Chapter 5

Interface with Experimental Detector in the High Luminosity Run

H. Burkhardt

CERN, BE Department, Genève 23, CH-1211, Switzerland

This chapter describes the upgrade of the interaction regions as relevant for the experiments.

1. Introduction

The machine upgrade for high luminosity requires major changes on the machine side. Key ingredients for the luminosity increase are larger apertures in the focusing sections around the experiments and higher beam intensities.

The experiments are upgraded for reduced inner beam pipes with more powerful vertex detectors. This is important for physics and essential for the increased pile-up. Other key design considerations for the upgraded LHC detectors include longevity at increased radiation levels and minimization of activation.

As is often the case in machine-detector interfacing, these are to some extent conflicting requirements, which require a coherent planning for experiments and machine together.

2. Overview of the Main Changes Relevant for the Experiments

In this chapter, we discuss more generally hardware changes of relevance to the experimental regions, with respect to the original design of the LHC as described in the LHC design report [1]. The changes required for the high-luminosity upgrade and the requests and planning of the experiments for the future running of the LHC have been discussed in two joint machine-experiments workshops [2, 3].

Figure 1 shows the schematic layout of the LHC with its four interaction regions.

The HL-LHC design is for four experiments, the two high-luminosity experiments ATLAS and CMS at IR1 and IR5, and the ALICE and LHCb experiments installed at IR2 and IR8.

Fig. 1. Schematic layout of the LHC with its four interaction regions which provide collisions to the ALICE, ATLAS, CMS and LHCb experiments.

Table 1 shows the target luminosities for the experiments in proton–proton collisions in the LHC as originally designed, and for the high-luminosity upgrade. The main luminosity upgrade is for the interaction regions IR1 and IR5 and will be implemented in the long shutdown LS3.

The ALICE and LHCb experiments installed in IR2 and IR8 will have their most significant detector upgrades during LS2 scheduled in 2018/2019 and will continue to run after LS3.

LHCb has asked for a luminosity increase up to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. This is possible without changes to the magnet layout in IR8 and the required detector and vacuum beam pipe upgrades can be implemented in the long shutdown LS2.

Table 1. Target luminosities $\mathcal{L}$ for p-p operation for the LHC and HL-LHC. For the HL-LHC, the ATLAS and CMS target luminosities include luminosity leveling which will allow for constant luminosities for the first hours during a fill.

IR	LHC $\mathcal{L}, \text{ cm}^{-2} \text{ s}^{-1}$	HL-LHC $\mathcal{L}, \text{ cm}^{-2} \text{ s}^{-1}$	Experiment
1	1×10^{34}	5×10^{34}	ATLAS
2	1×10^{31}	1×10^{31}	ALICE
5	1×10^{34}	5×10^{34}	CMS
8	4×10^{32}	2×10^{33}	LHCb

It should be accompanied by an improved shielding (including a minimal TAN at D2), to minimize the impact of the increase in radiation and heating of cold machine elements [4].

The low target luminosity for ALICE in p-p operation will require collisions with large transverse offsets.

The experimental programs of other smaller experiments (LHCf, TOTEM) do not extend beyond LS3.

In discussion with all experiments in the HL-LHC coordination working group during 2013, it was confirmed, that the LHC machine upgrade design can be considered as dedicated to high-luminosity and should not be constraint by other modes of operation, which can be completed before LS3. High- β^* ($\gg 100$ m) operation is not planned after LS3 and far detectors (ZDCs, roman pots, Hamburg beam-pipes) are not foreseen in IR1 and IR5 after LS3. While new proposals for extra detectors or special running conditions are not *a priori* excluded, they are not included in the HL-LHC design considerations and should not limit the high-luminosity performance of the HL-LHC.

The magnet layout in IR1 and IR5 will change significantly. This is shown schematically in Fig. 2 for the first 80 m from the interaction point and discussed in more detail in the following chapters [5]. Details like the exact length of the new triplet magnets are still under discussion. The distance of the first quadrupole magnet (Q1) from the IP will remain the same (23 m) as before the upgrade.

