHC at IP1.

Crab cavities will be inserted between D2 and Q4. One consequence is that D2 and the TAN (Target Absorber Neutral) will be shifted closer to the IP. The TAS (Target Absorber Secondaries) at the entrance of the Q1 magnet and

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[1] These numbers correspond to the virtual luminosities for head-on collisions. With crossing angle on: $L = 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$ for the nominal machine, and for HL-LHC the luminosity is levelled to $5\ 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$.

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the TAN 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 TAS and TAN is to reduce the energy flow from collision debries into the superconducting magnets at the high luminosity interaction regions (IR). 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 aperture 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 [5]: 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.
- 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 [6]. 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 [5]. 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 HL-LHC, there are remaining doubts on the possible increase of triggers due to UFOs.

Figure 2 shows the off-momentum particle trajectories, 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 IP5. In this scenario there is a

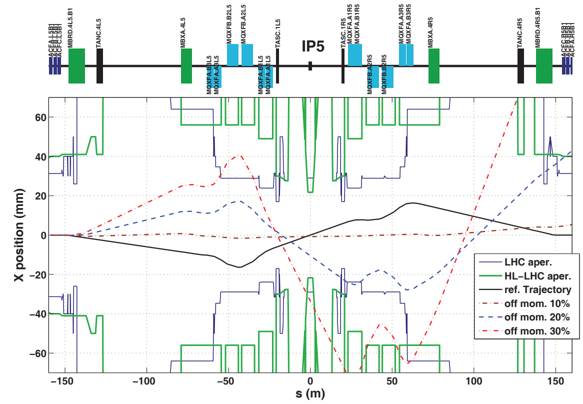

Figure 2: Possible trajectories in the horizontal plane of off-momentum particles which may be produced by the interaction of the beam with a UFO around IR5.

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: 30 % off-momentum particle). In the current LHC configuration these particles would end up in the triplet 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 statistics on the UFO machine availability impact as well as on the new mitigation strategies [5].

CRAB CAVITIES FAILURE SCENARIOS

Principle

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 expressed as:

$$\Delta p_t = -\frac{q}{E} V_0 \sin\left(\frac{\omega_0 z}{c} + \Phi_s\right) \quad (1)$$

with q the particle charge, E its energy, ω_0 the CC angular resonance frequency, Φ_s the synchronous phase and V_0 the voltage amplitude which depends on the β-functions and the crossing angle [7]. In normal operation $\Phi_s = 0$: particles at the centre of the bunch are not affected by the cavity field. But if an RF failure occurs and $\Phi_s \neq 0$ 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

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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 [5]. In a fast failure scenario, one has to ensure that these particles are intercepted by the collimation system and not lost in sensitive areas.

In this context extensive tracking simulations [9] [10] have been carried out with a modified version of the Six-Track code [11]; which includes the HL-LHC collimation system [12]. For these simulations two types of scenarios have been considered:

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

Several voltage, or phase, speed variation have been considered. Here we just comment on the worst case scenarios: corresponding to a voltage (respectively a phase) drop to 0 V (respectively 90°) in one beam turn (~ 100 μs). The performed simulations showed that even 10 turns after such a drastic failure, most of the beam core is not lost. To increase the statistics only particles beyond 3σ in the transverse phase space were simulated. 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, Figure 3 shows the losses distribution of 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 betatron collimator 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.

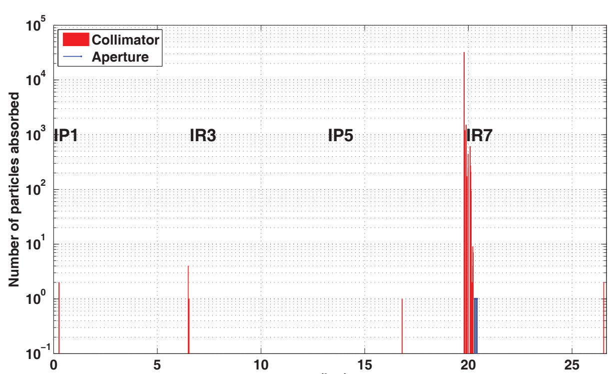

Figure 3: Results of a tracking simulation with 6.4 million particles : losses along the ring during 10 turns after the phase failure of one CC at IP5.

More statistics can be found in [9], 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, maximum deposited energy in collimators). Nevertheless, it is important to point out that the simulated scenarios were quite pessimistic. Indeed, when a failure occurs it is assumed 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 by at least ~ 75 %; depending on the type of failure [9].

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 represent 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 UFO risks around the interaction regions.

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