The most relevant machine modification for the experiments will be the installation of the new large aperture triplet magnets Q1–Q3 in IR1 and IR5. The inner coil diameter of these triplet magnets will increase by roughly a factor of two from 70 mm to 150 mm.

Fig. 2. Schematic magnet layout for the current LHC (top) and the HL-LHC in IR1 and IR5 (bottom) up to first separation magnet D1.

As presently the case, the magnet layout will be the same for IR1 and IR5, and also remain approximately left/right anti-symmetric with respect to the interaction points.

3. Experimental Beam-pipes

The four large experiments have asked for reductions of the diameter of the central beam pipes. Table 2 summarizes the original and reduced inner beam pipe radii [7]. For ATLAS and CMS the new beam pipes are installed during LS1. The reduction for ALICE has been requested but not yet approved from the machine side. The LHCb VELO is movable. It is only closed in stable physics to the value shown in the table, and retracted to 30 mm otherwise [6].

Table 2. Original and reduced inner beam pipe radii at the IPs.

IP	Original $r_{\min}$ mm	Reduced $r_{\min}$ mm	Experiment	When
1	29	23.5	ATLAS	LS1
2	29	18.2	ALICE	LS2
5	29	21.7	CMS	LS1
8	5	3.5	LHCb, VELO	LS2

The reduction of the central beam pipes for IR1 and IR5 was approved on the machine side for operation up to LS3.

4. TAS, TAN

The high-luminosity interaction regions IR1 and IR5 are equipped with 1.8 m long copper absorbers called TAS at 19 m from the interaction points, located in front of the first superconducting quadrupoles Q1, see Fig. 3.

Their primary function is to reduce the energy flow from collision debris into the superconducting quadrupole triplet magnets [8]. In addition, the TAS also acts as a passive protection. It reduces the flux of particles into the inner detectors of ATLAS and CMS in case of abnormal beam losses. The inner radius of the TAS as presently installed is 17 mm both in IR1 and IR5. This is significantly less than the central beam pipe radius of ATLAS and CMS. The radius of the reduced central beam pipes installed in LS1 was chosen such that they still remain in the shadow of the TAS, including alignment tolerances and sagging. This is of direct relevance for high- β^* operation in the LHC, where the beam size is approximately constant throughout the experimental regions.

For the HL-LHC upgrade, the inner coil diameter of the triplet magnets will increase from 70 mm to 150 mm. The inner TAS radius will also have to be increased from 17 to approximately 27 mm, which will be significantly larger than the radius of the central beam pipes. The TAS material, length and outer dimensions may remain as originally designed. Additional shielding will be installed around the beam screens in the triplet region. The energy deposition for the enlarged TAS to the triplet magnets has been determined by simulations and remains within specifications, see Chapter 10.

Increasing the central beam-pipes after LS3 in the same proportion as the inner TAS radius would compromise the vertex detector performance. Optimal vertex resolution for ATLAS and CMS is essential to deal with the increased pile-up after LS3. The working strategy is that we assume that the beam pipe radii will remain after LS3 at the reduced values given in Table 2, and to assure by detailed tracking simulations including all relevant failure cases and by fast active protection (beam loss detection and dump) that LHC operation will remain safe for the experiments at the HL-LHC, in spite of increased intensities and apertures.

There will also be major changes further outside in IR1 and IR5. The D2 magnet and neutral absorber TAN which is located in front of the D2 magnet will move by 13 m closer to the interaction points, to make space available for the installation of the crab cavities. The β -functions at the TAN will increase and require a larger TAN aperture. The half-crossing angle will roughly double for the HL-LHC (from typically 142.5 to 295 μ rad) and move the neutral cone from collision debris closer to the beam aperture of the TAN. The TAN surrounds both beams and also acts as passive absorber for the incoming beam. The increase in TAN aperture results in a reduction of passive protection compared to the present LHC, which can be minimized by closer matching of the holes through the TAN to

Fig. 3. Layout right of IR5 (CMS) with the TAS.

the beam geometry and by addition of movable collimators. Details remain to be worked out.

It appears un-avoidable, that the ATLAS and CMS detectors will be more exposed to accidental beams losses and machine induced backgrounds after LS3. Understanding, minimizing and mitigating any un-avoidable negative impact of the machine upgrade to the experiments is a key objective for the machine detector interface for the HL-LHC [2].

5. Failure Scenarios and Experiments Protection

Active machine protection, based on continuous beam loss monitoring (BLM) and fast beam dump (within 3 turns) has already been proven to be essential and reliable for the present LHC [9]. It will be even more important for the HL-LHC. In addition to the protection of the machine elements which will be discussed in a later chapter, we will have to rely on active protection for the experiments. This implies, that we have to identify all relevant failure scenarios which may result in significant beam losses to the experiments, and to make sure that these abnormal beam losses can be detected sufficiently fast and beams be dumped before they cause any significant damage to the experiments.

Detailed studies with particle tracking have started.

Most critical for experiments protection is the operation at top energy with squeezed beams. The potentially most relevant failures scenarios for the HL-LHC are:

- Crab cavity failures [10, 11];
- Asynchronous beam dumps [12];
- Mechanical non-conformities, i.e. objects which accidentally reduce the aperture (example rf-fingers) or UFO's (dust particles falling through the beam) resulting in showers with local production of off-momentum and neutral particles around the experiments [14].

Other more or less dangerous scenarios do exist and will also be followed up, together with any changes which may result in increased beam losses into the experiments:

- D1 magnet failures. The present 6 warm D1 magnets at either side of IP1 and IP5 will be replaced with single superconducting D1 magnets. It is expected that this will result in longer time constants in case of D1 trips, which would leave more time to safely dump the beams in case of D1 failures.

- Injection (kicker) failures and grazing beam impact on injection elements (TDI).
- Check that any new equipment and in particular moving objects are compatible with experiments protection. It was already decided to not use fast vacuum sector valves close to the experiments.
- Experiments protection for ALICE in IP2 and LHCb in IP8 with reduced beam pipes for HL-LHC beam parameters.

Figure 4 shows a schematic view of IR5 with beam envelopes and apertures. Beam-pipe apertures are shown as lines as implemented in present simulations, both for the LHC as originally build for RUN 1 (dark blue lines), as well as for the HL-LHC after LS3 (green). The colored bands show 5σ beam envelopes for $\beta^* = 15\text{ cm}$ as relevant for the HL-LHC. Two off momentum tracks with $\Delta p/p = -20\%$ and -30% are also shown. A -30% track originating at 150 m from the interaction point (originating by collisions of beam particles with dust particles, for example) will pass through the enlarged HL-LHC apertures and directly hit the central experimental beam pipe.

Figure 5 illustrates the beam envelope growth induced by an immediate 90° phase jump on a single crab cavity.

Early simulations suggest a growth of amplitudes by 14% within 5 turns. This would be a very fast, and potentially dangerous failure scenario. Detailed simulations also predict where the particles will be lost. As can be generally expected, the

Fig. 4. Schematic view of IR5 with beam envelopes and apertures.

Fig. 5. Schematic view the beam envelope growth induced by a crab cavity failure, resulting in a growth of 14% within 5 turns.

first simulations with crab cavity failures indicate that the losses will be mostly in the collimation sections and that only a small fraction will reach the experiments.

More detailed and complete simulations are being prepared. It is planned to develop a detailed model of the transient behavior of crab cavities. It is also planned to provide for fast detection of failures directly at the crab cavities and to reduce the effect on the beams, for example by turning cavities off on both sides of the interaction region in case of a single cavity trip. See also the chapters on crab cavity developments and machine protection. A close collaboration between the machine and experiments teams has started to re-design the beam pipe-layout in the experimental section. The CT2 chamber of CMS at approximately 15 m from the IP will have to be enlarged. Easy access and reduced activation (using preferentially lighter elements like Aluminium) are also important, for access and repair.

6. Machine Induced Backgrounds

Machine induced backgrounds in the LHC are dominated by beam gas scattering. Beam gas backgrounds scale with the beam intensity and vacuum pressure and are to a large extent generated locally in the straight section and dispersion suppressors around the experiments. Under normal conditions, they depend only weakly on optics details and collimator settings.

Background conditions have generally been very good in RUN 1 of the LHC [13]. Signal to background ratios of the order of 10^4 were observed in good running conditions in ATLAS and CMS in RUN 1.

For ALICE, which operates at much lower luminosity, machine induced backgrounds were already significant in proton–proton running even under good running conditions. Excellent vacuum conditions (pressures below 5×10^{-9} mbar) are essential for ALICE. During part of the proton–proton operation in 2012, machine induced backgrounds in ALICE were too high to permit data taking. This was related to heating in the injection absorber (TDI) region and is expected to improve in RUN 2 after hardware modification including increased pumping in IR2, implemented in LS1.

There are several reasons why machine induced backgrounds could increase a lot in future LHC operation. Continued efforts to monitor, understand and minimize backgrounds are important for all experiments.

Detailed tracking simulations for the HL-LHC have recently been started and will have to be updated as details of the new layout become available. From what we know so far, the detectors will be more exposed to machine induced backgrounds by the increase in apertures. The possible increases of backgrounds from geometry are expected to be moderate, below an order of magnitude and may partially be compensated by going to lighter structures in the central detector region, which reduce the number of secondary particles produced. Since luminosities will increase as well, the signal to background ratio should still remain comfortable for the high-luminosity experiments.

An increase in residual gas pressure would directly translate into increased backgrounds. Potential reasons for an increase are:

- synchrotron radiation, main step here will be the increase from 4 to 6.5 TeV at beginning of RUN 2;
- electron cloud due to reduced bunch spacing, main step 50 ns $\rightarrow$ 25 ns at beginning of RUN 2;
- electron cloud due to increased bunch intensities;
- local heating from increased intensities.

Two major changes, the increase in beam energy and the reduction in bunch spacing will already happen at the beginning of RUN 2. Observing and understanding backgrounds in RUN 2 by comparison with simulations and experience from RUN 1 should provide us with very valuable information for the optimisation of the experimental conditions at the HL-LHC.

References

- [1] O. Brüning *et al.* (ed.), LHC design report, Vols. 1–3, CERN-2004-003-V-1–3.
- [2] H. Burkhardt, D. Lacarrere and L. Rossi, Executive summary of the 1st Collider-Experiments Interface Workshop on 30 Nov. 2012.
- [3] ECFA High Luminosity LHC Experiments Workshop, Aix-Les-Bains, 1–3 Oct. 2013.
- [4] L. Esposito *et al.*, in *Proc. IPAC 2013*, tupfi022.
- [5] Magnets for Insertion Regions, HL-LHC work package 3.
- [6] M. Ferro-Luzzi, presentation in LMC 159 on 12/12/2012.
- [7] LHC Experimental Beampipes Committee, LEB.
- [8] N. Mokhov *et al.*, CERN-LHC-PROJECT-REPORT-633.
- [9] Machine protection, HL-LHC work package 7.
- [10] F. Bouly *et al.*, Preliminary study of constraints, risks and failure scenarios for the high luminosity insertions at HL-LHC, in *Proc. IPAC 2014*.
- [11] B. Y. Rendon, Simulations of fast crab cavity failures in the HL-LHC, contribution Presentation at the Annual HL-LHC meeting, Oct. 2013, Daresbury.
- [12] L. Lari *et al.*, Simulations of beam losses on LHC collimators during beam abort failures, in *Proc. IPAC 2013*.
- [13] Y. Levinsen, Machine Induced Experimental Background Conditions in the LHC, CERN-THESIS-2012-132 and LHC background study group: <http://cern.ch/lbs>.
- [14] T. Baer, Very fast losses of the circulating LHC beam, their mitigation and machine protection, PhD Thesis, 2013.